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A COMMUNICATION - LINK APPROACH
TO ACTUATION OF GRADE-CROSSING
MOTORIST-WARNING SYSTEMS

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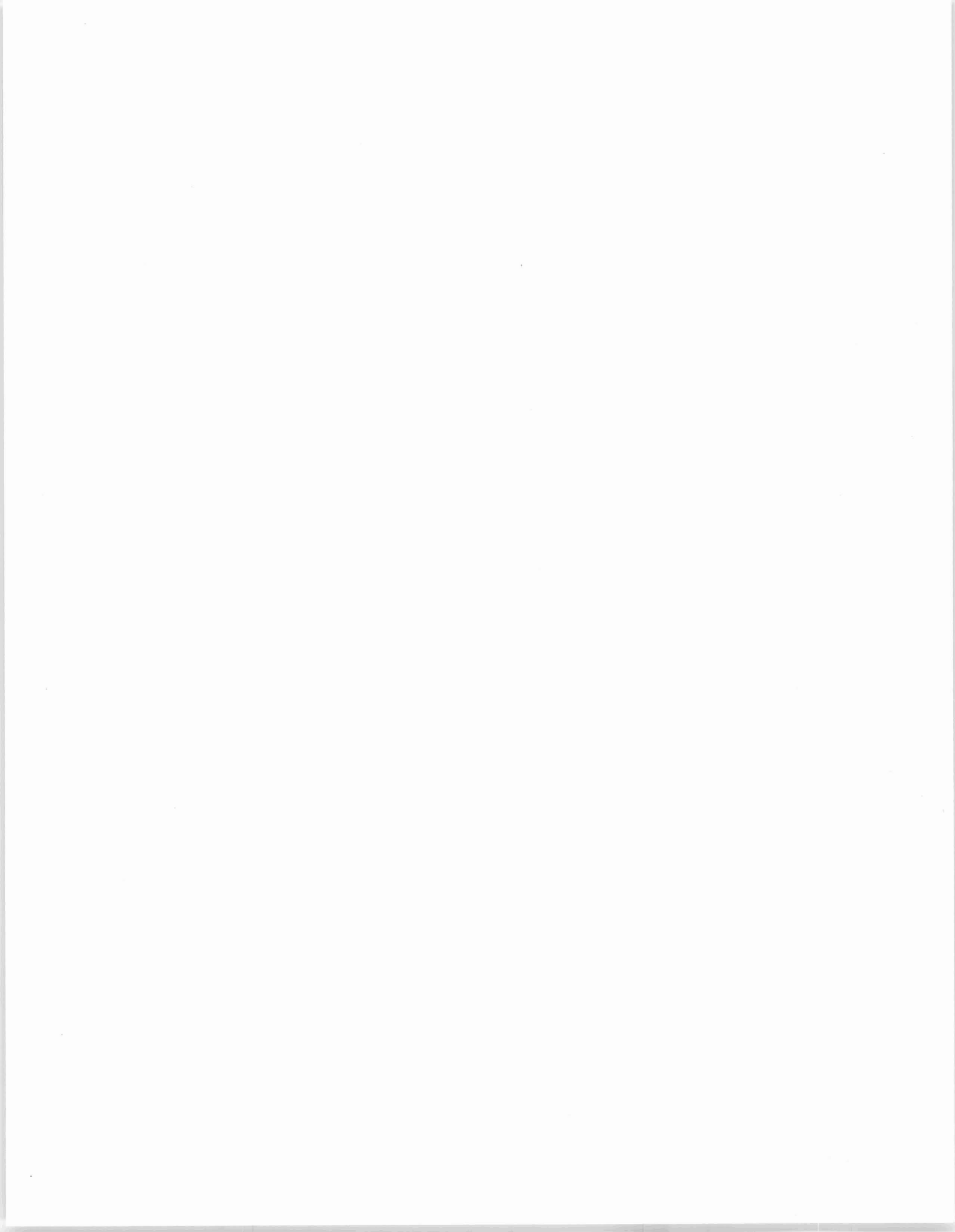


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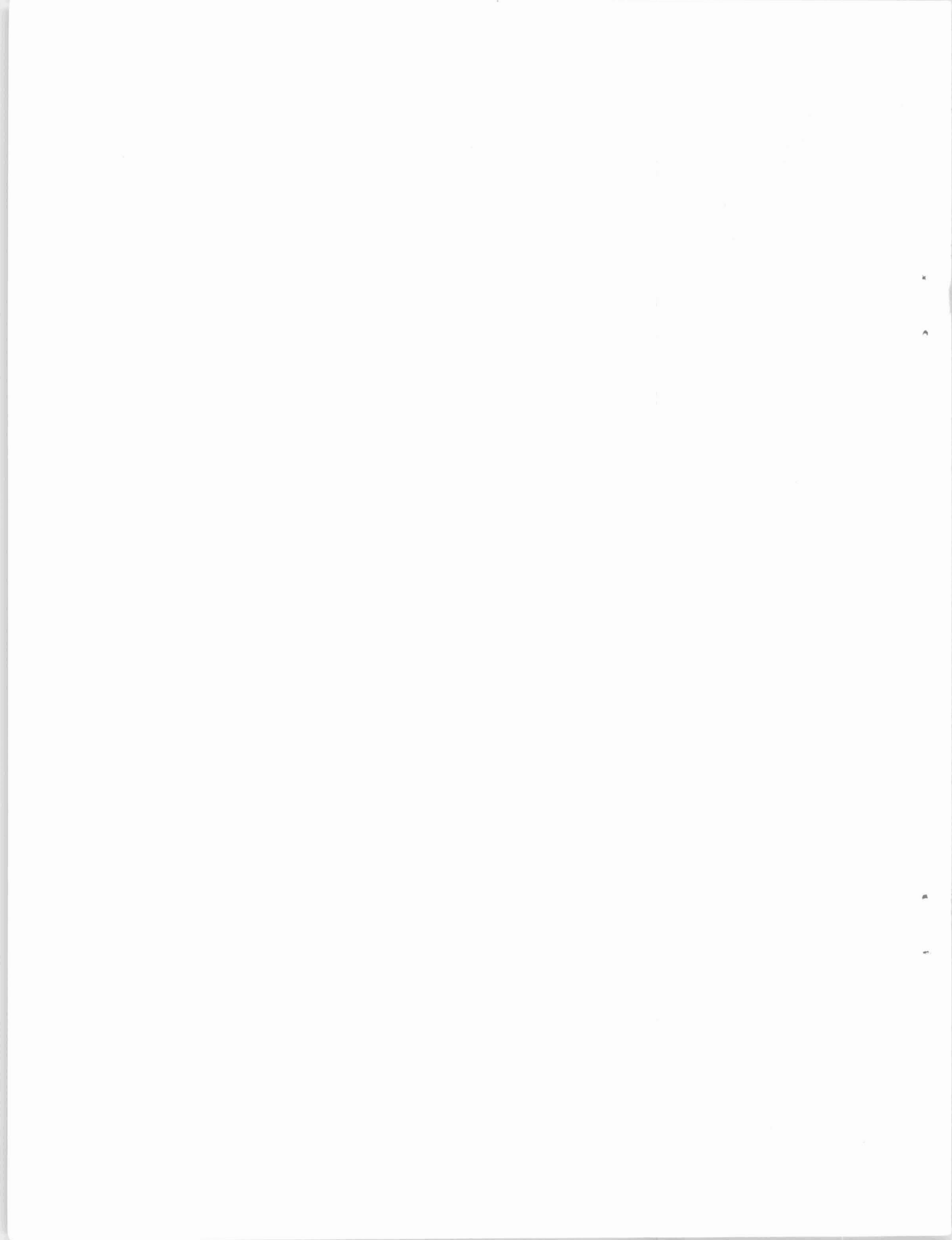
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16. Abstract Previous studies indicate that one promising avenue to grade-crossing motorist-warning systems, offering lower cost and independent of railroad-track circuits, is use of a radio-communication link for signal activation. By this means, the presence of a train approaching a crossing can be communicated to the crossing from an appropriate distance. This study describes analysis, development, and test activities carried out at the Transportation Systems Center to determine the basic feasibility and practicality of a microwave realization of this approach. A brief review of the conceptual framework is followed by detailed discussion of field-test procedures and results, with special attention then given to train detectors, microwave-propagation aspects, use of solar power, and radar train detection.					
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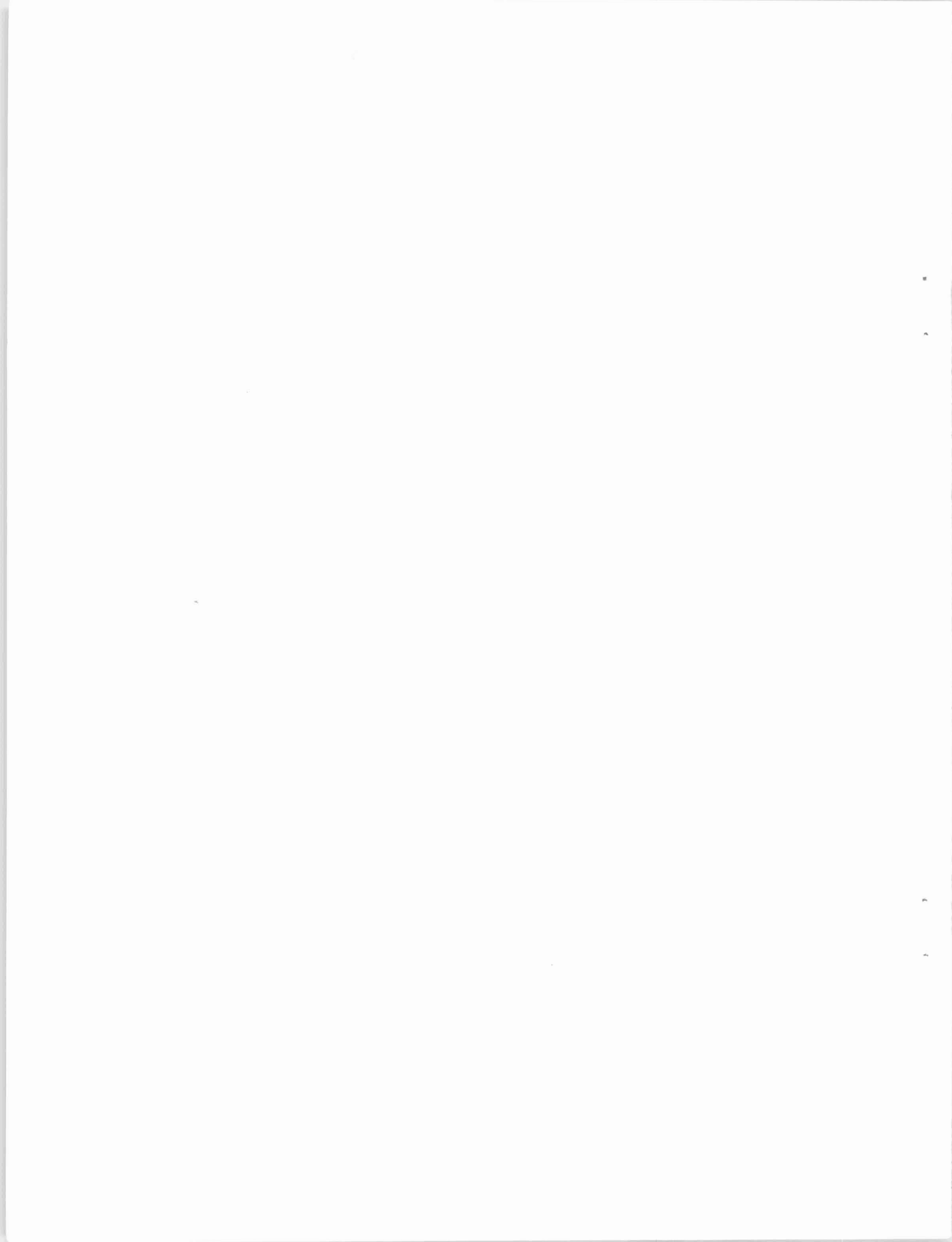


PREFACE

The work described in this report was performed in the context of an overall program of the Transportation Systems Center (TSC) to provide a technical basis for the improvement of grade-crossing safety. The program is sponsored by the Federal Railroad Administration, Office of Research, Development and Demonstrations. The program supports Government activities designed to promote greater safety in railroad freight and passenger service.

This study describes a major research effort to explore the feasibility of a communication-link approach for grade-crossing applications. The project has been carried out in the TSC Mechanical Engineering Division under the overall direction of J. Hopkins. R. Abbott, who has had general responsibility for field tests and system evaluation, prepared sections 3,4,6, and 7. Section 5 is drawn from studies carried out by Professor F.R. Holmstrom, Electrical Engineering Department, Lowell Technological Institute, under TSC contract DOT-TSC-589. Initial breadboard designs and circuit construction, and laboratory test and evaluation, have been the general responsibility of E. White. A.T. Newfell had primary responsibility for equipment acquisition and cooperative activities with the railroads. Their ingenuity in coping with difficult situations in a severe environment was crucial to the success of the project.

The effort has benefitted greatly from numerous discussions with many people associated with railroads, signal suppliers, the microwave and electronics community, and various levels and departments of Government. Special thanks are given to the many employees of the Boston & Maine Railroad who have contributed in great measure to the implementation of field tests.



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1. INTRODUCTION

1.1 OBJECTIVE

The track circuit, which observed its centennial in 1972, is a direct, elegant means of achieving train detection in a clear, fail-safe manner. It will undoubtedly remain the foundation of railroad signaling for the foreseeable future. However, when applied to the actuation of active grade crossing protection, this system, while highly effective, inherently imposes constraints which limit the implementation, economy, and effectiveness of new installations. The objective of the work described here has been exploration of the possibility that an alternative method might be developed which could remove certain of those limitations. Two points, however, must be emphasized: this work relates only to grade crossing signals, a very special case of railroad signaling, and the resulting concepts and hardware are not to be viewed as a perfect solution, replacing all previous methods, but rather as an expansion of the available options, to be applied (when fully developed and proven) only in those installations for which they truly represent improvements.

1.2 BACKGROUND

The basic framework of grade crossing safety is easily described. Of the approximately 223,000 public grade crossings in the U.S., about 47,000 (22%) now have active protection. Such warning systems are being installed at an annual rate of approximately 1500. Previous DOT studies 1, 2, 3 have determined that the most effective and beneficial expenditure of available resources in terms of safety is a program of installation or upgrading of active protection at approximately 30,000 public crossings (of the order of one-eighth of existing crossings). Implementation of such protection, it is estimated, would reduce the annual death toll by 30 to 50%. That is, a relatively small number of crossings - those with high traffic densities - are responsible for a high percentage of the casualties, so that

protective and research activities and resources are most efficiently concentrated on improvements appropriate to crossings in these categories.

The functional requirements, economic and institutional framework, and limitations upon innovation in this field were delineated in Reference 3, and will not be discussed extensively here. However, a review of the relevant basic technology is appropriate.

Discussion of grade crossing technology is facilitated by delineation of two quite separate functions - detection, at the crossing, of imminent train presence, and presentation of appropriate warnings to the motorist. It is sometimes useful to consider as separate the interface circuitry which connects the basic train detection equipment to the warnings. However, that function is often physically a part of the system which determines train presence, and will be so treated here. The basic principles of conventional techniques are easily stated, since practices are basically well standardized. The railroads have always carried out physical implementation of protection, so that the hardware and concepts associated with automatic protection arise directly from railroad signal technology and practices, and have been constrained through establishment of industry (AAR) standards, specifications, and requisites.

Train Detection

A brief review of the history and state of the art of such systems has recently been given elsewhere,⁴ and will not be repeated here. However, certain critical aspects deserve emphasis. The most fundamental and universal characteristic of active protection is use of the track circuit for train detection. Invented for general railroad signal purposes in 1872, it forms the basis of block signal technology, and was first applied to grade crossings in 1914. The basic concept is illustrated in Figure 1.1. The principle of operation is quite elegant. The battery at one end of a section of track - electrically isolated at both ends - is connected to a relay at the other end, using the rails as electrical

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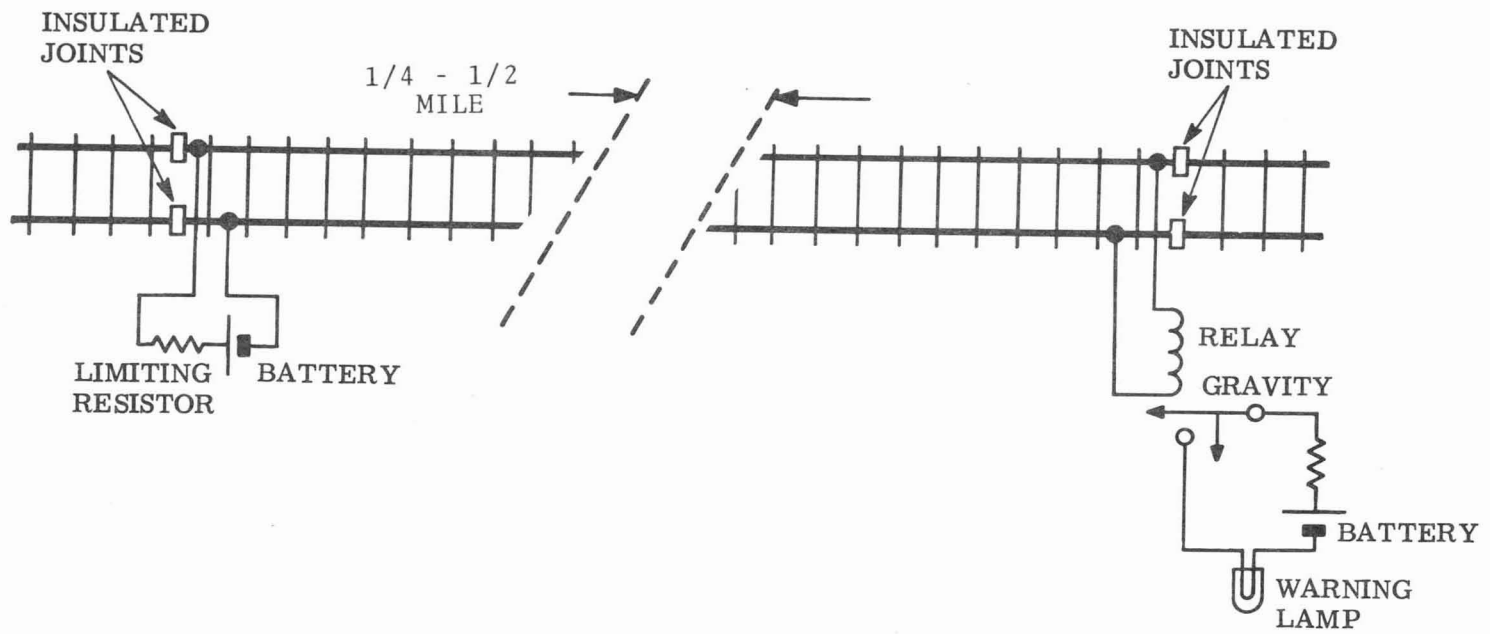


Figure 1.1 Basic Track Circuit

conductors, and holds the normally closed relay in an open position. A train between the battery and the relay short circuits the relay, and - thus losing current - it closes, activating any desired warning, such as a bell, light, or gate. Several features are particularly noteworthy. Any open circuit (break) in the rails or connections, or any short circuit across the rails, or failure of the power source (battery) causes the gravity-operated relay to close, actuating the warnings. Thus, with respect to all primary failure modes, the system is failsafe, in the sense that malfunction causes the most restrictive signal aspect - a fundamental criterion for all railroad signaling. (Actual achievement of a protective system approximating truly failsafe operation requires very careful attention to many details, particularly in the more complex realizations now used. Many years of evolutionary improvement have been required to provide the high level of performance now available.) Such a system also provides continuous detection, in that a train is detected constantly while in the block.

The most basic crossing protection system, then, entails a track circuit on either side of the crossing ("approach circuit"), with a third covering the region where the tracks actually cross the highway ("island circuit"). The length of the approach circuits must be sufficient to provide 20 to 30 seconds warning for the fastest train speeds allowed - approximately one-half mile (.8 km.) for a 60 MPH (97 kmph) train speed limit. In addition, logic functions - typically carried out with relays - are required to terminate activation after the train has completed passage of the crossing, prior to its leaving the "approach" block on the departing side. Modern realizations, utilizing audio frequency signals rather than DC, with solid state logic, have proven advantageous in many locations, but a number of constraints to this approach remain. The track segments involved must have electrical integrity throughout their length, and isolation at each end. A substantial quantity of power is required at the "battery" end (whether DC, AC, or audio frequency) - at least several watts - and this must be provided via special cables or existing track-side power lines. In addition, all active elements must have emergency

power - batteries - available for power or fuse failures. The challenging nature of the railroad operating environment - weather, temperature extremes, vandalism - should need little elaboration, but it is appropriate to note the less obvious difficulties, such as vulnerability to lightning and other power surges, and variation of the electrical impedance of the ballast between the rails.

In recent years, a new class of devices has been developed, also based upon the rails used as conductors, with train detection resulting from the shunting effect of the train wheels and axles. However, there are significant differences, and new functional capabilities, compared to the basic track circuit. The concept is illustrated in Figure 1.2, and is dependent upon measurement at the crossing of the electrical impedance between the rails. Although the rails have a very low resistance, it is not zero, so that as a short circuit (a train, for example) moves toward the crossing, the measured impedance decreases. Thus, it is possible to determine not only that the block is occupied, but whether the vehicle is moving, and the direction of motion - toward or away from the crossing. In the simpler realizations of this concept, such devices serve as motion detectors, eliminating unnecessary actuations when trains stop near a crossing, or when moving away from it after stopping and reversing. The more sophisticated forms can measure both range and closing rate with sufficient accuracy to activate warnings a fixed time interval prior to train arrival, regardless of train speed. This constant warning time feature appears to be highly desirable, partly to reduce unnecessary motorist delay, but - more importantly - it also provides a far more precise - and thus more credible - warning, and motor vehicle operators appear more likely to obey signals which experience shows to be truthful. Such devices require power only at the crossing (a passive termination is needed at the end of the block), but the more complex version (for constant warning time) also demands substantial power - tens of watts.

In summary, the track circuit approach is well proven, effective, and reliable, but it is also relatively labor intensive

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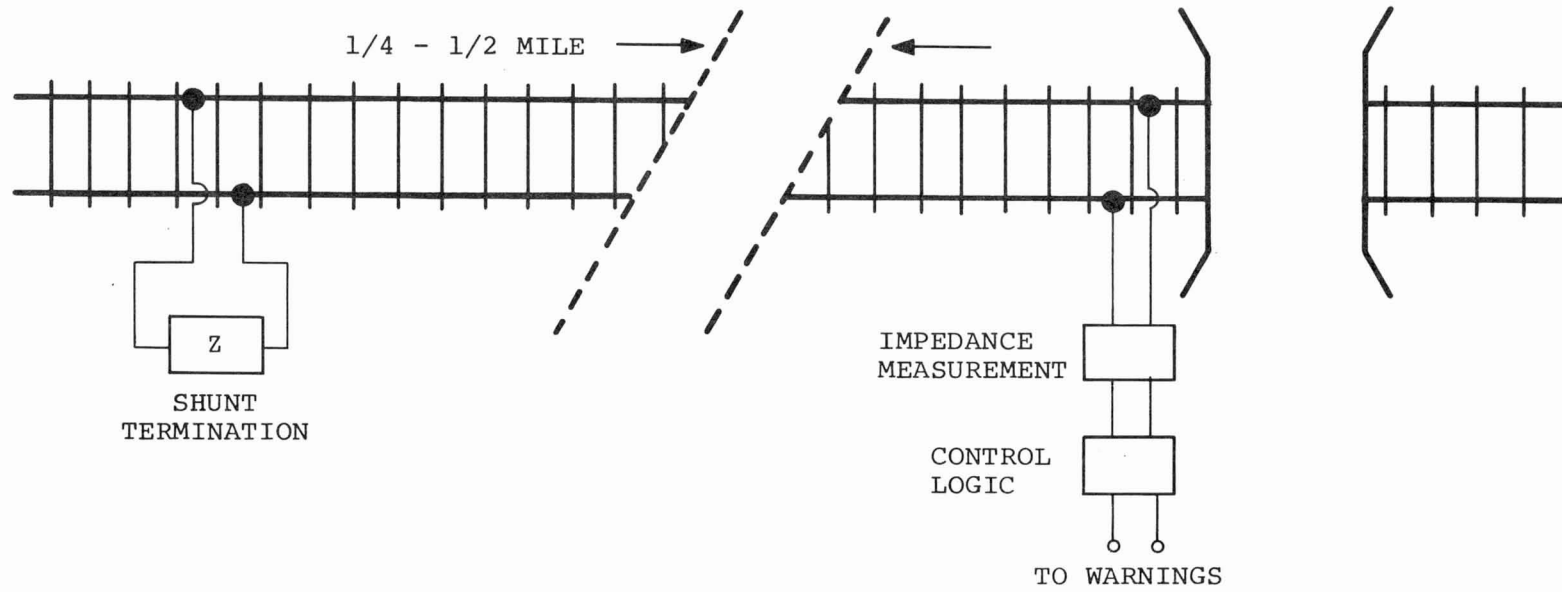


Figure 1.2 Impedance-Based Train Detection System

in both installation and maintenance, and is therefore not inexpensive. Although largely failsafe, system malfunction is generally not easily distinguished from train presence, leading to an undesirably high false alarm rate, with unfortunate impact upon system credibility and motorist response. An increasingly serious drawback is the inherent inseparability of track circuits from railroad involvement and responsibility for operation. It is clear that this technique - as effective as it has proven for the railroads - is totally inappropriate to implementation by any non-railroad body. Thus, total public responsibility for crossing protection can be achieved (if desired) only through alternative technology, for which there has previously been no strong demand.

GUIDELINES FOR RESEARCH IN NEW CONCEPTS

A brief examination makes clear the area most appropriate for investigation, in terms of efficiency of resource utilization. The active warning devices now used, while probably not optimal, do demonstrate impressive effectiveness (accident reduction) and represent a rather small portion of the expense of crossing protection - typically less than 20% of total costs. The logic and control circuits, which now include many large and expensive components, offer substantial potential for cost reduction through use of solid state circuits, modular design, etc. However, this avenue, which includes many severe challenges, is intimately bound to present-day technology and experience, and it appears to be more appropriate that such efforts be carried out primarily within the supply industry.

It is in techniques of detecting train presence and communicating such information to crossing control circuits that there appears to be maximum opportunity for meaningful innovation, particularly in view of the large expense associated with these functions at present. This conclusion is buttressed by the knowledge that sensing and communication of information are two of the most highly developed areas of modern technology, and therefore represent resources of great potential value to those activities to which they have not yet been applied fully. Further, the limited

size of the grade crossing hardware market makes major research into unconventional approaches economically unreasonable for manufacturers. Thus, it is this aspect - train detection and actuation of motorist warnings - to which the research reported here was directed.

GUIDELINES FOR SYSTEM CHARACTERISTICS

The basic general characteristics desirable in a protective system should be such that the task is accomplished economically, quickly, and effectively. Various aspects of present technology inherently introduce limitations in all three respects, as indicated in the following.

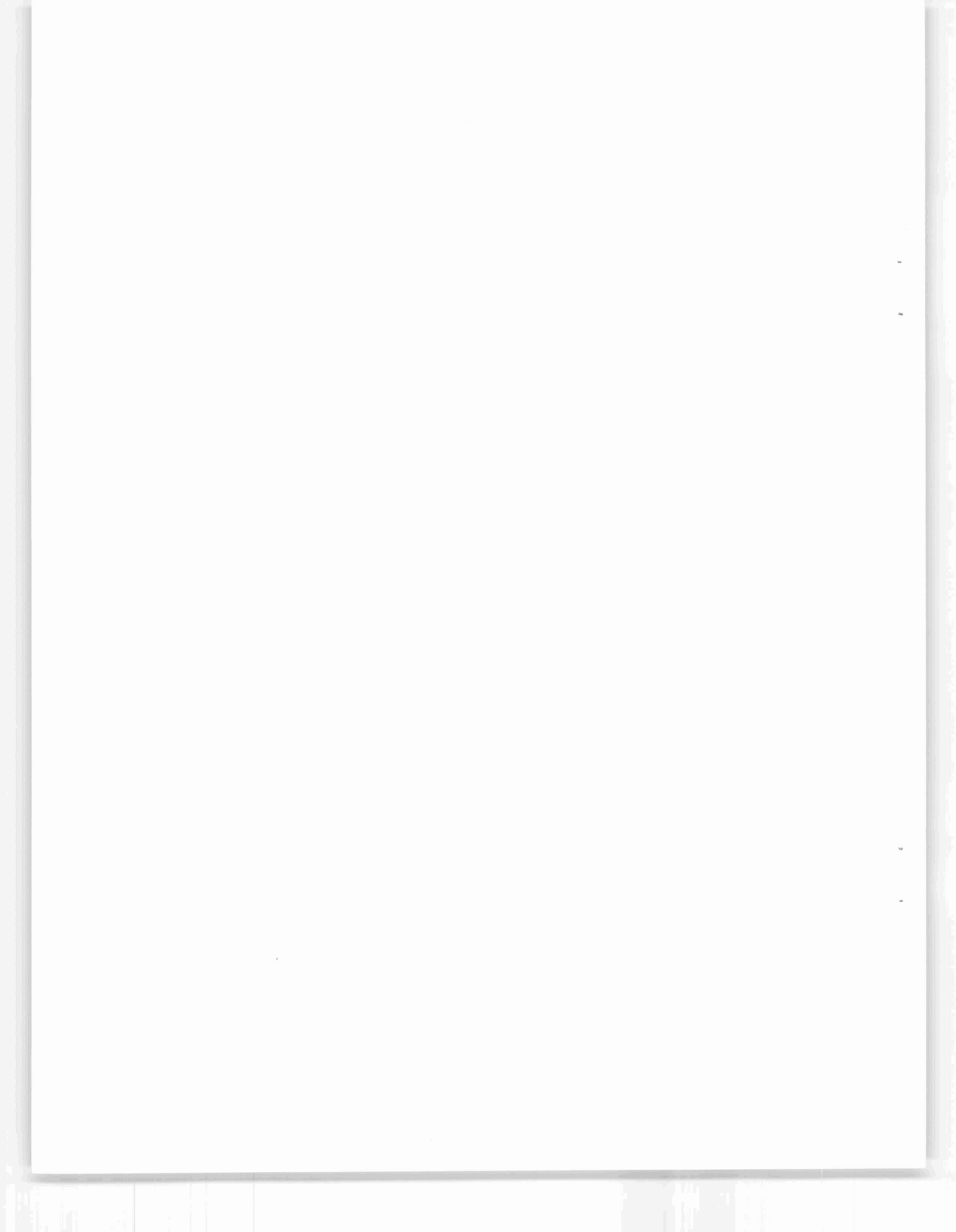
Economy. Examination of the cost elements in conventional installations reveals that at least half of both initial and maintenance costs are for labor. Much of this is related to the use of conventional track circuits, which require electrical integrity and isolation of the rails, and adjustment to permit proper operation for all likely ballast conditions. Line power is required at points 1/2 to 1/4 mile from the crossing, and attachment to the rails and power leads require careful attention to electrical surge protection. Thus, significant cost reduction appears most feasible through consideration of alternatives to track circuitry.

Implementation of Protection. The current legal framework, involving Federal, State, and railroad money, State and local decisions, and railroad purchase and installation, with several departments involved in each case, frequently imposes excessively complex procedural requirements, and consequent lengthy delay, upon implementation of protection. The heart of this problem, too, is the use of track circuits, for it is this factor which brings a private party - the railroad - into what could be considered a simple public function: provision of traffic control devices in the vicinity of a potential hazard to motorists. The electrical use of the rails immediately makes crossing protection hardware an integral part of the railroad's signal system, which - for a variety of legal reasons - can be installed, maintained, or replaced only by railroad personnel. There is no question that

the legal and liability problems associated with public assumption of responsibility for crossing protection are real, complex, and will require much time and effort for resolution. However, these questions are being faced, and it is particularly important that technology contribute means of at least eliminating the technical considerations.

System Effectiveness. The signals now used are without doubt highly effective, but there is some question as to whether they represent an optimal solution. Factors relating to this question are currently the subject of DOT and State investigation. However, any possible improvements in this area are dependent upon the information available, and track circuits require significant additional expense to provide information beyond mere train presence. Yet, information as to train speed, for uniform warning time, or the possibility of distinguishing between system failure and train presence - both most important to signal credibility - are highly desirable.

In the following sections, research directed toward long-term advances in grade-crossing technology - with the above described framework - will be reported. The basic concept developed at TSC - the microwave communication link - will be reviewed, followed by a summary of field test results (based upon early prototype hardware), a discussion of special electromagnetic propagation factors, optimal train detection, and studies concerning the possibility of utilization of solar power. Related research on the feasibility of radar train detection is also included.



2. THE MICROWAVE COMMUNICATION-LINK CONCEPT

2.1 TECHNICAL FRAMEWORK

The basic technical framework for the approach described herein will be found in Reference 3, and will merely be summarized here. Active systems require the accomplishment of several functions. The operation can be described in terms of a diagram such as Figure 2.1. Various systems may combine two or more of these elements. With track circuits, sensing of train presence and communication of that information to the crossing signals are combined. However, the alternatives considered here separate these functions.

Train presence can be determined in a variety of ways. Currently available methods, as well as some novel techniques, have been considered, and will be discussed in detail at a later point. However, as this is an area in which adequate - if not totally satisfactory - equipment characteristics are available, the primary effort has been directed toward realization of a satisfactory communication link.

The communication task may be simply defined. The basic requirement is transmission of information, at a very low data rate, over a distance typically less than 3000 feet (914 meters). The constraints indicated above must be met. One can easily imagine a number of possible approaches, but most can be ruled out immediately. For example, the cost of underground or pole-mounted cable, including installation and maintenance, is prohibitive. Of the electromagnetic approaches, optical devices also are too vulnerable to environment for the range considered - dust, snow, mud, fog, ice, vegetation, etc. all could drastically interfere with proper operation.

On the other hand, radio techniques are quite suitable. Radio communications can be carried out using readily available apparatus in the frequency range of fractions to tens of thousands of megahertz. Reduction of electromagnetic interference problems and low vulnerability to extraneous signals strongly suggest the

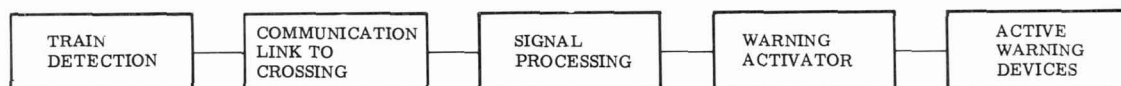


Figure 2.1 Basic Functional Elements of Protection System

desirability of a line of sight system, in which signals are either absorbed by obstacles or pass through the ionosphere with no reflection. High frequencies are also desirable because of bandwidth, frequency allocation, and antenna size considerations. Economical microwave sources and compact, highly directional antennas are best obtained in the frequency range of 10 to 20 GHz. Significantly higher frequencies (above 30 GHz) would increase cost substantially, as both oscillators and other components would require closer manufacturing tolerances. In addition, above 30 GHz attenuation from heavy rainfall can have significant effect on propagation distances. On the other hand, at 10 GHz no severe problems occur for rainfall of less than 5 to 10 inches per hour (12 to 25 cm per hour), a rate at which motor-vehicle traffic would presumably be at a standstill. An important weakness of low frequencies (below 1 GHz) is the lack of durable, small, highly directional antennas - use of a narrow beam can increase system efficiency by a factor of 10^3 to 10^6 when both transmission and reception are considered.

Considerations of this type lead to the conclusion that the most practical means of realizing the communication function is in the form of a simple microwave telemetry link, in which the short range and low information rate required make possible a simple, highly reliable, and low cost system.

2.2 THE BASIC CONCEPT

The basic system concept developed and realized at TSC within the above framework is indicated in Figure 2.2. It consists of a solid-state microwave transmitter at the train detection point (typically 1/4 to 1/2 mile from the crossing) with a receiver at the crossing. The normal (train absent) condition is with the transmitter on, with pulse modulation of low enough duty cycle to provide minimal power consumption - typically less than 1%. At the receiver, this signal is detected and processed to provide an output voltage as long as a signal is received. In the absence of such a signal, for whatever reason, there will be no output, and warnings are activated to provide failsafe operation. One could merely arrange to turn the transmitter completely

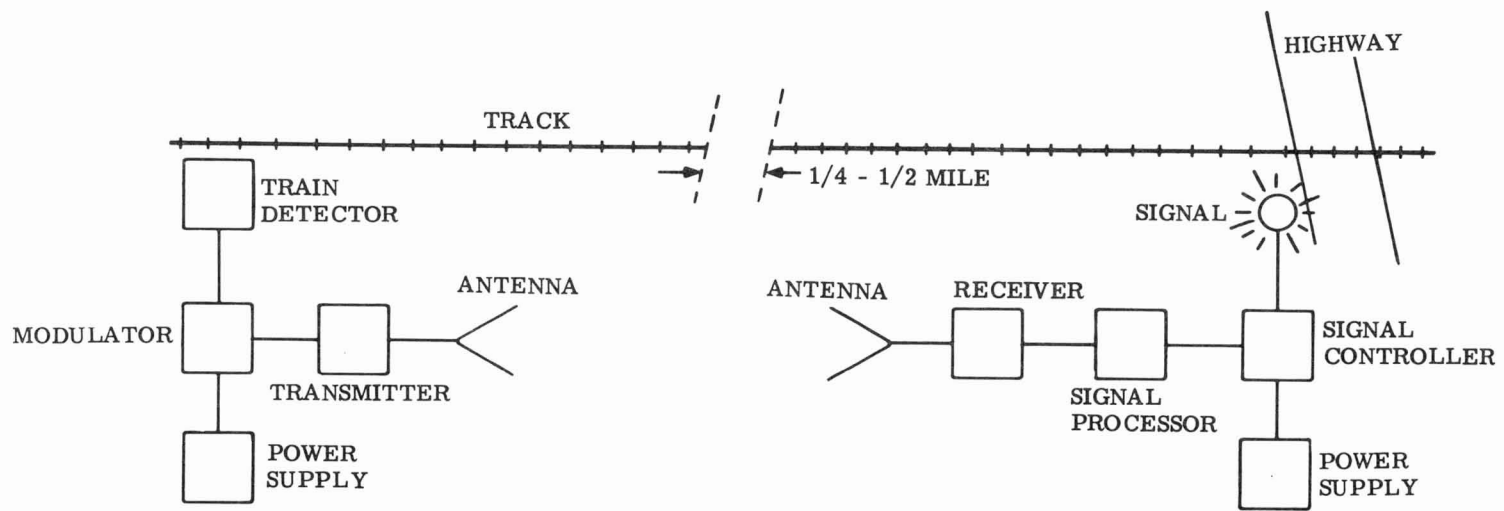


Figure 2.2 Basic Microwave Communication-Link System Concept

off when a train passes, but it is highly desirable that there be a detectable difference between system failure and train presence. Thus, the train-presence case is indicated by a change in the modulation, rather than total absence of signal. The receiver also has an input from a train detector at the crossing, so that it is reset to train absence (the warnings are de-activated) upon completion of train passage by the crossing. As is the case for track circuits, appropriate logic is necessary to keep track of train presence, direction, etc. in multiple track situations.

2.3 ELABORATIONS ON THE BASIC CONCEPT

A number of necessary features or highly valuable functional characteristics must be achieved in a practical, fully operational realization. It is desirable to have a significant number of alternative modulation modes to permit communication of a variety of data. For example, one could use a "clear" (train absent) mode, a secondary "clear" which indicates in addition a potential transmitter malfunction (low battery, high VSWR, etc.), and (for example) four different cases of train presence. These might provide four ranges of train speed, train direction on two tracks, etc. Such a multiple-mode system should be designed in a manner to permit very flexible use, so that a wide variety of system configurations can utilize the same basic hardware. A multiplicity of such modes is easily obtained by digital coding.

It is desirable that the receiver have a special output to indicate system malfunction for any modulation other than those intended, including zero, or inadequate received signal power. Once a train-presence indication is received, the receiver should then indicate the "train present" condition and continue to do so until reset. Reset signal will normally be provided by a connection to a train sensor located at the crossing. To insure that the entire train has completely passed over the crossing, reset should not occur until the sensor has detected no train for several seconds.

To contribute to failsafe operation, all information inputs to both receiver and transmitter are best designed to cause activation of the appropriate circuit when removed for a period of several milliseconds. In the case of the reset signal for the receiver, intended to indicate passage of a train through the crossing, many train-sensing means provide a reset signal when the train arrives at the crossing. It is therefore necessary, as described above, that the receiver not actually reset (implying deactivation of the crossing protective signals) until termination of the reset indication, indicating completion of train passage. Thus, resetting of the receiver requires not only removal of a voltage level for a brief period, but subsequent reimposition of such a voltage, followed by a brief waiting period to ensure that the train has indeed passed. (Many train sensors provide a pulse for each wheel, so that a sequence of signals is provided to the receiver.)

Two or more grade crossings frequently occur fairly close to one another. A receiver placed at one crossing could conceivably be exposed to signals from a second transmitter not nominally part of that system. It is important that there be no "crosstalk" problem; the necessary discrimination can be achieved through appropriate coding.

Another operational consideration is the possibility that a very rapidly moving self-propelled rail vehicle could pass the train-sensing point in less than one second. It is necessary that the transmitter stay in the appropriate mode for an interval sufficiently long to preclude any error at the receiver, even if a burst of high-intensity noise should happen to occur just simultaneously with a transmitted signal burst. It appears highly desirable, therefore, that at least several bursts of a train presence mode be transmitted any time that mode is activated at all. Alternatively, a very slow-moving train might present wheel-passage pulses spaced several seconds apart, and it is further possible that the front of such a train might simultaneously be at the crossing, providing potential reset signals. It is necessary that the telemetry system have sufficient delays or memory to cope with such situations.

For cases in which track curvature and topography prevent line-of-sight operation, repeater stations may be appropriate. Similar considerations arise in the vicinity of sidings, etc. As is the case for track circuits, problems of non-uniform train movements, switching, etc. provide difficulties, and it will be necessary to determine the optimal means of dealing with them. Substantial benefit appears to be associated with the broader informational capability of the telemetry system.

2.4 DEVELOPMENTAL STUDIES

After construction of several generations of laboratory prototypes at TSC, two somewhat more sophisticated microwave telemetry systems were developed under TSC contracts by commercial suppliers. One, built by Safetran Systems Corp., utilizes 10 msec bursts of 1 kHz modulation, with a burst-repetition frequency of 2 sec^{-1} for train absence, and 2.2 kHz modulation (other parameters the same) for train presence. Discrimination in the receiver is via filters and tuned amplifiers for each of the two channels. The other design, constructed by Rantec Division of Emerson Electric Co., uses the same modulation frequency in both cases - 100 kHz, (to minimize $1/f$ -noise) - with 0.12 msec bursts for train absence and .26 msec bursts for train presence. The burst repetition frequency in each mode is 3^{-1} Hz , and discrimination is via digital circuitry. A block diagram is shown in Figure 2.3.

Both systems use Gunn diode oscillators in the transmitter, with simple single-diode video detection in the receiver. More complete descriptions are given in the Appendix. It must be emphasized that these units represent only very basic prototype hardware, designed to demonstrate basic concept feasibility and delineate system parameters. In addition, they were constructed under extremely tight time schedules. Thus, they were not intended to represent either the operational characteristics or the sophistication of circuit design appropriate to a final system. Both systems operate at a radiated power level of approximately 100 mW peak. The very low-duty cycle compensates for the inherent inefficiency of the oscillators, and the units delivered show an average power consumption of 100mW in one case and 300 mW for the other, operating from a 12 V DC source. It is anticipated that this

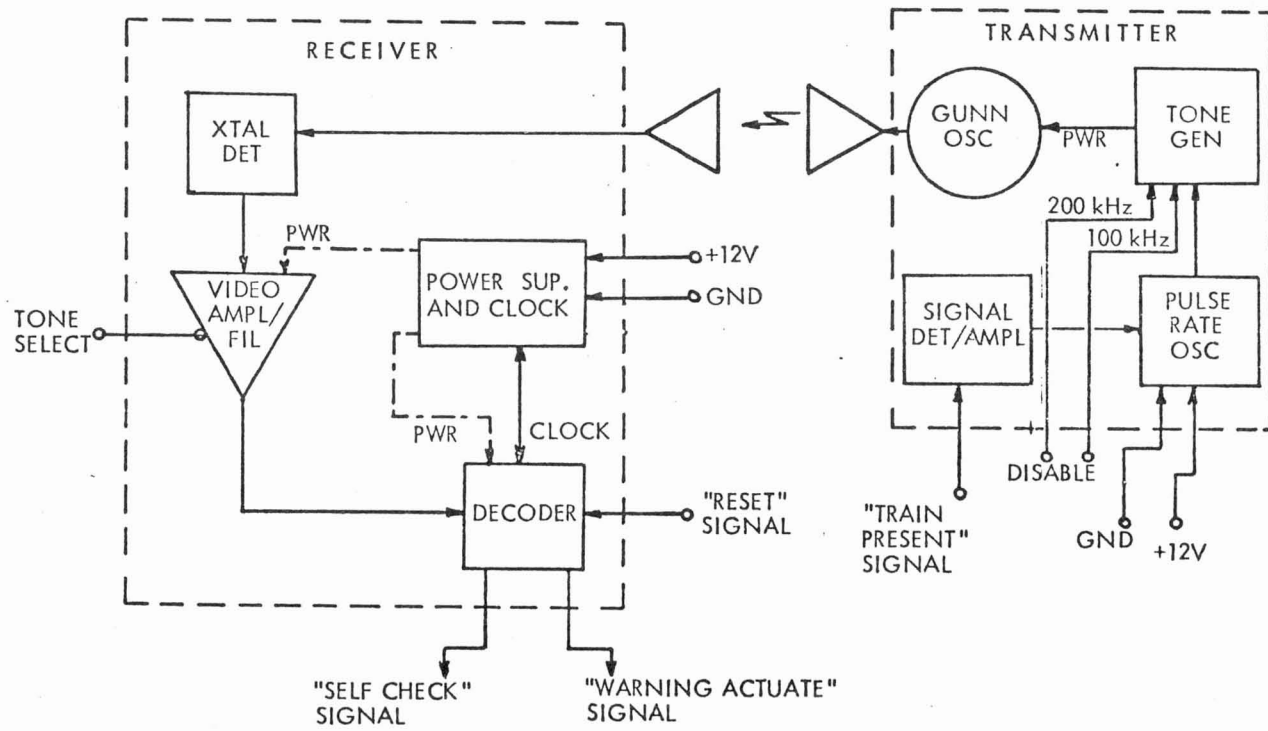


Figure 2.3 Block Diagram of Rantec System

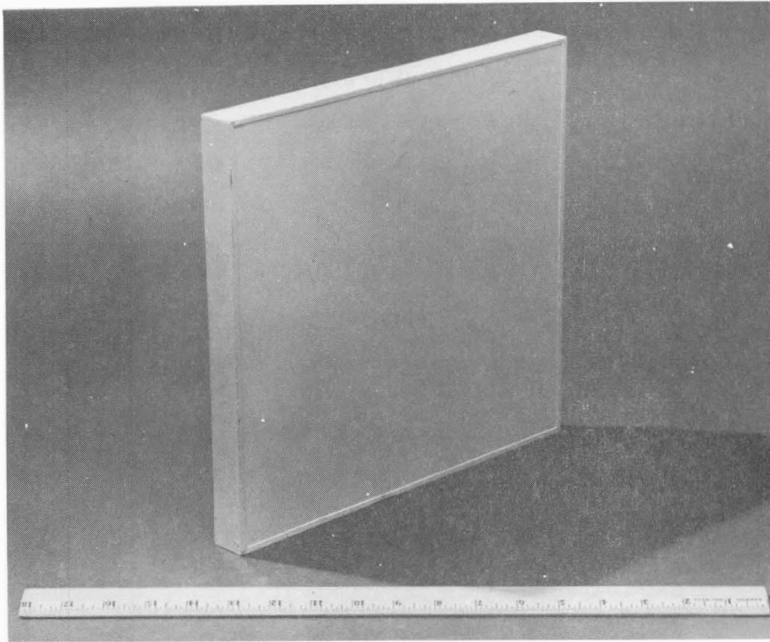
can be reduced substantially by improved circuitry and a different choice of supply voltage (to eliminate the necessary low-efficiency power conditioning.) Thus, the goal of operation from batteries alone, with attendant reduced installation costs, appears readily obtainable. The total energy drain of approximately 1 kW-hour per year can be met through annual maintenance, and is well within the limits of very conservatively rated small solar panels for re-charging.

The antennas utilized are inconspicuous planar units, 12" x 12" x 1", having a gain of 27 dB at the operating frequency of 10.525 GHz and a beamwidth of approximately 6°. See Figure 2.4. They were designed and constructed by AIL Division of Cutler-Hammer. The design principles and details of very similar antennas are described elsewhere.⁵ For this application they were encased in a Lexan/aluminum enclosure which provides an extremely rugged structure.

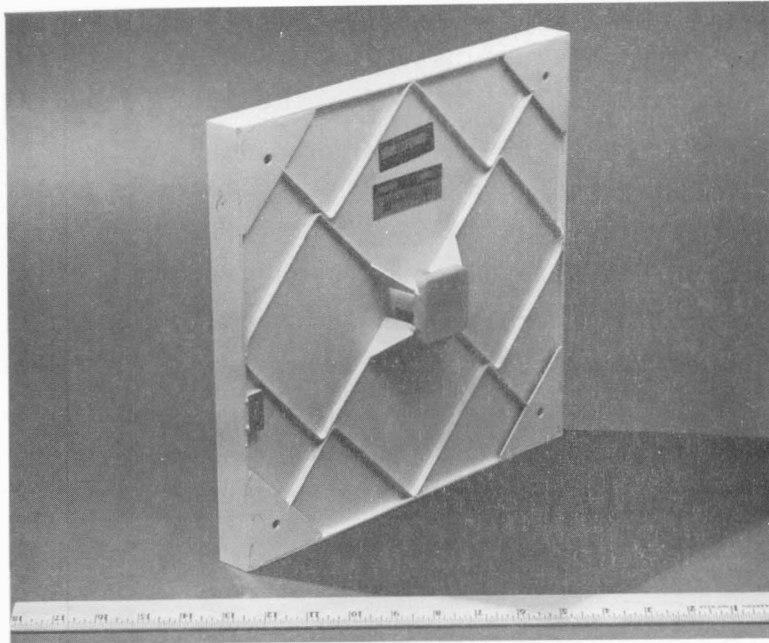
2.5 FIELD TESTS

Substantial testing has been carried out. Initially, a laboratory prototype system was operated between the roof of TSC and a 20-story office building 1/4 mile distant for approximately four months. There were no circuit failures, although one solid state oscillator had to be replaced because of damage resulting from inadequate weather protection. Also, relatively high power consumption in this early unit resulted in some battery problems.

The commercially designed and constructed units described above were subjected to extensive field testing, as described in Section 3. The means of train detection employed, and testing of a variety of devices, are covered in Section 4, and special studies concerned with microwave propagation - particularly multipath problems - are treated in Section 5. Test activities related to the use of solar power in charging the necessary batteries are described in Section 6.



(a)



(b)

Figure 2.4 Planar Antenna

3. FIELD TESTS

3.1 GENERAL DESCRIPTION

In order to gain a better understanding of the problems associated with using short-range microwave telemetry systems in a railroad environment, a series of extended field tests was initiated in February of 1972. The purpose was not to use the system to activate motorist warnings, but rather to test the system over an extended time period (at least one year) in a realistic environment.

Four different test-site grade crossings were selected. Each was on mainline track of the Boston and Maine Railroad. Each crossing had active protection, either gates or flashing lights, activated by use of a DC track circuit. The goal was to monitor both the microwave system and the B&M track circuit, in order to measure the performance of the microwave system against that of the time-proven track circuit. At each receiver an event recorder was installed, and output signals from the telemetry receiver were continuously monitored, as was other pertinent data. For test purposes, the B&M allowed access to a front and back contact pair of their XR, ESR, and WSR crossing relays at each test site. The test sites contain a wide range of possible situations: single and double track, rural and urban areas, and high speed as well as low speed crossings are all represented. In addition to the relay contacts described above, the B&M also furnished the necessary poles, boxes, drilling and electric power that was required for the tests.

In the first test installation, the 1 sq. ft. planar antennas were not available, so 2' parabolic dish antennas, were used. The transmitter was located on top of a pole already present as part of the railroad block signal system, as shown in Figure 3.1. The storage battery and train detector interface circuitry was mounted in the small case at the bottom of the pole. The receiver, shown in Figure 3.2, was mounted on a 20' pole, with batteries, event recorders, and interface circuitry in the large equipment box.



Figure 3.1 Transmitter Installation - First Test Site



Figure 3.2 Receiver Installation - First Test Site

In the installation of Figure 3.2 train direction and presence are sensed by the two magnetic wheel flange detectors bolted to the rail. As discussed in a later section a variety of different train sensors were used and the type shown here is only one of several tried. Commercial electric power was not used at the transmitter. Rather, an automobile storage battery was used as the main power source. A single such battery driving this load would have a design discharge time of about 9 months, but each battery was removed and re-charged once every three months.

In the later installations, for which the planar antenna was used, the transmitter installation was as seen in Figure 3.3, and the receivers were mounted on 14'-18' poles. Figure 3.4 shows a case in which the receivers for both directions were actually mounted on top of the flashing-light poles. In this case the batteries, recorders, etc. were in a nearby railroad relay case, connected by cables. At the receiver commercial electric power was used, powering a battery charger which kept a back-up storage battery at a full charge. The activation and malfunction outputs from the receiver, the status of the B&M XR crossing relay, the status of the resetting train sensors and the status of other train sensors under test were all monitored continuously by use of a paper-tape event recorder. Every two weeks the systems under test were manually checked and the tapes were changed and brought back to TSC for analysis. A block diagram of the system is shown in Figure 3.5a.

The field tests were operational for a total of approximately 35,000 hours (8000 hours per system) and the specific results, problem areas and preliminary conclusions are described below.

3.2 RESULTS

3.2.1 Environmental Effects

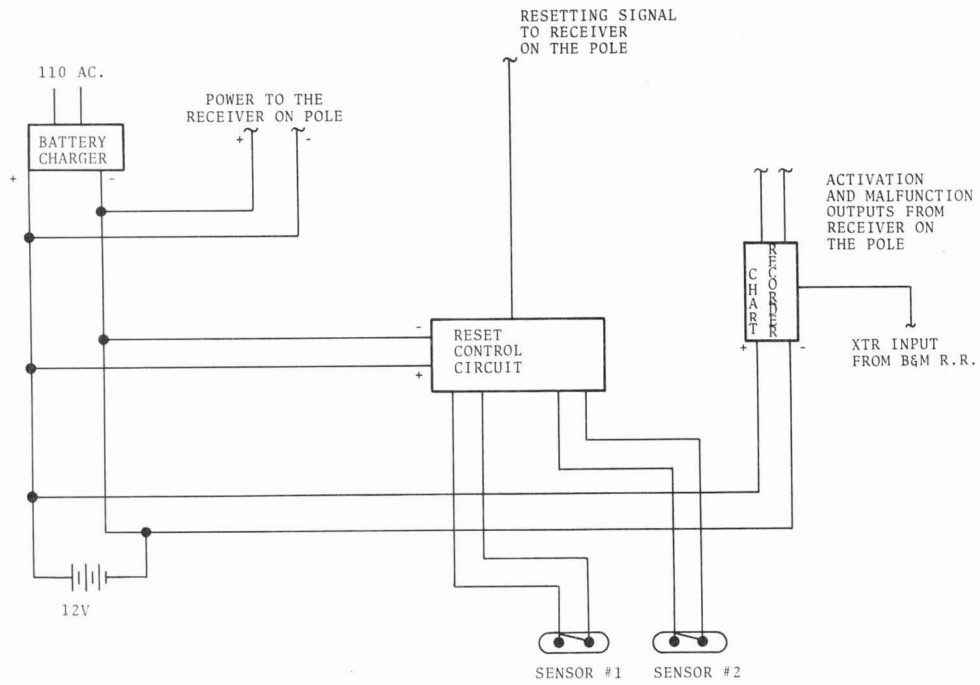
During the test the experimental systems were exposed to blizzards, hurricanes, and other weather extremes. At no time has the weather caused the system to malfunction or give a false indication.



Figure 3.3 Transmitter Installation - Typical of Later Sites



Figure 3.4 Receiver Installation - Typical of Later Sites



Block Diagram of a Typical Receiver Installation

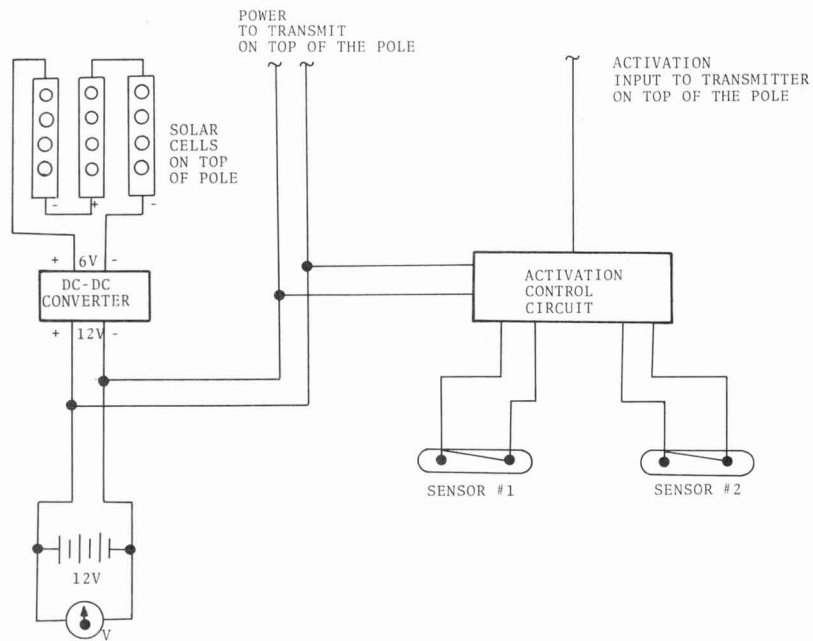


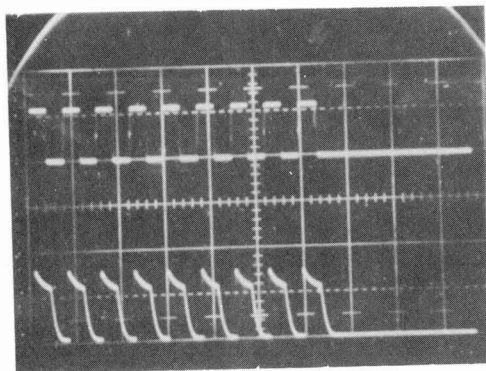
Figure 3.5a Block Diagram of Field Test Installations

A carrier frequency of 10 GHz provides a signal which is reasonably impervious to rain, fog, snow, etc. All of the electronic components in the transmitters and receivers, except the Gunn-effect microwave source, have an operating temperature range of -55 to 125 degrees C and an operating range for humidity of 0 to 100 per cent. The overall electronic design also compensates for temperature variations as well. The transmitters, receivers, and antennas were all packaged in watertight enclosures. Thus problems with weather extremes were neither anticipated nor experienced.

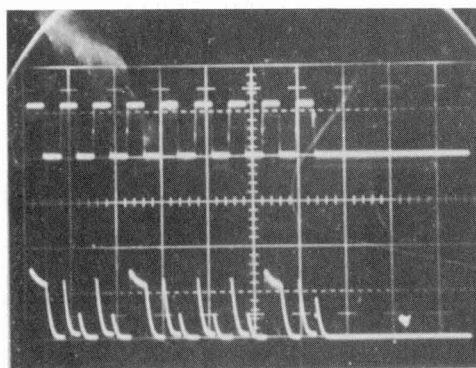
However, a potential problem with the microwave source was noted. It was observed that at low temperatures, the diode would often miss pulses. That is, the device would fail - momentarily to oscillate. This effect is shown in the oscillographs of Figure 3.5b. The particular traces shown are the responses of the Safetran unit, but similar effects were also noticed with the Rantec unit.

During our tests the telemetry link never failed to operate correctly. The design of both receivers allows correct operation even if a few pulses are missing from the transmitted pulse train.

This problem has been discussed with manufactures of solid-state oscillators. One relevant factor is that the operating voltage region -- the region within which the diode oscillates, corresponding to the negative resistance section of the diodes I-V curve -- is a function of temperature. Both the upper and lower limits of that region are inversely proportional to the diode's ambient temperature in degrees Kelvin. Thus, during cold weather the minimum driving voltage for oscillation increases. The problem is complicated by the fact that the ambient temperature of the diodes is constantly changing due to localized heating during pulses. The problem is even further complicated by an aging process which also shifts the I-V curves. It was not possible to determine details concerning this aging process (most manufacturers consider this information proprietary), but it appears that up to some leveling-off point, as age increases, both the upper and lower limits of the operating voltage region also increase. Most manufacturers do "burn in" their most expensive Gunn diodes for about



(a) 25 Degrees C



(b) 0 Degrees C

Figure 3.5b Oscillographs of Driving Voltage and Microwave Detected Output for Safetran System

1,000 hours. These three factors indicate that what is needed is a device that has as wide an oscillatory voltage range as possible, so that when large changes in temperature or even aging causes the limits to shift, the fixed driving voltage will still remain within acceptable limits for oscillation. Measurements were taken on Gunn diodes from five different manufacturers and one was clearly superior with an operating voltage range of 6 volts to 24 volts, at room temperature. All of the Gunn diodes were replaced with units from that manufacturer and there have been no problems with missing pulses ever since that time.

3.2.2 Mechanical Breakage

There have been some problems with mechanical breakage. One of the antennas at an early test site was broken off the mount by vandals. Because of this experience and because vandalism is generally a severe railroad problem, steps were then taken to make the hardware as vandal proof as possible. All of it was then enclosed in either a steel or lexan case, and there were no subsequent problems due to vandalism. Near one test site, a B&M relay case was smashed open by vandals, but the microwave unit with the new protection was not damaged at all.

About one week after the first prototype unit was installed an internal electrical connection broke and the unit was returned to the manufacturer. The unit was repaired, returned to TSC and then re-installed. Since that time there has been no trouble with broken connections. It would appear that this problem was peculiar to that original unit and not a general problem area.

In over 20,000 hours of field testing since those early failures were discovered, there has been no recurrences and neither has recurred since the units were modified. Figure 3.6 shows a photograph of the transmitter assembly complete with solar panels. The interior of this assembly is shown in Figure 3.7.

3.2.3 Interference

Interference from spurious radio frequency sources has not been a problem. The systems have been operated successfully in the centers of towns, adjacent to railroad relay cases, beneath

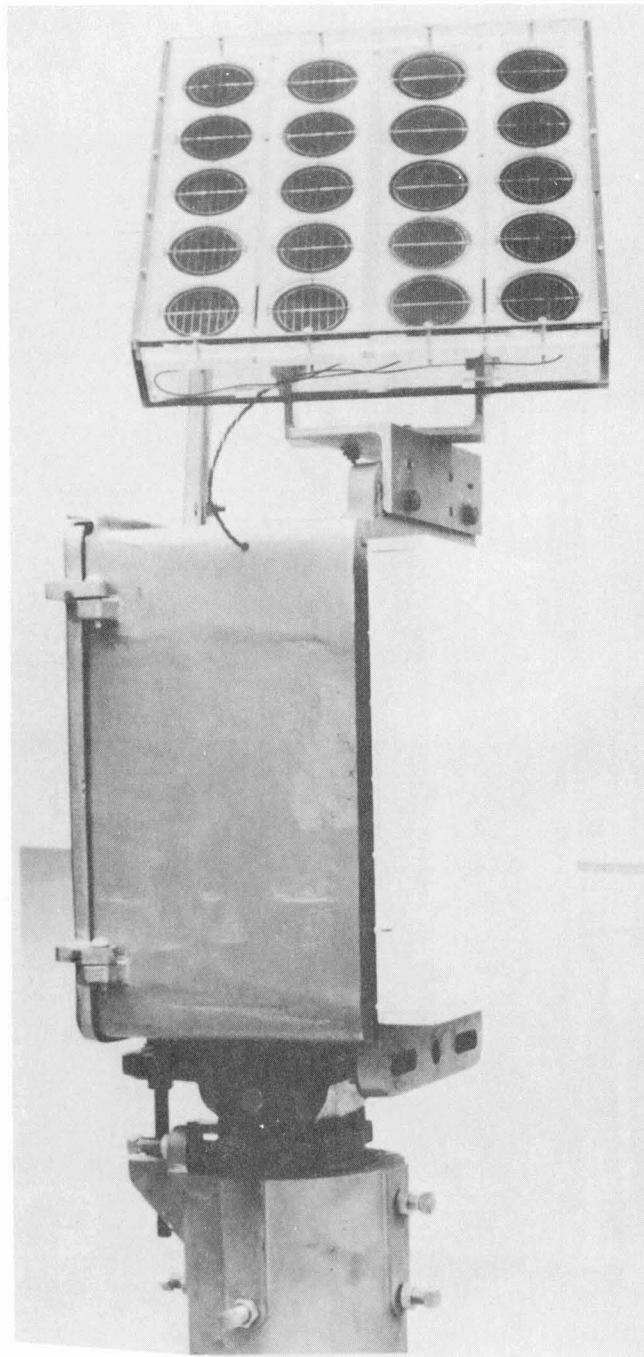


Figure 3.6 Complete Transmitter Assembly, Including 1 Sq. Ft. Planar Antenna and Solar Cell Panel

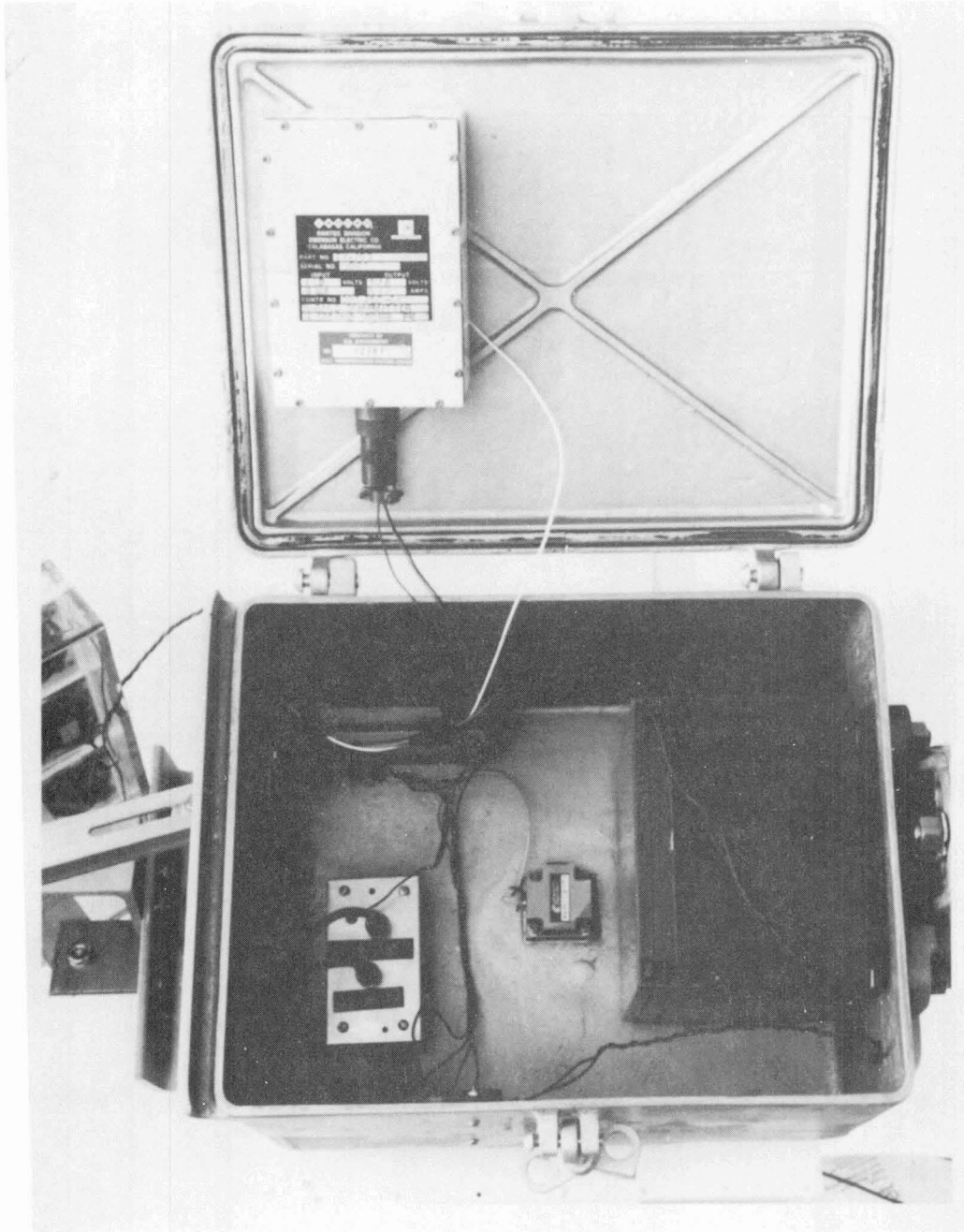


Figure 3.7 Interior of Transmitter Assembly

high voltage electric power feed lines, and adjacent to industrial parks with factories containing large amounts of heavy electrical processing equipment. Indeed, they have been operated successfully in the most hostile environment, in terms of electrical interference, that could be found. The system design of our transmitter/receiver pairs has been such as to provide as much protection as possible. The directive antennas tend to reject most unwanted signals. The signal processing circuitry contains sharp filtering to reject most of the electrical noise, and-being digital in nature, offers further noise reduction. All of the electronic circuitry in the transmitter/receiver pairs was packaged to minimize interference problems inside of a grounded steel enclosure. The carrier frequency of 10.525 GHz is an area of the electromagnetic spectrum that is fairly clean, in terms of electrical interference.

Figure 3.8 shows a diagram of the test site configuration that was used to evaluate the interference caused by adjacent telemetry systems. The objective was to determine if the transmitter from link #1 would interfere with the receiver from link #2 and vice-versa. The receivers for both links #1&2 are mounted on the same pole, but, of course, face in opposite directions. It was also of interest to see if the transmitter from link #1 would interfere with the receiver of link #3. There was no problem at all in the first case. Again, the highly directive antennas limit operation to line of sight and the transmitting and receiving antennas must be oriented to within 10 degrees of each other before the two signals could interfere with each other. The second case was more interesting in that each transmitter or receiver in the test could be operated with a modulation frequency of either 100 kHz or 200 kHz. With link #1 and link #3 both operating at 100 kHz, the transmitter from link #1 did interfere with the receiver of link #3 and link #3 did malfunction occasionally. However, after that time, link #3 was converted over to 200 kHz operation and the interference problem ceased. (The receiver rejects by 20 dB at 100 kHz signal if the receiver is set to receive a 200 kHz modulated signal.)

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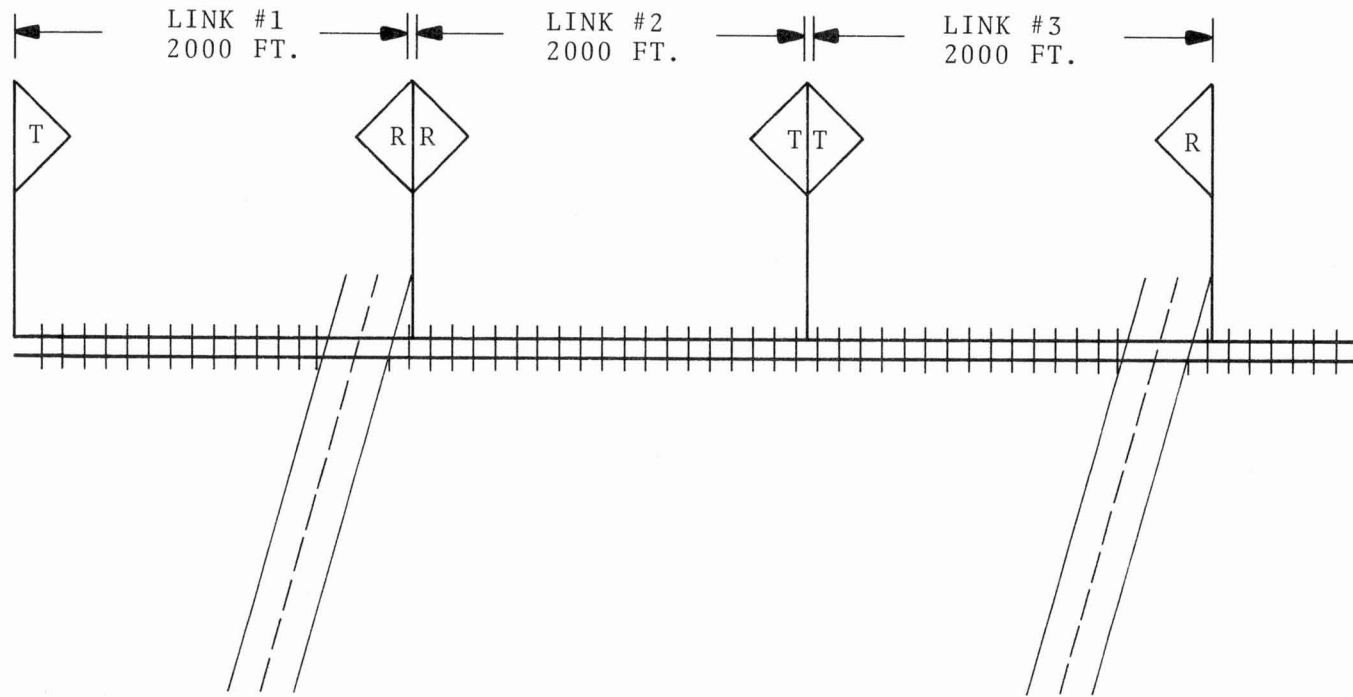
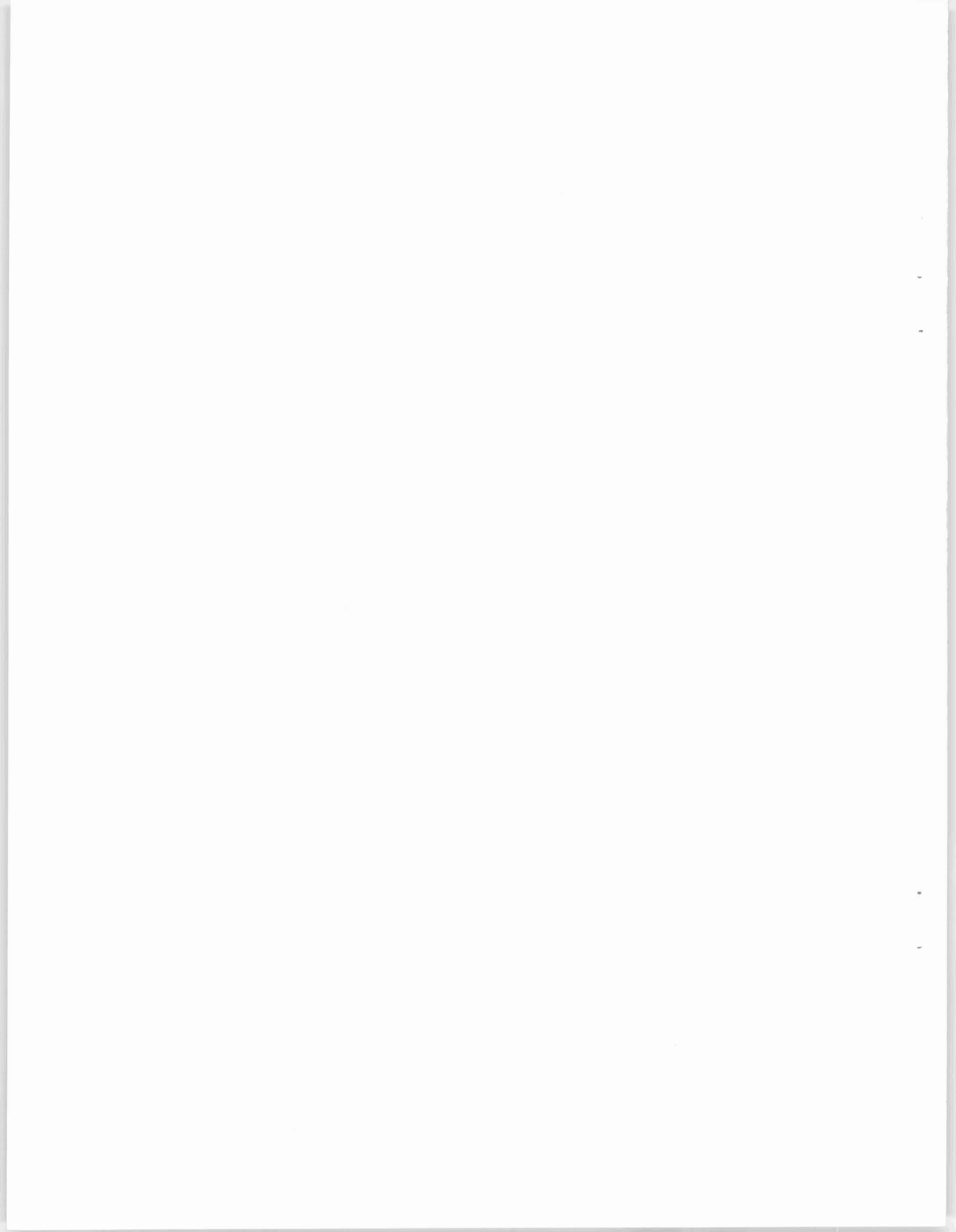


Figure 3.8 Test Site Configuration During Interference Test

3.2.4 Preliminary Conclusions

The problem areas mentioned above appear to have been relatively minor and essentially have been overcome. At present two more-serious problem areas are multipath propagation effects and train sensor reliability. Both of these subjects are discussed, in some detail, in subsequent sections. The problem of multipath effects -- though more severe than originally anticipated -- does appear to be readily soluble. The problem of train sensor reliability, however, is more formidable.



4. TRAIN DETECTION

4.1 DETERMINATION OF TRAIN PRESENCE

With track circuits, sensing of train presence and communication of that information to the crossing are combined. The alternative considered here, however, separates these functions. Train presence can be determined in a variety of ways. Currently available techniques as well as some novel methods were considered and are described below.

4.2 GUIDELINES FOR ANALYSIS OF TRAIN DETECTION TECHNIQUES

Before considering any particular method of train detection, it is appropriate to examine the inherent system constraints within which any particular sensor must operate.

- a. Failsafe Operation. As with all railroad vital components and circuitry, failsafe operation is of paramount importance. Care must be taken so that non-failsafe failure modes are virtually eliminated. As a single requirement, however, near failsafe operation is probably not as foreboding a requirement as one might assume. Hardware developed for safety applications in other areas has been designed to be virtually failsafe by careful system design, often making extensive use of redundant and self-check processes. A simple example of this technique is the dual braking system, now required by law on all automobiles sold in the U.S. Automobile braking is accomplished by two separate sections of the system. One section contains all the brake cylinders, lines, shoes, drums, and master cylinder for the right-front and left-rear wheels, while the other section, which is completely independent from the first, contains all the apparatus necessary to brake the left-front and right-rear wheels. Under normal driving conditions either braking section is sufficient to stop the automobile. The system also contains a self-check section that, in the event that one of the braking

sections fail (from a leak in one of the lines, etc.), a warning, in the form of a dash-board indicator light, is conveyed to the operator.

In terms of the grade crossing application, these techniques would involve the use of multiple sensors and extensive self-check logic. If the sensors failed to agree with each other as the question of train presence or if the self-check logic failed to give a "System OK" signal, a suitable warning -- preferably a different warning aspect than "Train Approaching"-- would be sent to the motorist.

While a careful system design, multiple sensors, and self-check circuitry may well render the train detection system virtually failsafe, these techniques will also tend to increase the cost of the system as well as to increase the likelihood of safe failures. As is generally true, the introduction of a more-nearly failsafe design increases the likelihood that failure will occur (as by a component failure in the self-check section), thus activating the signals even though the train detection system is working perfectly. Care must then be taken to insure that, in the pursuit of a virtually failsafe design, other system constraints--that is, cost reliability, etc.,--are not compromised beyond control.

- b. Cost. During the process of evaluating different train sensors, one of the more serious constraints to be kept in mind is cost. A single-track installation would require, if non-directional sensors are to be used, a minimum of four train sensors. If, as will probably be the case, redundant sensors are necessary, eight or twelve sensors might be required.
- c. Environmental Constraints. It would seem to be almost impossible to overestimate the harshness of the railroad environment. Extremes of temperature and humidity ranging from desert to tropical to arctic conditions are

to be assumed. Electrical noise, especially in areas near high-voltage feeder power lines or on electrified rail lines, can be extremely severe. The build-up of soot, dirt, or oil films can also be quite severe and should be guarded against. The weight of railroad rolling stock imparts great stress, strain, and vibrational shock to the rails, ties, and ballast. This effect must be accounted for in all potential sensor designs.

Train speeds can vary greatly and any potential sensor should be able to detect trains from 0 to 110 mph. Multiple-track topographies are common and care must be taken that a sensor does not falsely trigger due to trains traveling on tracks adjacent to the track for which the sensor was intended. Vandalism is a fact of life in the railroad environment. The sensor should not only be packaged so as to make it virtually impervious to vandalism; ideally, the sensor should also be designed to make the possibility of attempted vandalism extremely unlikely -- for example, installing the unit below the rails, and only sensitive to large metal objects.

- d. Power Consumption. As with the transmitter/receiver pairs, low power consumption is also a design goal for the train detector. Of course, this is especially important at the transmitter site where line electric power will probably not be available. If solar panels are to be used as the main power source, the cost per watt of electrical power could be as high as \$500 including installation. In addition, it would be desirable to keep transmitter-site hardware as inconspicuous and unobtrusive as possible. Solar power output power densities can be as low as .5 Watt per sq. foot of panel area. Thus a large and conspicuous and expensive physical area would be required if the total power requirement for the train detection system exceeded approximately 0.5 Watt.

- e. Rail Independence. It would be highly desirable for the sensor to have both electrical and mechanical independence from the rails. This would offer two major advantages. The first is that the sensor would be general in design and would be able to conform to all rail sizes and signal systems, and thus would not require the custom designs or installations. Secondly, a sensor that was completely independent from the rails could be installed and maintained by local highway departments with only limited railroad involvement.

4.3 POSSIBLE ALTERNATIVES

4.3.1 Background

Since 1872 the task of reliably sensing the presence of railroad rolling stock has, in safety applications, always been accomplished by use of the track circuit. The track circuit has proven to be an extremely reliable, failsafe, and often expensive means. While the severity of the constraints tends to suggest caution, several alternative methods can be identified, in addition to radar which is discussed in Section 7.

- a. Mechanical
- b. Magnetic
 - 1) Wheel Flange
 - 2) Train
- c. Beam Interruption
- d. Weight
 - 1) Strain on the Rail
 - 2) Pressure on the ballast
- e. Short Track Circuit

4.3.2 Mechanical Sensors

Mechanical sensors or treadle switches do not appear to be at all promising. Figure 4.1 shows a picture of a treadle switch that is used in Europe and occasionally in the U.S. in non-vital, non-failsafe applications. The sensor is bolted to the inside of either rail. Passing wheel flanges contact and depress both of the

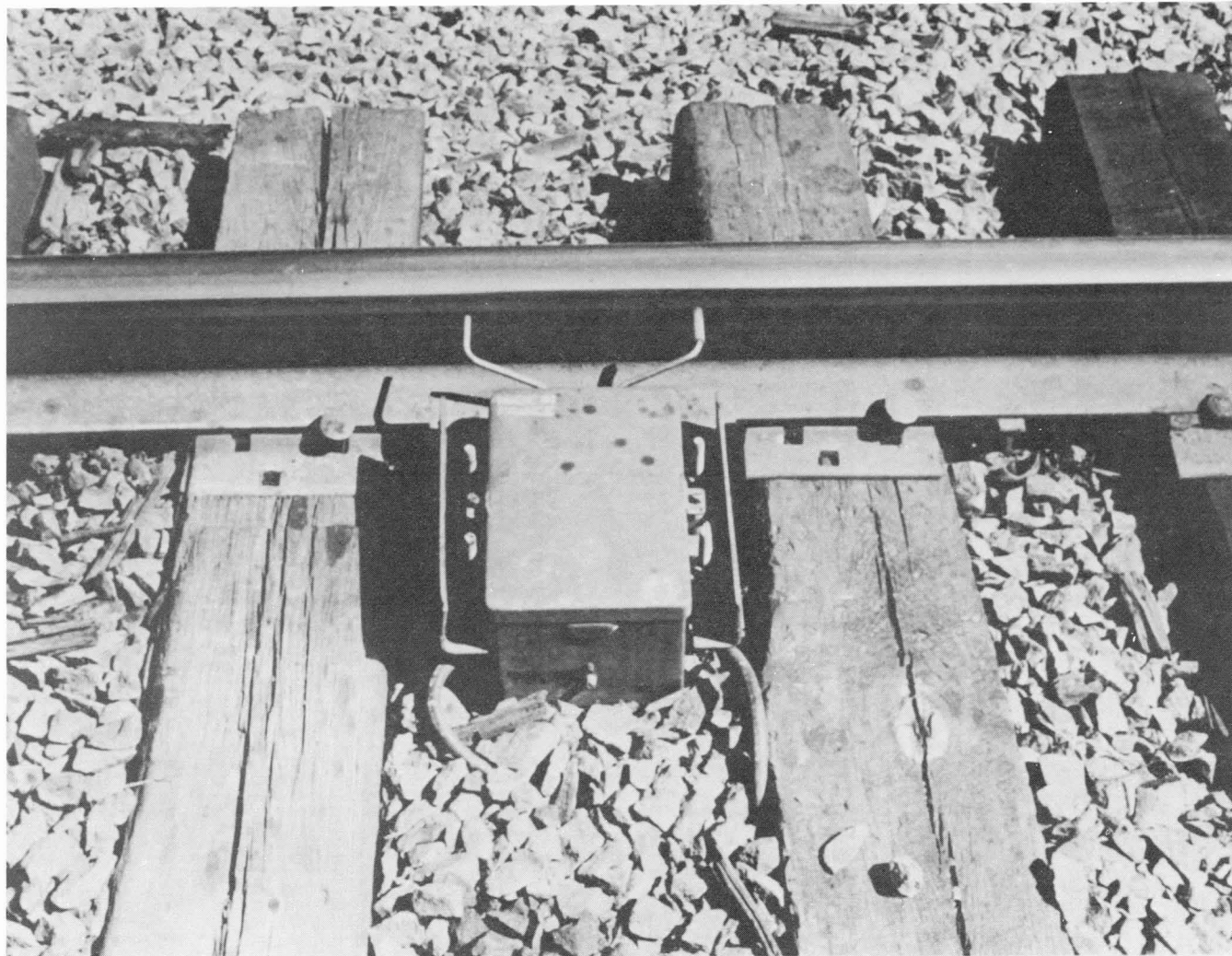


Figure 4.1. Mechanical Wheel Detector

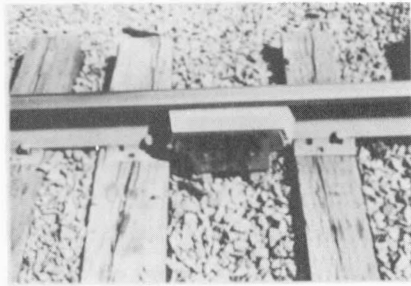
arms. By this action, the armature of a mechanical relay is moved to cause contact closure. Direction of travel information is obtained by sensing which one of the arms was depressed first.

The unit of Figure 4.1 was installed, by TSC, at one of our field test sites. The unit was subject to vandalism, as the arms are easily depressed or even broken off by normal body weight. It is subject to damage from dragging equipment. The unit had a tendency to freeze-up in the winter, particularly when it became surrounded by packed ice and snow. It was also found to give false alarms and incorrect direction-of-travel information. It would appear that these are problems with the overall concept of mechanical sensors and are not problems peculiar to the unit itself. The concept of mechanical sensors does not seem to warrant and did not receive any additional effort.

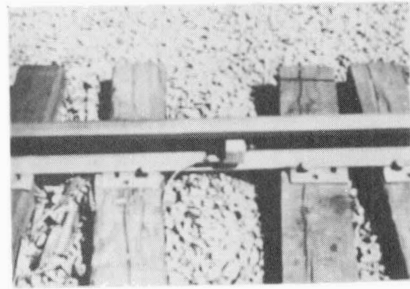
4.3.3 Magnetic Sensors

A common technique used in vehicle detection is that of magnetic sensing. There are two basic types of magnetic sensors; magnetometers and magnetic-inductive sensors. Both require an internally generated, steady-state, magnetic field. Also fundamental to both devices is a receiving mechanism whereby the strength and directivity of the received magnetic field is sensed. This receiving mechanism -- usually just a coil of wire -- effectively nulls out the steady-state field. If sufficiently large conducting or metal objects pass into the region of this radiating magnetic field the field is necessarily perturbed and the received field is thus different from the steady-state field. This change in the field is then sensed by the receiver and the appropriate indication is relayed ahead for further processing.

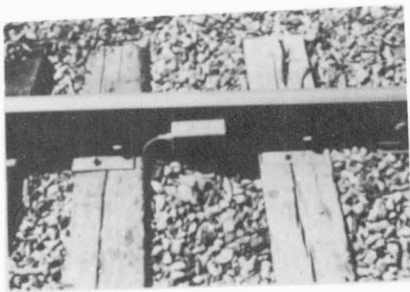
Figure 4.2 shows a photograph of four different commercially available wheel-flange detectors. All four are magnetic sensors which bolt to the inside of either running rail and sense the passage of the steel-wheel flange. While each of the four units was designed for a railroad use, none of the four was designed for a grade crossing application. They were designed for non-vital, non-safety, applications -- automatic carwashers, hotbox



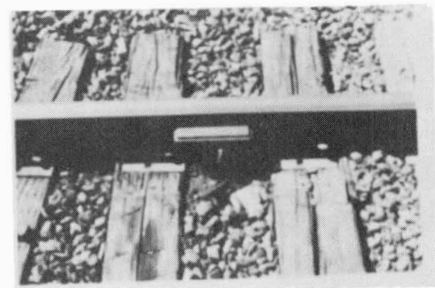
(a)



(b)



(c)



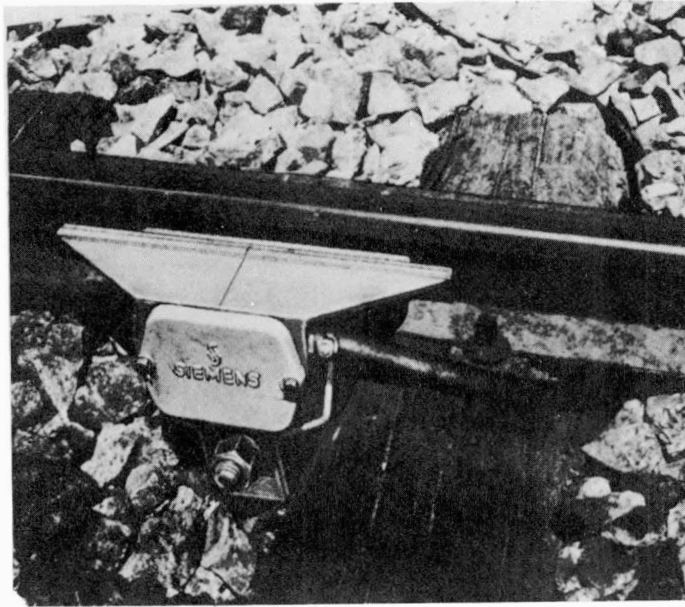
(d)

Figure 4.2 Magnetic Wheel-Flange Detectors

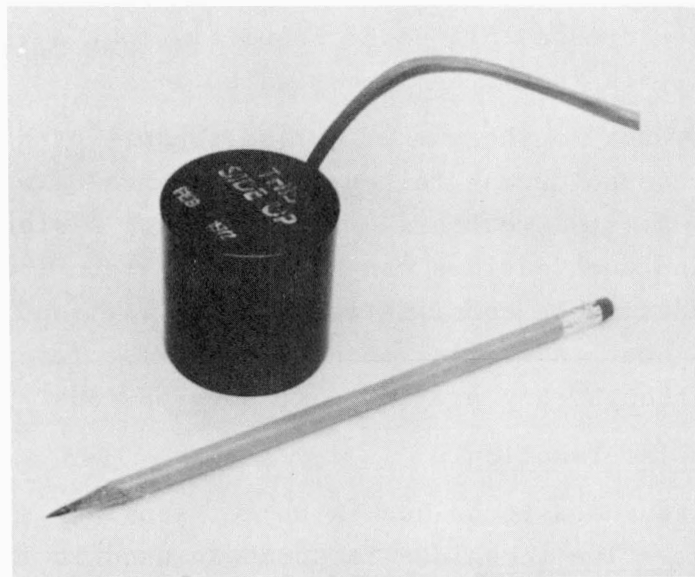
detectors, ACI systems, etc. Each of the four was installed and monitored by TSC. Units "a" and "d" are totally passive and either produce a pulse or provide switch closure to indicate train presence. Units "b" and "c" are active and consume 0.5 to 1.0 Watt of power each. The retail cost of the four units ranges from \$100 to \$300 each. Each unit shown is directional, is available in a directional model, or can be used in a directional application, by the use of two such sensors, mounted two to three feet apart. Although all of the sensors functioned reasonably well, within the constraints for which they were designed, none of the units shown on Figure 4.2 would be acceptable for a grade crossing application. The overall sensor reliability was insufficient. False alarms, probably due to low signal levels and poor noise immunity, was a problem with all four units. False alarms caused by trains on adjacent tracks also appeared to be a problem in one of the units. Most damaging was the fact that throughout our tests none of the four was totally effective.

Figure 4.3 shows two additional sensors that were also purchased, installed and monitored by TSC. The unit shown in Figure 4.3a is a magnetic wheel flange detector that is used for grade crossings (and general signaling) in Germany. The unit is totally passive and will detect trains moving at high speeds (160 mph) and will also detect standing trains. The particular unit shown is not directional but directional units are also available. The cost for the non-directional unit is \$500; \$900 for the directional unit.

Unfortunately, this particular unit was the last sensor to arrive, and has not been subject to as long a testing period as have the other sensors. However, on the basis of a limited 10 week test -- compared with 50 weeks for the sensors of Figure 4.3 -- it would appear that this particular unit might be acceptable for a grade crossing application. Ten weeks of testing included passage of approximately 800 trains. While the power consumption is satisfactory and the reliability at this point also appears good, the cost is rather high, and - as the unit is attached to the rail - it is conspicuous and subject to vandalism. The unit does



(a) Siemens (Wheel-Flange Detector)



(b) Magnetometer

Figure 4.3 Additional Magnetic Detector

appear to meet the constraints, but further testing is necessary before any real conclusions as to concept viability are possible.

Figure 4.3b shows a photograph of a magnetometer head that was purchased and installed as part of our effort. The unit was designed as a vehicle detector to automatically control highway traffic signals. The retail cost for a single head, including associated electronics, is approximately \$100. The unit was buried, between the rails, about one foot below the ballast surface. The unit has worked extremely well, has been in operation 6 months -- approximately 5,000 trains -- and has never missed a train or given a false presence indication. The unit installed was adjusted so that false alarms would not be caused by cars, shovels, trailbikes, or any object likely to be found in the area. Being buried below the ground, the sensor is inconspicuous and therefore protected against most forms of vandalism. This would appear to be a highly acceptable sensor except that the power consumption is rather high, 1.0 Watt per head, and that a minimum of two heads are required per transmitter as the basic unit is not directional. Four heads are probably necessary to insure the required high degree of reliability against non-failsafe failure modes. It is probably possible to decrease this power requirement by a factor of four or more and this should be investigated.

A drawback to the use of buried sensors of any type is the problem of damage during railroad maintenance-of-way operations. This is not a fatal weakness - some existing systems have buried elements, and such devices can be accommodated - but this represents an undesirable complication for non-railroad installation and maintenance. A similar problem can arise for rail-mounted sensors, although they are at least more obvious.

4.3.4 Beam Interruption

An often-used technique in object sensing is that of beam interruption. The technique is commonly used in indoors applications -- intrusion alarms, supermarket doors, etc. -- and is just beginning to be used in an outdoors environment. The method usually involves an infra-red beam, but lower frequency microwave systems are also possible.

Figure 4.4 shows a diagram of three possible configurations. In each a beam would be originated on one side on the track and then transmitted across to the other. The beam would, in the train absent case, then be reflected to the crossing, or be reflected back across the tracks and be received. The system design is basically failsafe as the absence of a signal indicates train presence. Power consumption could be kept quite low by the use of low-duty cycles and other rather standard techniques. IR beam interruption sensors are presently being used, in a similar application, as overheight detectors just preceding bridges or overpasses, of course there is the problem of false actuations caused by vandals covering the transmit/receive lenses with mud, snow, sticks, etc., and this should be designed against. The retail cost of a single unit is approximately \$150. Because of time limitations it was not possible to field test this type of sensor.

4.4 RECOMMENDATIONS

Because of time limitations it was not possible to investigate as many sensing techniques as would have been preferred. However, the magnetic sensing does appear, at this point, to present an interesting alternative. The use of a magnetometer buried between and below the rails is especially promising and the prospect of operation at lower power levels should be investigated. Vehicle-sensing magnetometers are now being manufactured by at least three different manufacturers and each of the three units has a power requirement of 1 watt per head or greater. The units were all designed for highway use and it was assumed that commercial electric power would be available in virtually unlimited supply. Low-power consumption was not one of the original constraints.

An additional technique that should also be investigated is that of weight sensing. Pressure pads are presently being used as highway vehicle detectors in the same application as are the magnetometers which are mentioned above. As with the magnetometers, the pad would be buried between and below the rails. Pressure pads are 3-5 times as expensive as magnetometers and do require

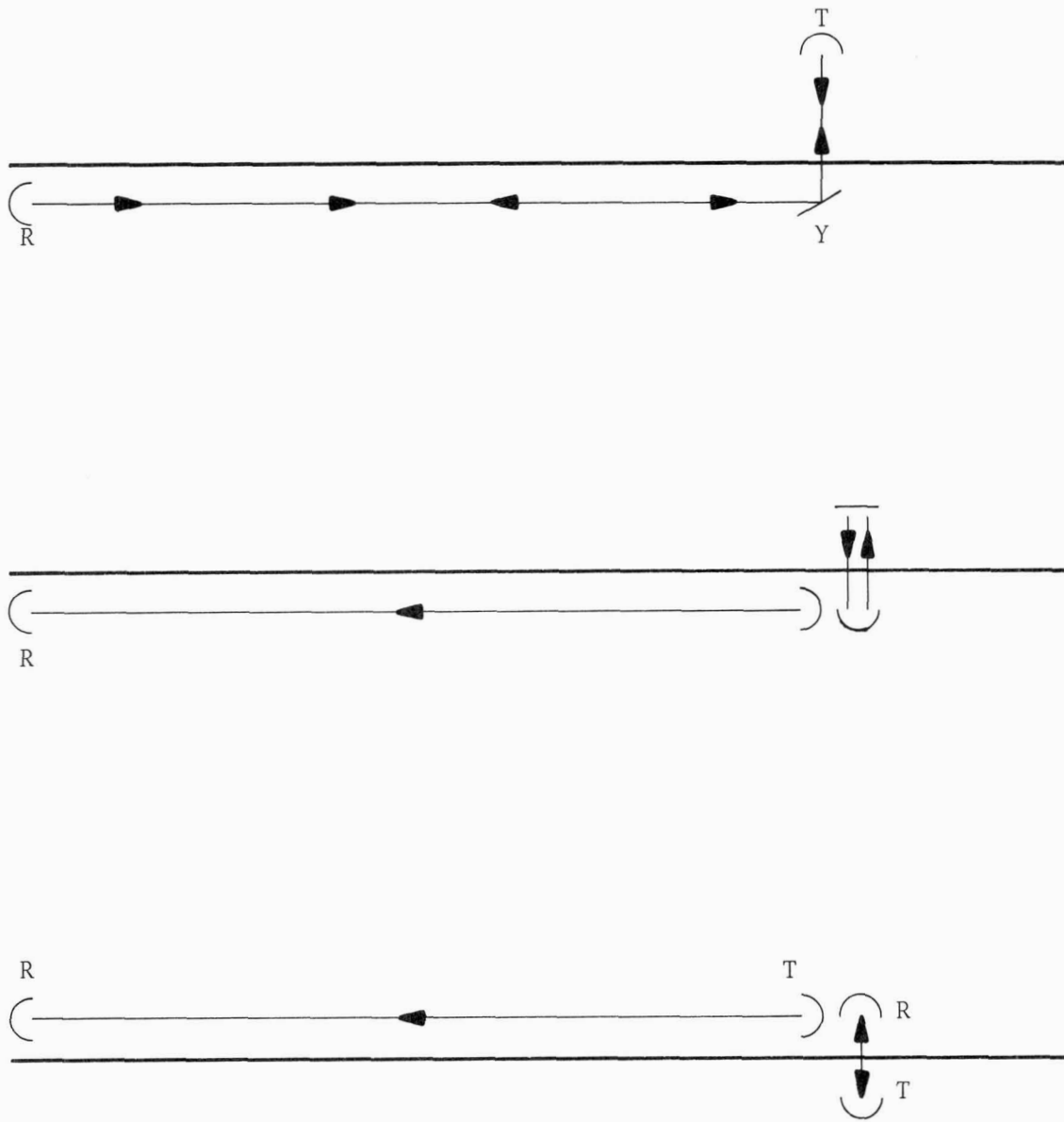
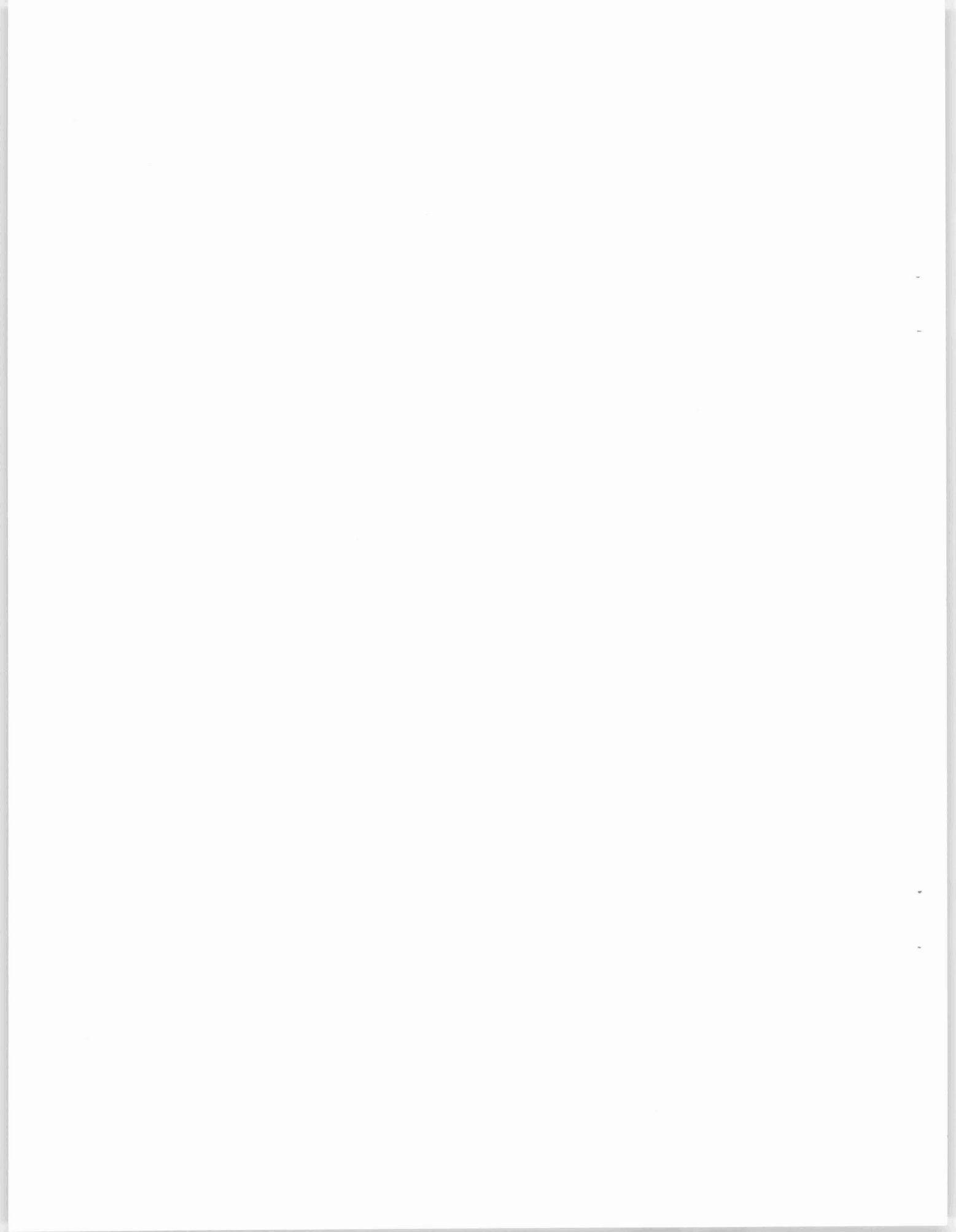


Figure 4.4 Possible Beam Interruption Configurations

considerably more installation expense as special supports are often necessary. Weight sensing is also often accomplished by the use of strain gauges. Strain gauges are small electro-resistive devices which measure minute changes in dimension. In this application, they would be mounted on one side of one of the running rails. The weight of the train, transferred to the rails, would cause a slight deformation in the rails. This slight change in dimension would be detected by the gauge and the information could then be processed accordingly. Strain gauges are, by themselves, quite inexpensive but must be packaged and mounted to the rail properly and those last two expenses would dominate. Both strain gauges and pressure pads should probably be investigated.

As a last-resort train-sensing technique, should none of the above methods prove feasible, a short, jointless track circuit might be considered. Here the track circuit would be used as a sensor only, would have an effective length of 10 to 40 feet, and would be operated at a high frequency, in the order of megacycles. For example, at 3.0 megaHertz the driving point impedance of an infinite section of track would be 125 ohms, and the signal would attenuate at a rate of 3.2 dB per 10 feet -- this is assuming the typical values of 5,000 ohms per foot of shunt resistance and 0.5 microHenry per foot of series inductance. This means that power requirement, for a 3 volt track circuit could be as low as 0.4 watt, including transmitter and receiver losses. In terms of the vhf signal interfering with the existing signal system, the 3.0 volt signal would have an amplitude of 0.12 volt, at a distance 100 feet from its point of origin. This is far from the ideal sensor, but is a possibility.



5. MICROWAVE PROPAGATION PROPERTIES OF THE TELEMETRY LINK

5.1 REVIEW

The typical grade crossing microwave telemetry link described in this report is approximately 1,000 meters long. All of the links used to date have been line-of-sight, from a transmitting antenna mounted at the top of a pole 5 to 7 meters high standing near the tracks, to a receiving antenna similarly mounted at the crossing. Under conditions of line-of-sight propagation between two points in empty space, the path loss in dB at 10 GHz operating frequency would be

$$\text{Path Loss} = 53 + 20 \log_{10} (L_{\text{meters}}) - G_{\text{rec}} - G_{\text{xmit}} \text{ (dB)}$$

where L is the length of the path, and G_{rec} , G_{xmit} are the antenna gains. In practice, a number of effects were noted that caused the observed path loss to depart from this figure, sometimes markedly.

The most deleterious effect observed was complete cancellation of the received signal due to multipath interference between the direct transmitted signal and the signal that is reflected off the ground as it propagates from transmitter to receiver. Other effects were the decrease of a few dB in received signal when a train or other vehicle was present on the tracks between receiver and transmitter site, even though the line of sight was not intersected. The third effect was a slow random fluctuation of a few dB with a period of approximately 30 seconds not due to any apparent cause. These effects, plus suggestions for system design to counteract them, are discussed in this section.

5.2 MULTIPATH INTERFERENCE

Multipath interference occurs when the direct line-of-sight signal transmitted from a transmitting antenna to a receiving antenna is cancelled by the signal that is reflected off of the ground and thus follows a longer path from the transmitter to the receiver. This effect is undoubtedly a factor at each telemetry site employed in this study. Detailed measurements of multipath

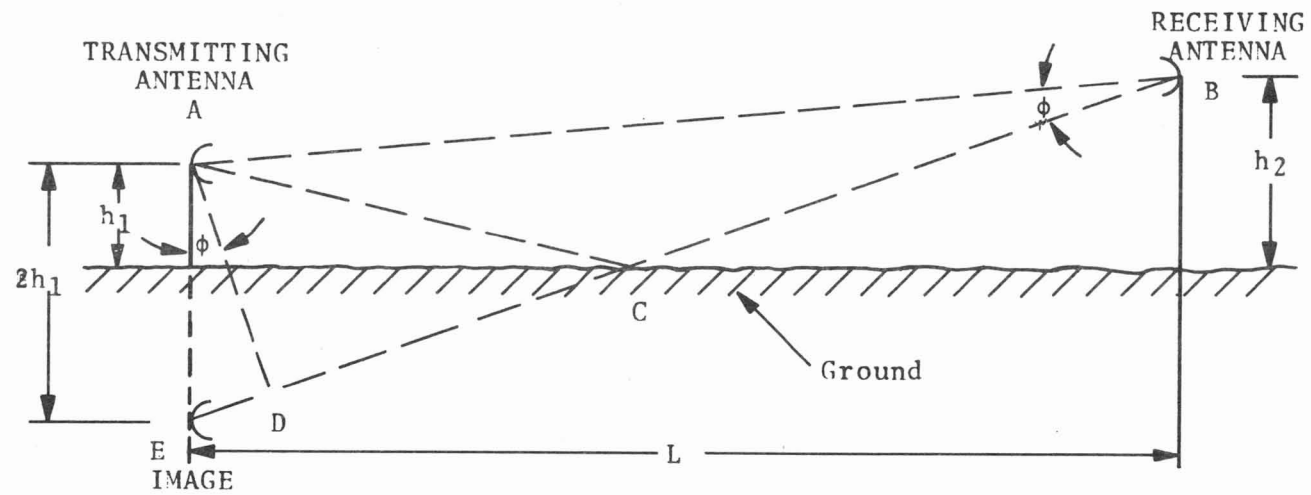
interference were made at one site, after it was discovered that the original receiving antenna installation was such that the received signal was so weak that the system was inoperable.

The fact that almost perfect cancellation between direct and reflected signals can occur is due to the fact that practically any ground surface becomes a very nearly perfect reflector of microwaves as the angle between the surface of the ground and the direction of propagation of the waves becomes very small. The effects of dielectric mismatch between air and earth are magnified, and the effects of surface irregularity are greatly diminished at small grazing angles. When a vertically polarized electromagnetic wave reflects off a dielectric surface at very small grazing angles, there is a 180° phase shift between incident and reflected waves, but imperceptible attenuation.^{6,7}

Figure 5.1 shows the geometry of multipath interference. For perfect cancellation of the line-of-sight signal by the reflected signal, it is necessary, given the 180° phase shift on reflection, for the direct path and the reflected path to have a difference in length of an integral number of wavelengths. For small values of the grazing angle ϕ , the approximate relationship between antenna heights $h_{1,2}$, length of the path L , and wavelength leading to perfect cancellation is

$$h_2 = \frac{\eta \lambda L}{2h_1} .$$

When the difference between the length of the direct path and the reflected path is an integral number of wavelengths plus one half wavelength, the direct and reflected signals add constructively and actually increase the received signal strength by 3 dB over what would be observable in empty space. A theoretical graph of received signal strength vs. receiving antenna height h_2 for a hypothetical link of length $L = 1000$ meters, transmitting antenna height $h_1 = 5$ meters, and wavelength $\lambda = 3$ cm is shown in Figure 5.2.



For Small ϕ , $\frac{h_2}{L} \approx \frac{DE}{2h_1}$. For multipath cancellation,
 $\overline{DE} = n\lambda \therefore h_2 = \frac{n\lambda L}{2h_1}$.

Figure 5.1 Geometry of Multipath Interference

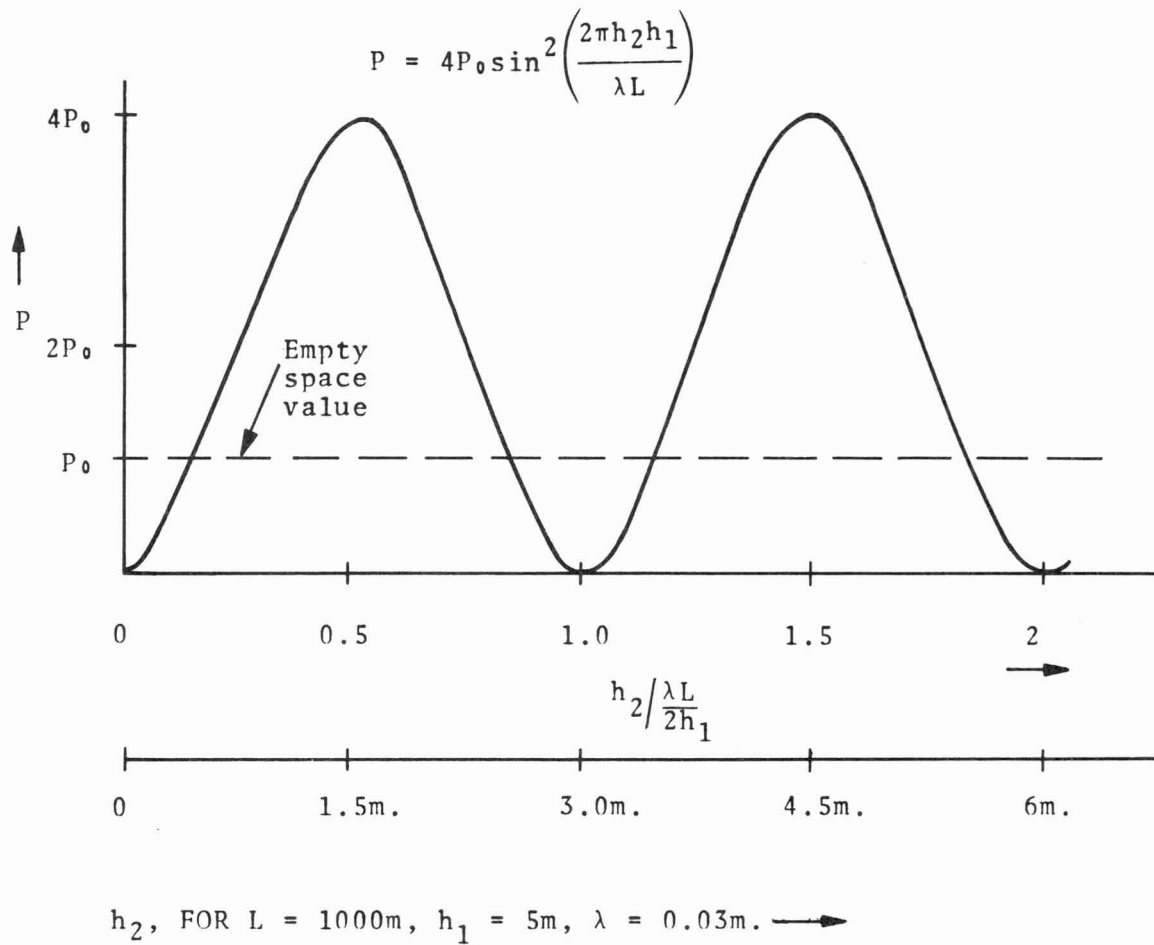


Figure 5.2 Theoretical Received Microwave Power Versus Receiving Antenna Elevation (Multipath Interference Case)

In a real situation, where the ground between transmitter and receiver is not of uniform grade, the antenna heights must be measured with respect to some average grade level taken midway between antennas. However, if fluctuations in grade are great, there are likely to be effects of focusing or defocusing of the reflected wave or of reflection at an angle slightly different from the angle of incidence. These effects would greatly complicate theoretical calculations of any real situation. In addition to these effects due solely to the ground, partial reflections probably also occur from trees and other objects at the sides of the right of way. These further complicate the theoretical picture.

In spite of the analytical difficulties offered by the real situation, the most important aspect of multipath interference is that it does occur and must be dealt with. Figure 5.3 shows the measured signal strength of the received signal as a function of antenna height at a particular telemetry link. The important fact about the results is that at certain antenna elevations nulls of received signal strength did occur.

5.3 ALLEVIATION OF MULTIPATH INTERFERENCE EFFECTS

One difficult aspect of multipath effects is that in the New England environment the ground level shifts in elevation throughout the year as snow falls and melts. In addition, the reflective characteristics of trees vary as they lose and replace their leaves. Therefore, a receiving antenna position that is optimum in one season could be a null position at some other time. In order to alleviate the potential problems that could arise due to such seasonal fluctuations, the following system design concept was investigated:

Two receiving antennas, positioned apart by an amount that was approximately equal to the distance between a null and a maximum of received signal strength, were used in a short telemetry link set up in the laboratory. The signal received by each antenna was detected by means of a crystal detector, producing a voltage proportional to instantaneous microwave power received.

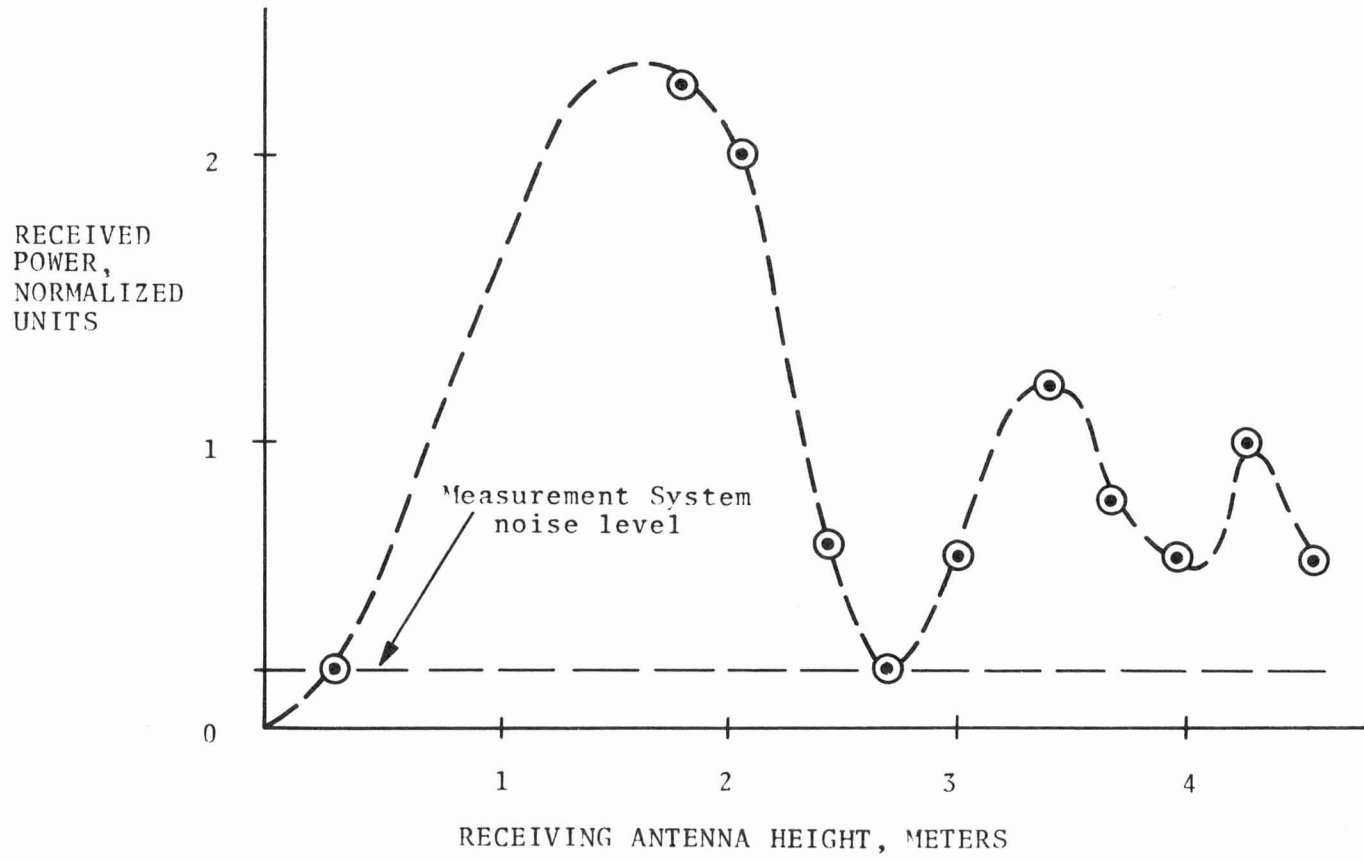


Figure 5.3 Measured Signal Strength as a Function of Antenna Height

The detector output voltages or signals were summed and the sum was recorded as the two-antenna array was varied in elevation. In this case, the array of antennas is not an antenna array in the usual sense, since they are functions of the received microwave powers that are added and not the instantaneous field strengths of the microwave signals themselves.

The measurements of detected signals showed that whereas one antenna alone produced detected signals showing very sharp nulls at uniformly spaced intervals of elevation, the sum of detector output signals from both antennas varied by only 3 dB as the two-antenna array was moved up and down. This is simply due to the fact that the antennas were positioned so that as the signal received by one antenna was decreasing, that of the other antenna was increasing, as the array was moved. It is believed that this space-diversity receiver technique could eliminate completely the threat of telemetry system failure due to shifts in multipath interference patterns.

5.4 SIGNAL FADING DUE TO PRESENCE OF TRAIN OR OTHER VEHICLE BETWEEN TRANSMITTER AND RECEIVER

It is well known that the microwave energy directed from one antenna to another antenna a considerable distance away is not confined to a tubular region of space with a cross section equal to the diameter of the antennas. Rather, wavefronts propagate away from the transmitting antenna and spread out filling a conical beam. For instance, in the TSC telemetry system the antennas used had a beamwidth of 6° .

A small scattering object placed immediately in the line of sight between the two antennas will only cause a small perturbation in shape of the total wavefronts--the perturbation will be larger nearer to the scattering object than farther away from it. A quite large scattering object will only cause partial loss of received signal due to the fact that only a portion of the wavefronts are intercepted. By the same token, a scattering object placed off the line of sight but sufficiently near to it will also perturb the wavefronts and cause a decrease

in received signal. This decrease is a function of size and positioning of the scattering object. The larger the scattering object and the nearer it is to the line of sight, the greater the decrease.

It was observed at one telemetry location that the received signal strength was reduced by an amount somewhat greater than 6 dB when a train occupied the track between transmitter and receiver. The sudden onset of signal strength reduction with arrival of the train caused the telemetry link to malfunction. The cause of malfunction was the small dynamic range of the final stages of signal processing circuitry coupled with a slow response time of the AGC circuit in the receiver. The final stages of signal processing required full normal signal strength in order properly to interpret the signals and decide whether a train was present or absent. Upon sudden arrival of the train, the signal would almost instantaneously be diminished by approximately 6 dB, and would not recover for a time slightly greater than 3 seconds. The loss of sufficient signal for proper system performance would initiate an indication of malfunction.

In order to obtain an accurate picture of the microwave propagation effects involved in this phenomenon, received signal strength was measured at the site where the problem was most acute as a panel truck was slowly driven down the access road paralleling the track. A gradual decrease in received signal strength was at first observed as the truck proceeded away from the receiver, followed by faster rate of decrease as the panel truck neared the midpoint. When the truck was midway between transmitter and receiver the reduction in signal strength was greatest and was approximately 6 dB.

While the panel truck was probably intercepting parts of both the line-of-sight waves and the waves bounced off of the ground, it is believed that the reflected wave reaching the receiving antenna was most affected. It is somewhat surprising that an object as small as a panel truck could cause such a marked decrease in signal transmission. The transmitting and

receiving antennas were approximately 800 meters apart and were atop poles approximately 7 meters high. The beamwidth of both transmitting and receiving antenna patterns at the midpoint is a full 40 meters. The panel truck cross section was only (approximately) 4 m^2 . The magnitude of the observed effect at that particular telemetry site might be aggravated by the fact that tall trees adjacent to both sides of the right of way form a relatively narrow duct down which the microwaves must propagate, thus decreasing the relative space for waves to go around the truck.

An additional ducting phenomenon that might be present is one that is usually encountered in microwave propagation over water at elevations of tens of meters or less, but also has been observed frequently over land.⁷ Under certain circumstances such as when surface moisture is evaporated by the heat of sunlight, the air immediately adjacent to the surface contains more moisture than the air at greater altitudes. This air has a greater relative dielectric constant and therefore a greater index of refraction than the air immediately above.

Microwaves directed upward at an angle slightly above the horizontal will be refracted downward again by the negative gradient of index of refraction. The ground and some point above the ground will essentially form the bottom and top of a duct that contains the microwave energy. Whereas this effect is most pronounced over water, the fact that it can occur over land might account further for the magnitude of signal reduction due to the truck because of concentration of the transmitted microwaves into the region within a few tens of meters of the ground.

The gradual variation of a few dB in received signal strength that was observed even in the absence of the truck or trains is probably due to the expected fluctuations in properties of the duct due to the effects of breezes and variation in rate of solar evaporation of moisture from the ground.

5.5 SYSTEM DESIGN TO DIMINISH EFFECTS OF FADING

Under all observed circumstances to date, fading severe enough to cause the signal to disappear into the noise has never been observed in any grade crossing telemetry link. Fading problems have arisen because of limitations on instantaneous dynamic range of receivers used. Given that signal-to-noise ratios are generally adequate even when fading is at its worst, it appears that it is not necessary to depend entirely on a slow-acting AGC circuit together with linear signal amplifiers in the receiver in order to provide maximum attainable signal-to-noise ratio while at the same time maintaining signals at their proper levels.

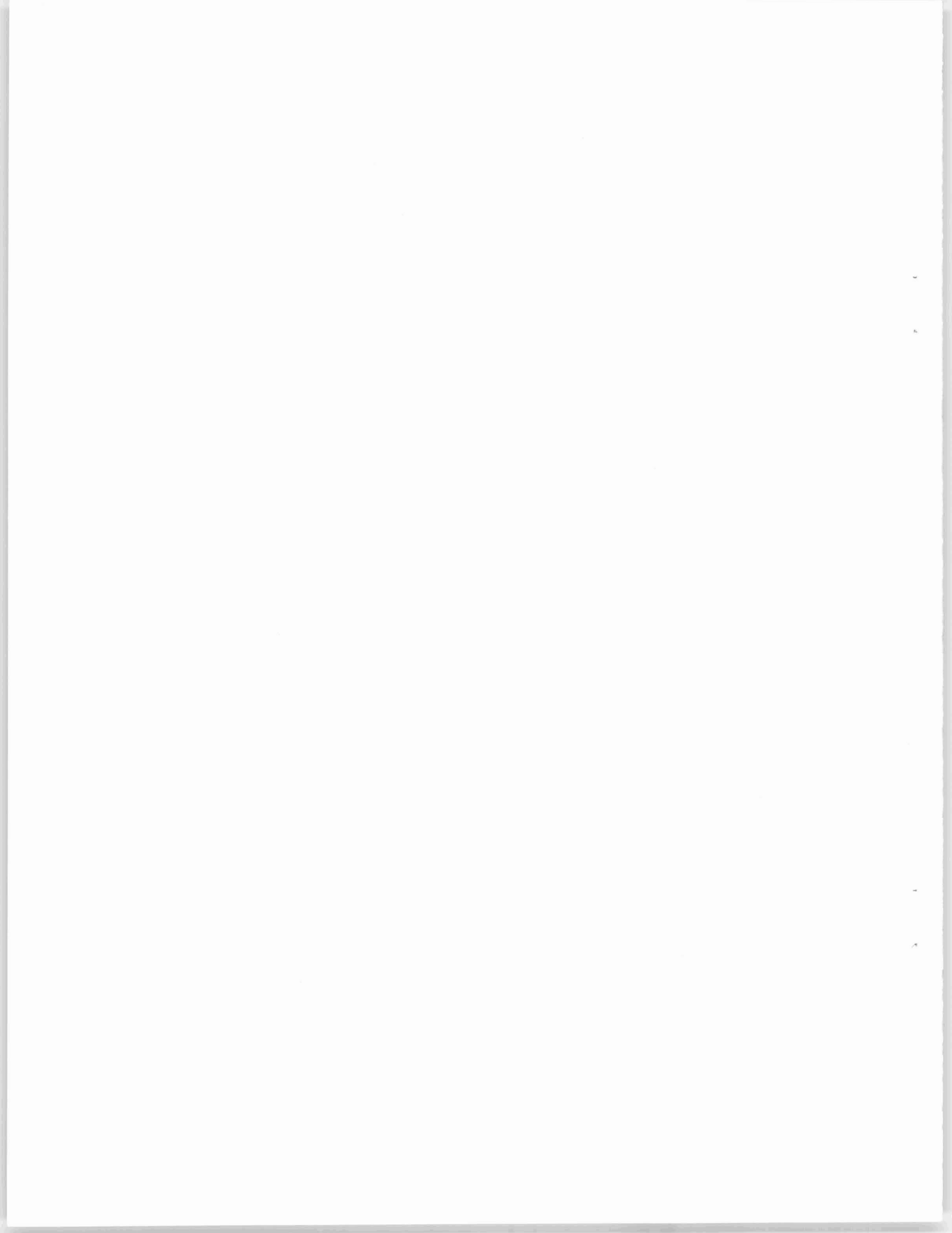
Analysis of observations of telemetry system performance to date indicates that the following system configuration might best be employed in future versions of the grade crossing telemetry system. The first stages of signal amplification after the microwave crystal detector should be controlled by an AGC circuit so that the signal, after the first few stages, is always approximately of constant value, independent of long-term fluctuations in microwave signal received at the antenna. The signal-to-noise ratio at the output of these first few stages will be maximum attainable since amplification has been linear. Then there should be a stage of amplification and limiting, probably in conjunction with narrow-band filtering, to produce a signal whose amplitude will not vary even when the input signal to the limiting stage suffers sudden decreases by as much as 10 dB. That is, there should be approximately 10 dB of limiting. When employing a narrow-band limiter the signal-to-noise ratio at the input of the limiter stage is essentially preserved as long as a signal much larger than the noise is present. The nonlinear amplification causes the noise output to be decreased in amplitude as the signal increases above the threshold for limiting. When the signal disappears at the input, the noise is no longer reduced and therefore the noise output suddenly increases in amplitude. For signal-to-noise ratios much larger than unity, the ratio of signal to noise when signal is absent is decreased by an amount

directly proportional to the amount of limiting used. Therefore such a system can only be used in a situation in which the signal-to-noise ratio is entirely satisfactory. This is the case for the TSC grade crossing telemetry system. Such design of the signal amplification and equalization stages of the telemetry receiver should overcome the effects of both long-term and short-term fading in the microwave transmission link.

The coding and modulation scheme employed to impress information on the microwave beam should be compatible with these signal-amplitude control techniques. If tone-burst modulation is used in which the frequency of the modulation envelope is varied to indicate train presence vs. train absence, the modulation frequencies should not be harmonically related. Use of non-harmonic frequencies will eliminate the problem of the nonlinear limiting process generating spurious signals that can be falsely interpreted by the receiver circuit.

5.6 CONCLUSION

Field observations of the performance of the TSC grade crossing telemetry system have provided data on both short-term and long-term fluctuations of transmitted signal strength. The observed behavior generally agrees with well-known theories of microwave transmission. The ultimate test of a microwave transmission system is observation of the signal-to-noise ratio at the receiver, and judgment of whether it is adequate for proper system performance. In spite of the fluctuations in signal transmission observed in the TSC grade crossing telemetry systems, signal-to-noise ratios were always adequate. Employment of an array of two antennas and detectors at the receiver end of the telemetry link should protect against the potentially most severe problem--that of complete signal cancellation due to multipath interference. Proper design of the receiver amplifier and signal processing circuit should eliminate all problems of fading and fluctuation of transmitted signal that have been observed to date.



6. SOLAR POWER

6.1 REVIEW

The transmitters for the telemetry system are generally to be located as much as 1000 meters from the crossing. Commercial electricity to power the transmitter will often not be available. It is therefore appropriate to consider using an alternative power source.

As an alternative, solar power appears to be quite promising. The basic configuration would consist of an array of solar cells, devices which convert solar energy directly into electrical energy, charging a storage battery. The battery would then supply power during night or cloudy conditions. Research and testing of solar cells has been extensive for the last twenty years -- supported primarily by NASA and Bell Telephone Laboratories. Solar panels are now commercially available from at least three different manufacturers. These panels are capable of generating average power densities of 0.5 to 2.0 watts per sq. foot of solar panel area, depending on the geographical location in the U.S., and costs are approximately \$100 to \$400 per watt of average output power. These cost figures include the costs of both the solar cells and the batteries. This technique was tested as part of the telemetry system field test program.

6.2 BASIC PRINCIPLES

Figure 6.1 shows a photograph of a five cell solar panel. Each of the cells is fabricated from single-crystal silicon and has an overall conversion efficiency of about 12 percent. Solar cells have also been fabricated from selenium, cadmium-sulfide, and germanium, all achieving much lower efficiencies.

Unfortunately, physical principles restrict their operation to the red to infra-red portion of the solar spectrum. This is the region that is most affected by clouds and fog, so that even a high, thin cloud layer will greatly reduce the output of the

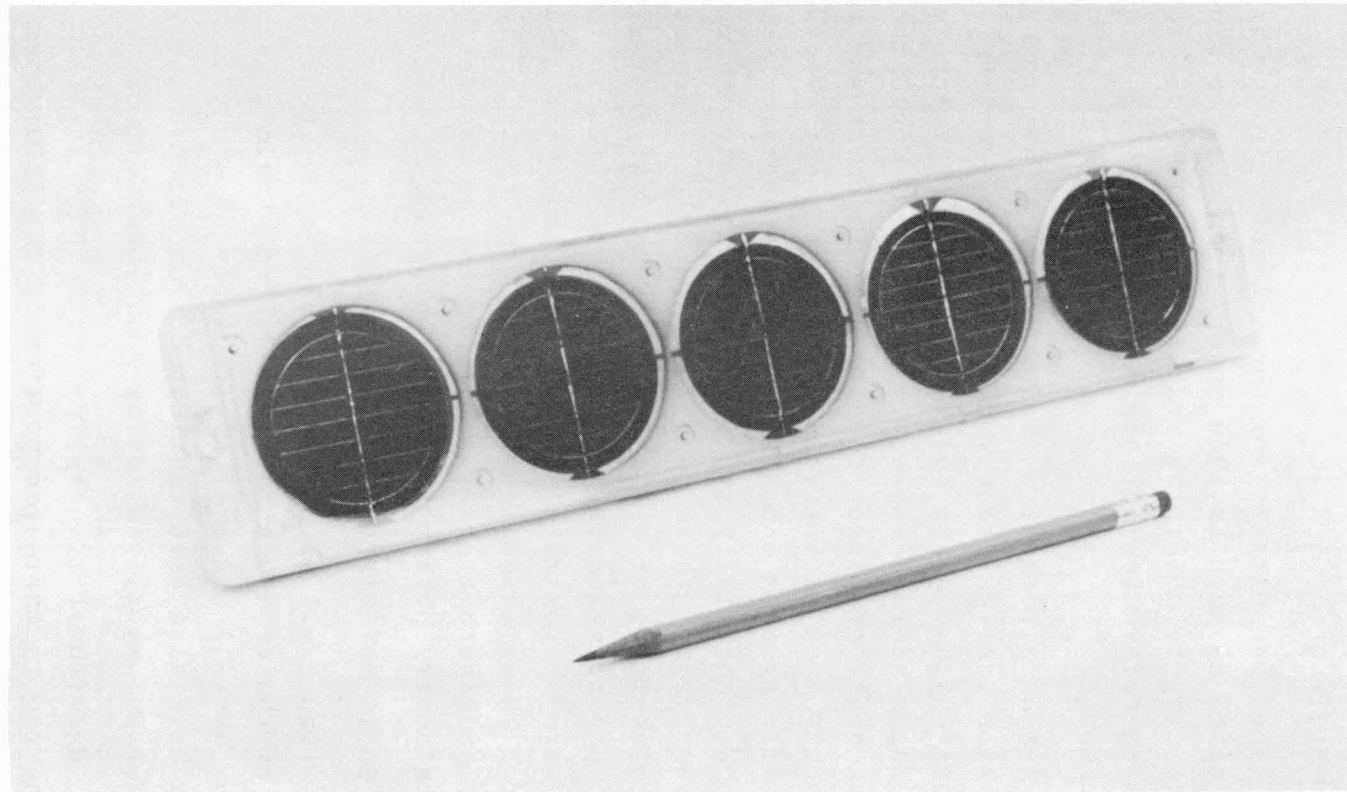


Figure 6.1 Five-Cell Solar Panel

panels. However, even with this problem, there is no location in the continental U.S. where solar panels would not be effective. The United States Weather Service has, over the past forty years, been gathering data on the amount of incident solar energy, for various parts of the country, at various times of the year. While there is some variation as to the average radiation that a particular location receives, the worst location (northern Minnesota), which receives only half as much sunlight as the best location (southern New Mexico), is still an area where solar panels could be effective.*

The surface of the solar panels will probably never require cleaning. The panels, in the U.S., will always be mounted at a substantial angle from the horizontal, and wind and rain should keep the panels reasonably clean. Also, the panels will be mounted some twenty feet off the ground, and will be above most of the mud, dirt, and snow drifts. Flat microwave antennas have been exposed to the railroad environment for over a year with no apparent dirt formation on the surface.

6.3 TEST AND PRELIMINARY CONCLUSIONS

The panel shown in the photograph of Figure 6.1 was the model that was purchased for field testing. The panel cost \$30, and when exposed to direct sunlight, generates 1 watt of electric power. Four of these units were mounted in an enclosure under a 1/4" sheet of clear polycarbonate (Lexan). The plastic cover does decrease the panel's output by about 20 percent, but offers substantial protection against vandalism, and was therefore used. If solar cells were to find a major market in a railroad environment, the cells could be encased directly in thicker plastic at a 1 percent decrease rather than a 20 percent decrease in efficiency. The four enclosed solar panels, a storage battery and a DC-DC inverter were installed at both of the transmitters at one

*For a good discussion on the physics of solar cell operation, as well as weather and mounting data, see Zarem, A.M., and Erway, D.D., Introduction to the Utilization of Solar Energy, McGraw-Hill, New York, 1963.

test site. The inverters were necessary to convert the 2 volt output from the panels to the 12 volt input to the transmitters. The inverters which have an overall efficiency of 88 percent were purchased from the solar panel manufacturer.

The panels were mounted in a fixed position, facing South, which in the Northern Hemisphere is the direction of greatest intensity. The panels are also pitched at an angle from the horizontal equal to the latitude of the test site -- 42 degrees. A unit ready for field test was shown in the photograph of Figure 3.6.

In addition to the use of a fixed mounting, consideration has been given to the effectiveness of placing a clear dome-shaped lens or concentrator over each of the cells, and also of having the solar panels move and thereby track the sun, as methods of increasing the total amount of received solar energy. While placing lenses over the cells would increase total output power, the cost per watt gained is greater than the cost of using more panels. Neither does tracking appear to be practical, in a small installation of this type, since it would take more power to move the panels than would be gained by such a scheme.

Data from the U.S. Weather Service indicates that, on the average, the Boston area receives about 3.6 hours of peak sun light per day, assuming the mounting condition described above. This means that the solar power unit of Figure 6.1, taking into account losses due to the plastic cover and the inverter, would be able to supply 0.4 watt of average power to a load. The transmitter and the associated flange detector circuitry at that test site represent an average load of 0.130 watt, so that the solar panel system has a design safety factor of 3. The units were installed at the site and the battery's depth of charge was measured periodically for three months. Both systems have consistently powered the transmitters and held the batteries to a 70 to 100 percent charge.

Judging from these limited field tests, as well as other reported solar panel tests, it would appear that when an expenditure of \$100 to \$400 per watt is warranted, solar power can be an effective means of providing remote electric power.

7. RADAR STUDIES

7.1 FEASIBILITY OF RADAR

The task of locating objects, characterizing relative location and velocity, is one that has been solved in many applications over the last thirty years by the use of radar. In essence, a radio signal is transmitted and the required information is obtained by analysis of any reflected return signal. A closely related application of this technique is that of highway speed monitoring used by many police departments. The concept as applied to grade crossings would consist of the use of two such radars, one for each direction, to indicate the approach of trains, so that warning signals could then be activated.

Microwave radar, used for detection of train presence and/or motion, can serve three different functions in crossing protection. The first is that of an arrival time predictor, making the appropriate measurements and supplying the necessary information to provide a uniform warning time, regardless of train velocity. In this application (case #1), the radar is supplementary to other basic train detection means. Alternatively, radar can be used as a primary detection means, either crossing-located, with a range of approximately 3,000 feet for 80 mph trains (case #2), or -- in short form -- as the down-track sensing component in the basic telemetry system (case #3). These latter cases offer the potential of relatively low cost, but will require careful development in order that non-failsafe failure modes are virtually eliminated.

While there are many advantages and benefits involved in using radar for crossing protection -- constant warning times, low cost, installation by local highway departments with only limited railroad involvement, etc. -- the constraints and problems are quite severe. The task undertaken was to consider the general feasibility of a radar approach, and the remainder of this section deals with that question.

7.2 AREAS OF TECHNICAL CONSIDERATION

7.2.1 Information Requirements

Case #1: In a case #1 application, the two radar units would be located at the crossing and would be used in addition to either a track circuit or telemetry link. The radar would not normally be operating, but would be activated by the "train approaching" signal from either the track circuit or telemetry link. After activation, the radar would continuously monitor the train's speed and direction. This information, integrated with time, along with the exact time that the radar was first activated, and the fixed length of the track circuit, is all that is necessary for an accurate prediction of the train's arrival at the crossing. This configuration would be able to supply a constant motorist warning time, independent of train velocity, acceleration or even switching movements. This would clearly be an advantage if not a necessity at many future crossings, where perhaps both high speed passenger trains and lower speed freight and work trains might use the same track.

In this application the general problem is complicated somewhat by the requirement for long range operation -- 2,000 to 4,000 feet. Failsafe operation and high radar reliability, while still very serious problems, are somewhat less critical here than in cases #2 and #3, as the primary sensing is done by another part of the system. The track circuit or telemetry link would really be the major factor in providing protection here. If, at any time, the radar was determined (by internal self-check circuitry) to be potentially in error, the track circuit or telemetry link would assume full control and an immediate warning would be given to the motorist. The self-check circuitry would, conceivably, test for a weak or non-existent radar return signal, physically impossible changes in train speed or direction, multiple train velocities, etc.

Case #2: In the second and most difficult application, the radar would be the primary means of detection and would also furnish a continuous measurement of the train's speed, direction of travel, and range. The configuration would be similar to the first case,

but would not involve the use of either a track circuit or telemetry link. In this application the radar must provide a continuous range measurement since the information is not available from any other source. Of course, the radar would have to be operating continuously and the failsafe and reliability requirements would be extremely severe.

From a railroad standpoint this case would appear to be the ideal application. In addition to all the benefits of a case #1 application, installation and operation would be completely external from railroad property, track, and circuitry. Thus installation and maintenance could be performed by local highway departments with only limited railroad involvement. Unfortunately, however, this application is also the most difficult in terms of the technical requirements.

Case #3: In the third application the radar unit would be used as a sensor only. The units would be mounted on the telemetry transmitter poles, some 2,000 to 4,000 feet from the crossing. The radar would sense train presence, speed, and direction. This information would then be communicated back to the crossing, via the telemetry link, so that constant warning times could then be calculated.

The general-radar problem is eased considerably here, due to the relatively short distance (less than 100 feet) over which the radar operates. However, the specific problems of the necessity of very-high reliability and absence of non-failsafe failure modes is paramount here, as the radar is the only means of train detection.

This application is also limited by the fact that velocity is not monitored continuously, but rather just at the acquisition point. Therefore, accelerating or decelerating or switching movements will tend to confuse the radar. For example, if a train is traveling towards a particular crossing at 30 mph and if the telemetry transmitter is located 3,000 feet from the crossing, with no acceleration or deceleration, the train will arrive at the crossing 68 seconds after being sensed. For a 25-second

warning time, this requires a delay of 43 seconds. But if immediately after being sensed at 30 mph, the train accelerated at a rate of 0.1 ft per sec. (a rate easily obtainable by many passenger trains) the train will arrive at the crossing 43 seconds after being sensed - with no advance warning. While the situation just described is probably not a common one -- except at crossings near stations -- it does tend to limit the unit's effectiveness. The normal warning time must then be sufficient to provide a minimum warning time of 25 seconds even if the train accelerates at full power. Therefore, normal warning times, in instances with no acceleration, will be considerably longer than 25 seconds. And in those instances where the train decelerates or even undergoes switching movements, the delay will be even worse.

7.2.2 Train/Crossing Cooperative Systems

Among the most frequently suggested radar techniques are those which involve placing some sort of microwave radar device on each locomotive. In one scheme, the device would code train related information onto the radar signal before reflecting it back to the crossing. In another, the device would be used to enhance the locomotives reflectivity and thereby increase the signal strength of the return radar signal. In still another application, the device would be used to code the reflected radar signal, so as to differentiate it from signals reflected back from near-by buildings or moving cars and trucks, in cases where a highway runs parallel to the tracks. The FAA, in its Microwave Landing System radar, uses a similar technique and requires all aircraft performing major passenger service to be equipped with such a device.

In a railroad application, however, there are several inherent major defects associated with such systems and any system using this scheme is quite undesirable. All locomotives which might cross the intersection in question must be appropriately equipped, and for most such systems, the locomotive has to precede all other rolling stock. In general, this would be difficult to ensure, particularly in view of the practice of

locomotive interchange among railroads and the common situation of cars being pushed in switching moves. Further, the equipment must be in operating order, which raises the question of a failure during general operation. One then has also the undesirable situation that different departments within the same railroad company have responsibility for the maintenance of different elements of a single system. This problem is even more acute for interchange equipment. Failsafe operation is impossible, as an unequipped train will be indistinguishable from a no-train situation. Finally, anything approaching uniform warning times will be difficult to obtain from such a system, as will be proper activation regardless of the orientation of the locomotive or its position in the train.

Simple field tests, performed by TSC, indicate that locomotives and all major classes of rolling stock do produce a sufficient reflection to make the use of on-board radar signal enhancement unnecessary. Using the one-foot antennas shown in Section 3, and the 100 milliwatt Doppler module shown in Figure 7.1, it was possible to detect all locomotives and rolling stock at ranges of approximately one mile. The radar cross section of various rolling stock was measured and found to vary between 50 and 1,000 square feet.

7.2.3 Clutter

One of the most serious problems to be overcome and a factor that tends to limit the scope of possible radar techniques is clutter. Clutter is defined as the sum of all the spurious radar signals reflected back from the ground, rails, trees, vegetation, buildings, poles, rain, snow, etc. Radar theory, as well as TSC tests, indicate that for reasonable RF power levels the clutter return will mask the return from a train more than 100 feet away, unless the radar responds to moving targets only. Clutter is a well-known radar problem, and often is the factor which most limits the low altitude effectiveness of aircraft-surveillance radars. There are only two major techniques for coping with this problem. The first is to code the returning-radar signal by use

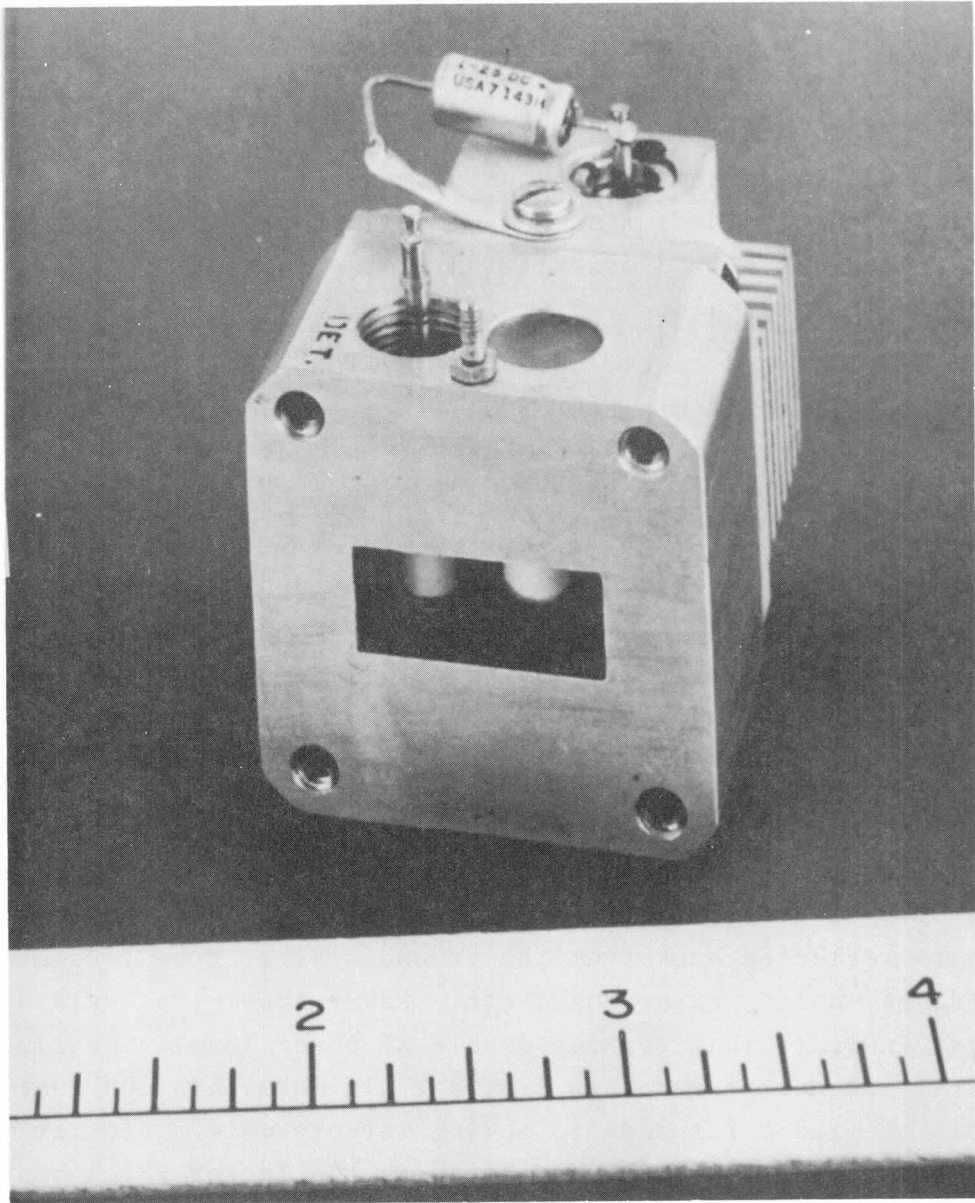


Figure 7.1 Doppler Module (X-Band)

of a microwave transponder mounted on the locomotive; this has been shown to be undesirable. The other approach is to design a radar which responds to moving targets only. The latter case of radars are known as MTI radars (Moving Target Indication) and almost always make use of the Doppler effect.

Doppler radars work on the principle that when a wave, such as a microwave radar signal, is reflected off of a moving object, the frequency of that reflected wave is shifted slightly. If the target is moving toward the radar, the frequency received is increased, and if the target is moving away from the radar, the frequency received is decreased. Stationary targets do not produce this frequency shift. In an MTI radar, the transmitted and received signal are compared. If the target is stationary, the frequencies will cancel and the output will be ignored. If the target is moving, however, the two signals will not cancel and the frequency difference between the two signals is proportional to the target velocity. All radar experimentation described here was performed at a microwave frequency of 10.5 GHz, and this frequency results in a shift of 30 Hz per mph. Using this approach, trains moving as slow as .3 mph can be detected. Because of the clutter problem, most of this effort in the area of radar train detection was devoted to Doppler/MTI radars.

While the use of a Doppler/MTI radar will greatly minimize the clutter problem, it will not totally eliminate it. Tree branches, vegetation, rain, and snow all are apt to be blown about by the wind and these moving objects will all produce clutter. The effect of rain and snow, often quite severe, can be lessened somewhat by the use of a circular polarizing antenna and by use of a lower radar carrier frequency. At this time it is difficult to estimate just how troublesome this clutter problem would be. It may well prove to be an unsolvable problem in a case #2 application. However, in a shorter range, or less demanding application, such as cases #1 and #2, the problem appears to be solvable.

7.2.4 Multipath Effects

Multipath effects probably are unlikely to be a serious problem. The physical size of railroad rolling stock tends to diminish the probability of wave cancellation. It is quite difficult, and probably not worthwhile, to develop a theoretical model of all the possible radar multipath effects, but field tests conducted by TSC indicate that multipath effects are not a problem. At four different crossing locations, different types of locomotives and rolling stock were tracked from 5,000 to 100 foot ranges and at no time was a multipath null sharper than 6 dB detected.

7.2.5 False Targets

The most serious potential problem is that of false targets. This includes false targets due to people walking, nearby cars or trucks, motorcycles, or even snowmobiles on the roadbed. (The practice of riding motorcycles or snowmobiles adjacent to railroad tracks, while unwise, is certainly not uncommon.) This category would also involve crossings where highways parallel the tracks. In any of these cases, the radar may not be able to distinguish a car or snowmobile from a train. For this category of false targets, there seems to be no acceptable solution. The use of a microwave transponder mounted on each locomotive would solve the problem, but as detailed in Section 7.2.2 the use of such devices is quite undesirable. This problem area does cast some doubt as to the feasibility of using radar as the primary means of detection as in a case #2 long range application. In a case #1 application, where the radar is not the primary means of detection, the false target problem is not critical.

An additional false target problem occurs when, in a double track or single-track-with-a-siding situation, two trains are moving, both within the "field of view" of the radar. For example, with one train ("A") 100 feet from the crossing and moving away (and thus of no interest to the radar), another train ("B") may be approaching the crossing from 3,000 feet away. The radar return from Train A can be as much as 90 dB (a billion times) stronger than the return

from B. Thus the return from A will tend to mask or at least interfere with the return from B. The only major technique for dealing with this problem is to design a radar that has the ability to be range-gated. That is, the radar must be able to "view" the entire range a small section at a time. For example, from 1,500 to 1,600 feet, then from 1,600 to 1,700 feet, and so on. Using this approach, the echo from train A can be effectively tuned out and the radar can concentrate on the farther train, train B. While the approach would solve this last problem, a new constraint has been added to an already long list: the radar must be range-gated.

7.2.6 Reliability

With any system that is to be used in a safety application, the system's overall reliability - particularly reliability with respect to non-failsafe failure modes - is of paramount importance. There is no conceivable radar design that is intrinsically failsafe. A "no train" situation is represented by the absence of information. Antenna mis-alignment, component failures, or even large obstructions over the antenna surface could all lead to non-failsafe failure modes.

In order to decrease the probability of non-failsafe failure modes, extensive use of internal self-checking procedures is required. This would involve the use of redundant transmitting, receiving, and signal-processing circuitry within the radar. The outputs from redundant sections of the radar would be compared and only if they agreed would the radar processing be used. If the outputs failed to agree, a malfunction signal would then be communicated to the motorist.

As a further check on the electronics and also as a specific self-check against antenna mis-alignment, the use of one of the configurations of Figure 7.2 seems appropriate. This would require the use of a passive reflector or reflector/encoder located down track, some 1,000 to 4,000 feet from the radar. Passive structures can be designed to provide very-high reflectivity for a specific frequency and direction, higher than will be found for any object

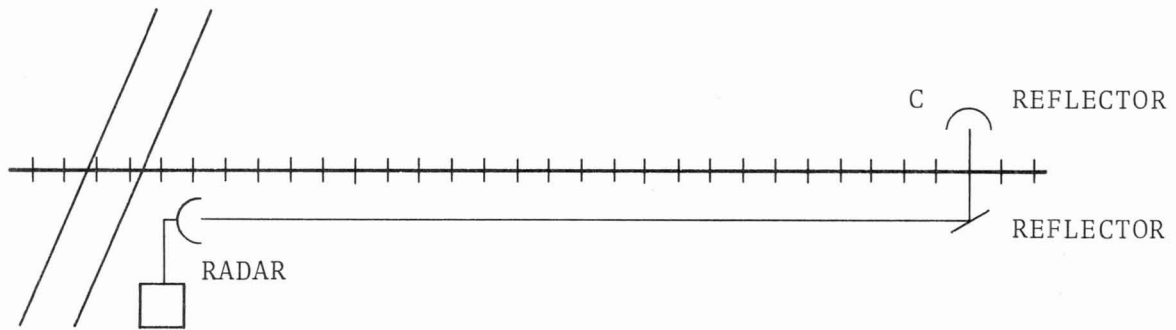
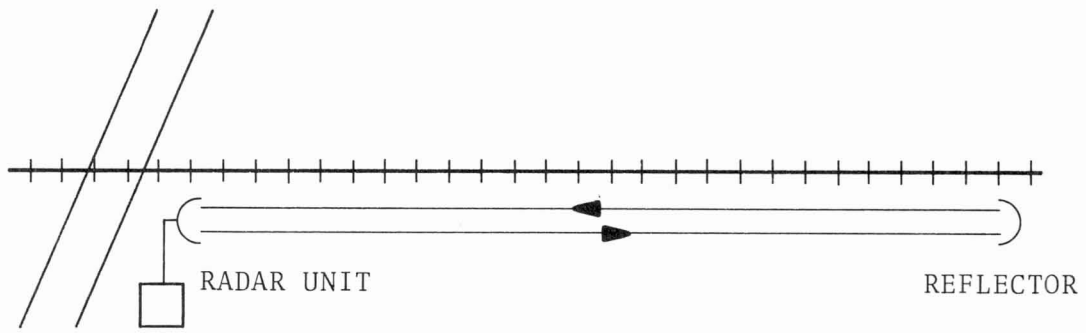


Figure 7.2 Antenna Alignment Self-Check Configuration

or surface normally likely to be in the vicinity. In addition, passive microwave signal encoders have been designed at high operating efficiencies. While such a reflector could be quite inexpensive, materials and labor for the installation and mounting of poles might add as much as \$500 to \$800 to the total cost of the protection. Of course, the use of existing structures for reflector mounting would reduce this drastically, and should often be possible.

In those applications where the radar is used as the primary means of detection, especially in the long range application, the use of a passive reflector is probably a necessity. In all cases the use of internal self-check circuitry is also mandatory. In terms of component or propagation failures, non-failsafe failure modes could be all but virtually eliminated by the techniques described above. Unfortunately, however, the introduction of more-nearly failsafe design, in addition to increasing costs, increases the likelihood that failures will occur (as by movement of the reflector or by damage to it), thus activating the train detection signals even though the train detection system is working perfectly.

From reliability data on systems of similar complexity, it would appear that a MTBF of five years is a reasonable goal for failures which result in failsafe-system failures, as a result of only either component or propagation failures. MTBF of 200 years for component failures resulting in non-failsafe modes also seem to be a reasonable goal.

7.3 FIELD TESTS

As part of the radar investigation, a limited field test program was carried out. The purpose was not to test the overall feasibility of radar crossing protection, but rather to aid in understanding of the problems involved. This effort involved two separate phases. The first phase consisted of a series of day trips where specific radar data (clutter effects, locomotive reflectivity, multipath effects, etc.) was taken. These efforts

involved taking laboratory equipment to crossings and using it to evaluate various radar techniques and systems. Secondly, an experimental Doppler radar was installed, for an extended time period, at one of the telemetry test-site crossings. This radar was not designed to be a prototype for a crossing protective system, but rather was designed as a tool to aid in assessment of general feasibility.

As an example of the equipment used, and also to illustrate the state of the art in radar devices, Figure 7.1 showed a photograph of a Doppler radar module. The module contains all the necessary microwave components needed for a Doppler radar, with the exception of the antenna. These units sell for \$150, in unit volume, have an output power of 100 milliwatts, and are used primarily in police-radar and intrusion alarm applications. Units with higher output powers and greater complexity -- suitable for amplitude, frequency, phase, or pulse-modulation applications -- are also available at higher cost. Figure 7.3 shows a photograph of a radar system, including the Doppler module, that was developed for TSC by Rantec Corp. These units are quite flexible and contain all the necessary electronic circuitry to perform a variety of different modulation techniques. These units were used both during day trip tests and for our extended crossing test. Figure 7.4 shows a photograph of one of the Rantec units, mounted at a crossing during one of our extended tests.

As an example of the state of the art in low-cost, non-military radar systems, it is appropriate to mention two complete radar systems that were utilized in this investigation. The first, a police speed monitoring radar, was a Doppler/MTI radar. The unit was hand-held and displayed the relative speed of approaching or receding vehicles. These units typically retail for between \$1,000 and \$2,000 (a substantial portion of which is due to the packaging and display) and make use of a solid state Doppler module similar to the unit shown in Figure 7.1. The particular device tested worked well, used circular polarization, was not affected by clutter of light-medium rainfall and had a maximum range (for a locomotive or freight car) of about 1.5 miles.

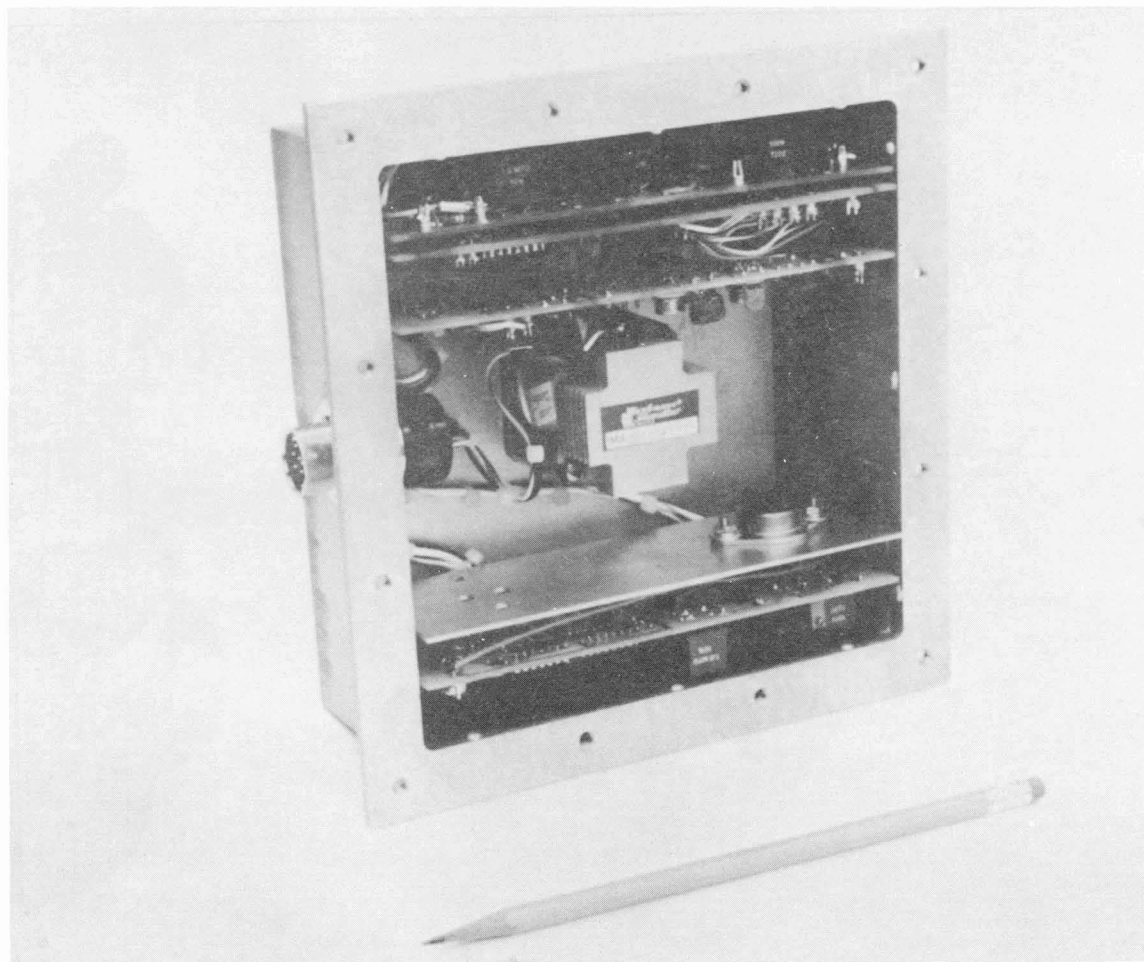


Figure 7.3 Rantec Experimental Radar System

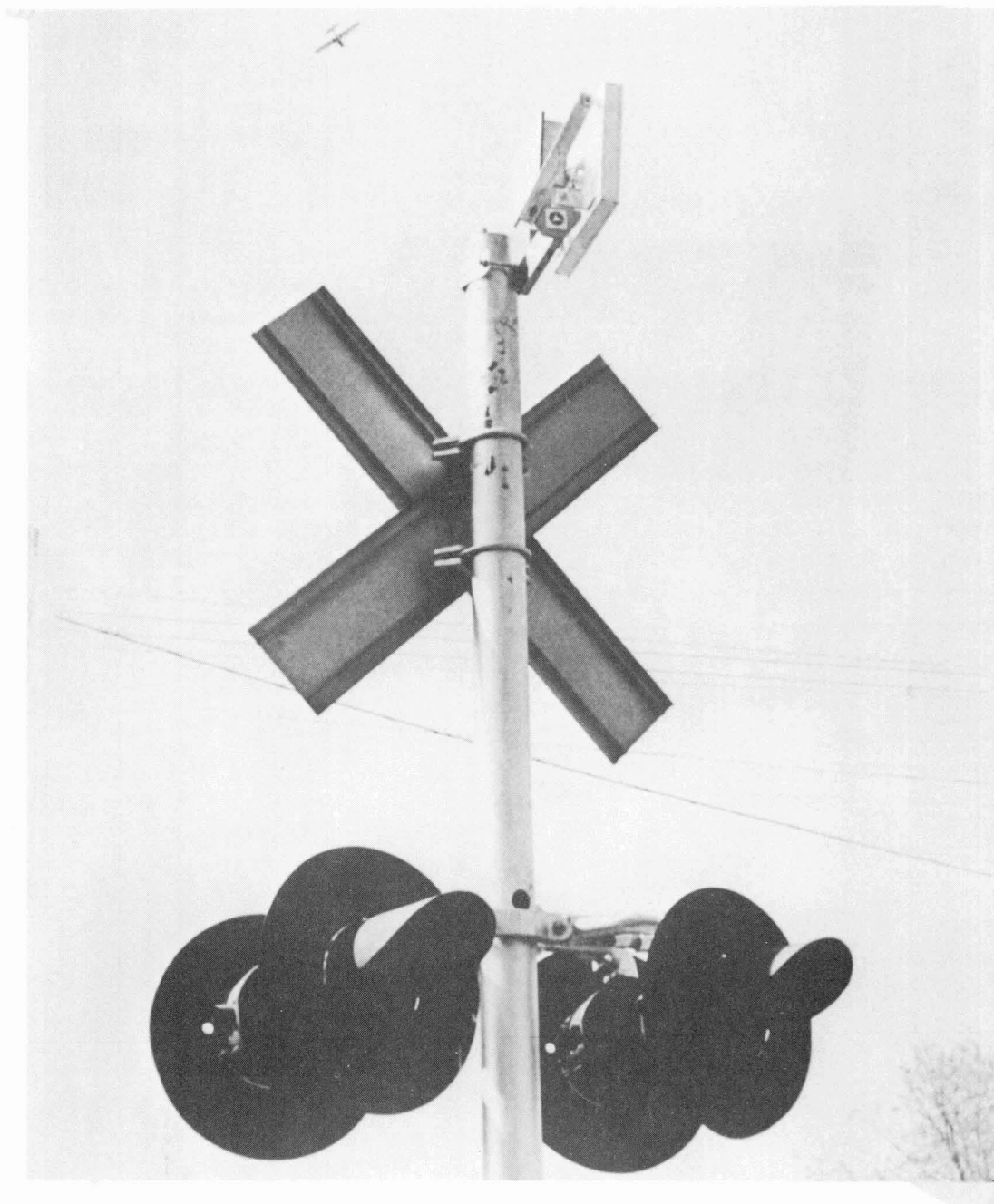


Figure 7.4 Rantec Radar in Use

The other radar was designed primarily as a navigational aid for the operators of small boats. While at sea the radar is used to detect and supply range information on boats, buoys or shore-lines within a 2 mile range. This information is provided to the operator by use of a tone heard through headphones. The unit cost \$400 and was not a Doppler radar, but rather was a triangular waveform frequency-modulated radar. Since the unit was not a MTI radar, the clutter return was too strong and masked returns for objects more than 100 feet away. (At sea there are not as many clutter causing objects and thus this problem is significantly reduced.)

Most of the information and experience gained by test effort was incorporated into Section 7.2 above. None of the standard radar techniques examined with the Rantec unit seemed to meet all the constraints, especially if costs were considered.

A unit that did appear to be promising was a radar borrowed from the U.S. Air Force. During the past 5 to 10 years the military has devoted substantial effort to develop a radar with many of the same characteristics: low cost, ruggedness, small size, imperviousness to weather, low power consumption, MTI, clutter rejection, range-gating, and high reliability. It may be that the radar techniques developed by the military will be of benefit to the grade crossing case. Their application was identification and tracking of moving targets at night or through heavy foliage. The technique used in these radars is relatively new; the radars are known as pseudo-random serially coded CW Doppler radars. The unit that we borrowed was an AN/PPS-12, and is shown in Figure 7.5. The particular radar borrowed was not adaptable to an extended field test. However, during the briefer tests, it appeared promising. The radar is range gatable and rejected by 100 dB targets outside of the selected range gate. This would be quite helpful in eliminating false targets. The radar is a CW Doppler/MTI radar and offers continuous range, speed, and direction of travel information. The radar was designed for battlefield use and is rugged, lightweight, and physically small. The development cost to the Air Force was \$12,000 per unit, but

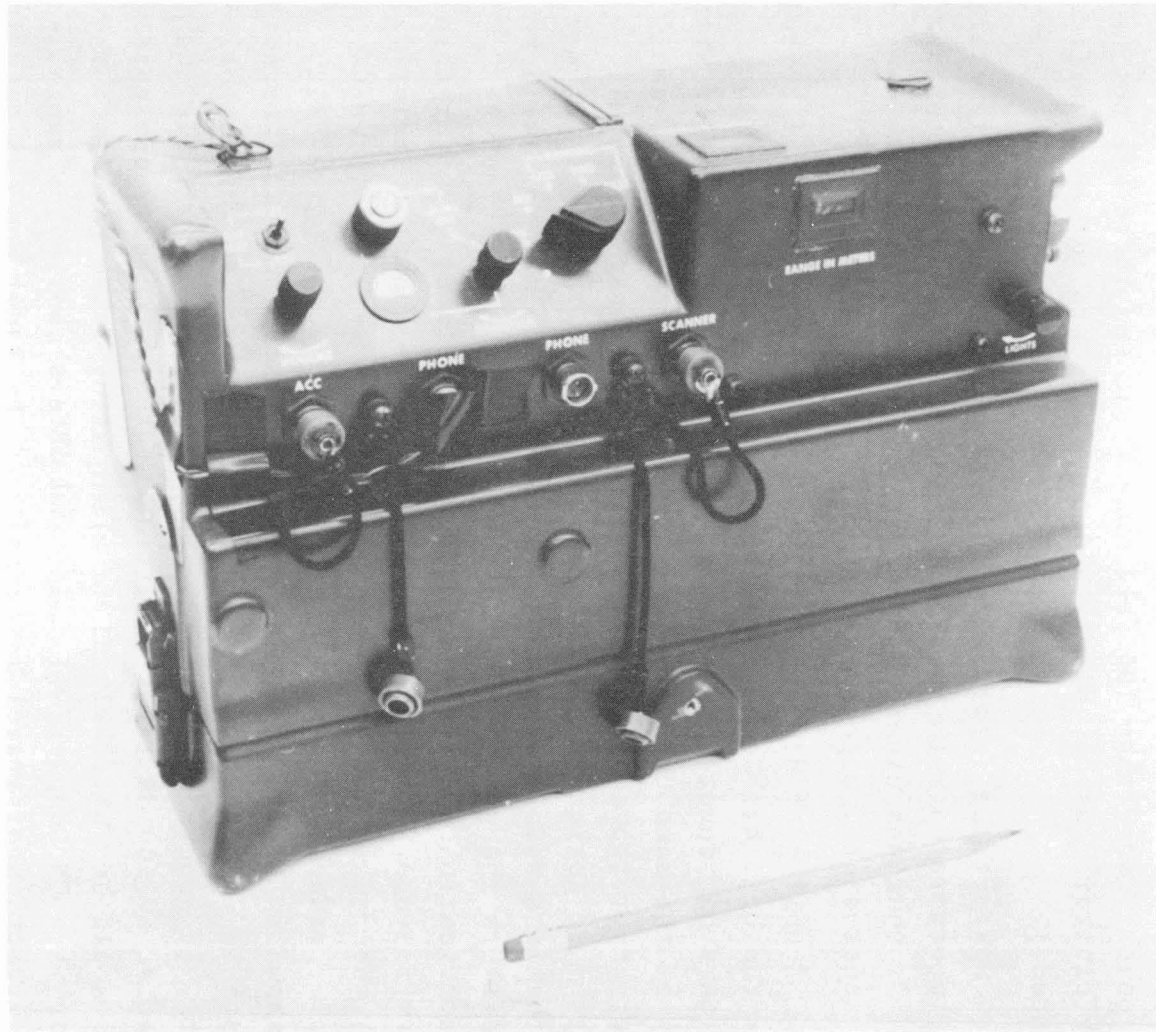
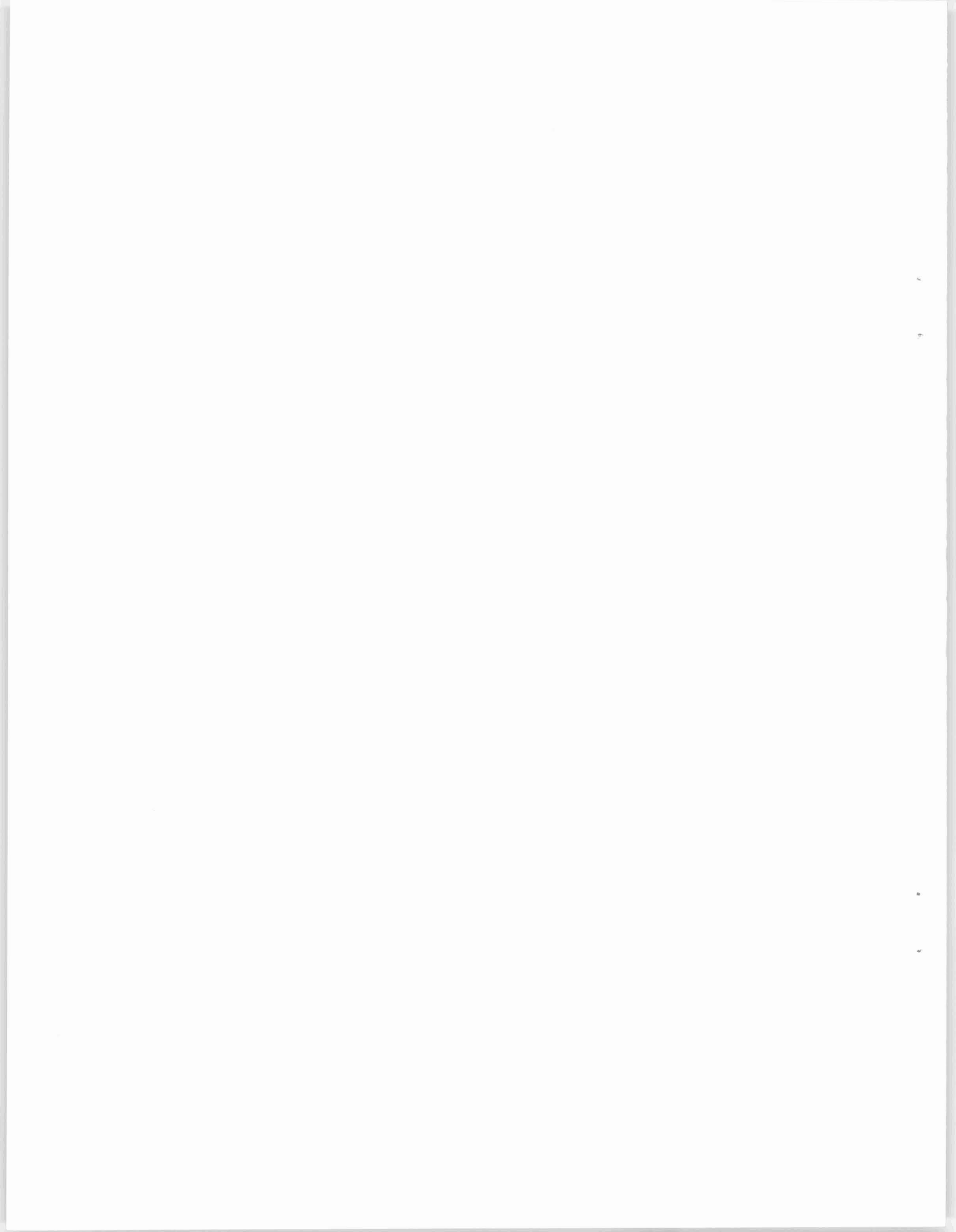


Figure 7.5 AN/PPS-12 Radar Unit

the manufacturer feels that in quantities of 1,000 to 5,000 units per year, the cost could be as low as \$2,000 per unit. This \$2,000 figure is for the radar alone, and does not include the cost of the flashing lights, gates, installation, interface circuitry, or automation of operation.

7.4 PRELIMINARY CONCLUSIONS

While the desirability of using radar for purposes of crossing protection is clear, the technical feasibility remains unproven. The requirements for very high reliability and absence of non-failsafe failure modes are extremely severe. The performance of the military radar offers some promise and indicates a promising direction for future work. Unfortunately, however, even with a modified AN/PPS-12, the overall system constraints may well prove to be too severe to permit any viable solution, especially in a case #2 or #3 application, where the radar is to be used as the primary means of detection.



8. CONCLUSIONS AND RECOMMENDATIONS

8.1 MICROWAVE COMMUNICATION LINK

The studies reported here provide preliminary confirmation of the basic technical feasibility of the concept proposed. As is the case for conventional techniques, certain situations (such as sharp curvature of right of way, or trackside obstructions) will require special treatment, with added complexity and expense. Other cases; e.g., multiple track, are readily and efficiently accommodated. Constant warning time is easily achieved when train acceleration is zero; stopping and reversing moves will lead to some unnecessary activation. Installation and maintenance at the downtrack location can be reduced to a low level, although not eliminated. System malfunction can generally be distinguished from train presence, permitting display of more accurate information to the motorist. The electronic complexity, and hence the basic expense and reliability of the equipment, are comparable to those for conventional systems.

Estimated costs in 1972 dollars are shown in Table 8.1 for equipment required to provide train-activated motorist warnings at a single-track grade crossing utilizing only flashing lights, for both conventional AFO track circuits and a communication-link approach. Although such numbers can vary considerably from crossing to crossing, these values are considered to be representative, within the substantial uncertainty inherent in predicting the cost of a fully developed communication-link system. Table 8.2 carries the comparison further by including the remaining cost elements. The major difference in addition to hardware is installation labor because of the limited track-related work required for the communication link. A total reduction of 16 percent is predicted for the new system. Changes in maintenance expense are difficult to project but reduced concern for cables and electrical integrity of the tracks and reduced battery/power supply concerns at the

TABLE 8.1 DETAILED EQUIPMENT COSTS

<u>Item</u>	<u>Track Circuit</u> (dollars)	<u>Communication Link</u> (dollars)
Flashing lights, poles, etc.	620	620
Flasher, logic, etc	600	600
Housing	450	500
Cable	200	200
Batteries	150	100
Rectifiers	50	50
AF receivers	1500	
Joints, arrestors, etc.	250	
Communication Receivers		600
Antennas		100
Detector		200
Solar Panel		100
Subtotal (Crossing-located)	3820	3070
AF Transmitters	1500	
Rectifiers	50	
Joints, arrestors, etc.	250	
Batteries	150	100
Housings	200	250
Communication Transmitters		600
Antennas		50
Detectors		600
Solar Panels		200
Subtotal (Downtrack)	<u>2150</u>	<u>1800</u>
Total Hardware	5970	4870

TABLE 8.2 OVERALL COST COMPARISON

<u>Item</u>	<u>Track Circuit</u> (dollars)	<u>Communication Link</u> (dollars)
Hardware	5720	4870
Labor	5600	4480
Design	1400	1120
Misc.	<u>1400</u>	<u>1400</u>
Total	14,120	11,870

downtrack location suggest the possibility of a reduction of approximately 20 to 30 percent. For multiple-track installations, the multiplex capability of the communication link is likely to provide significantly greater savings; track circuits must be duplicated (and maintained) for each track.

Two major restrictions must be placed on these estimates. First, the tendency for new systems to escalate dramatically in cost during development is well known. Unforeseen or apparently trivial difficulties can be expensive to correct. Thus, a margin indicated could be dramatically reduced in the course of product engineering. Second, other track circuit technology may offer equivalent benefits with less risk and uncertainty. Use of standalone impedance-based motion-sensing equipment, now in service on some railroads, offers elimination of active downtrack components and greatly reduces crossing-located logic hardware. If concerns over possible failure modes and liability can be resolved, this approach is likely to have costs highly competitive with estimates of communication-link systems. Thus at best, the new approach described here offers very limited improvement in cost and warning-system credibility when compared to recent developments in conventional technology.

However, the most important characteristic of the concept is independence of the railroad signal system. Indeed, the lack of compatibility with current practices would be likely to make railroads reluctant to adopt such a system, even if completely proven. Thus, the equipment market would be small, with concomitant high costs, unless public bodies were to choose to accept full responsibility for all aspects of crossing protection, producing a substantial market. The likelihood of such a major restructuring of current institutional practices is outside the realm of this study. The historical trend is in this direction, and this topic is receiving increasing attention. At this point, however, one can only note that the communication link provides for potential elimination of the present rigid technical obstacles to a change of this nature. In essence then the innovative concept reported

here is primarily of importance in the context of public responsibility, a context sufficiently complex that the value of this new technique is at present uncertain.

8.2 RADAR TRAIN DETECTION

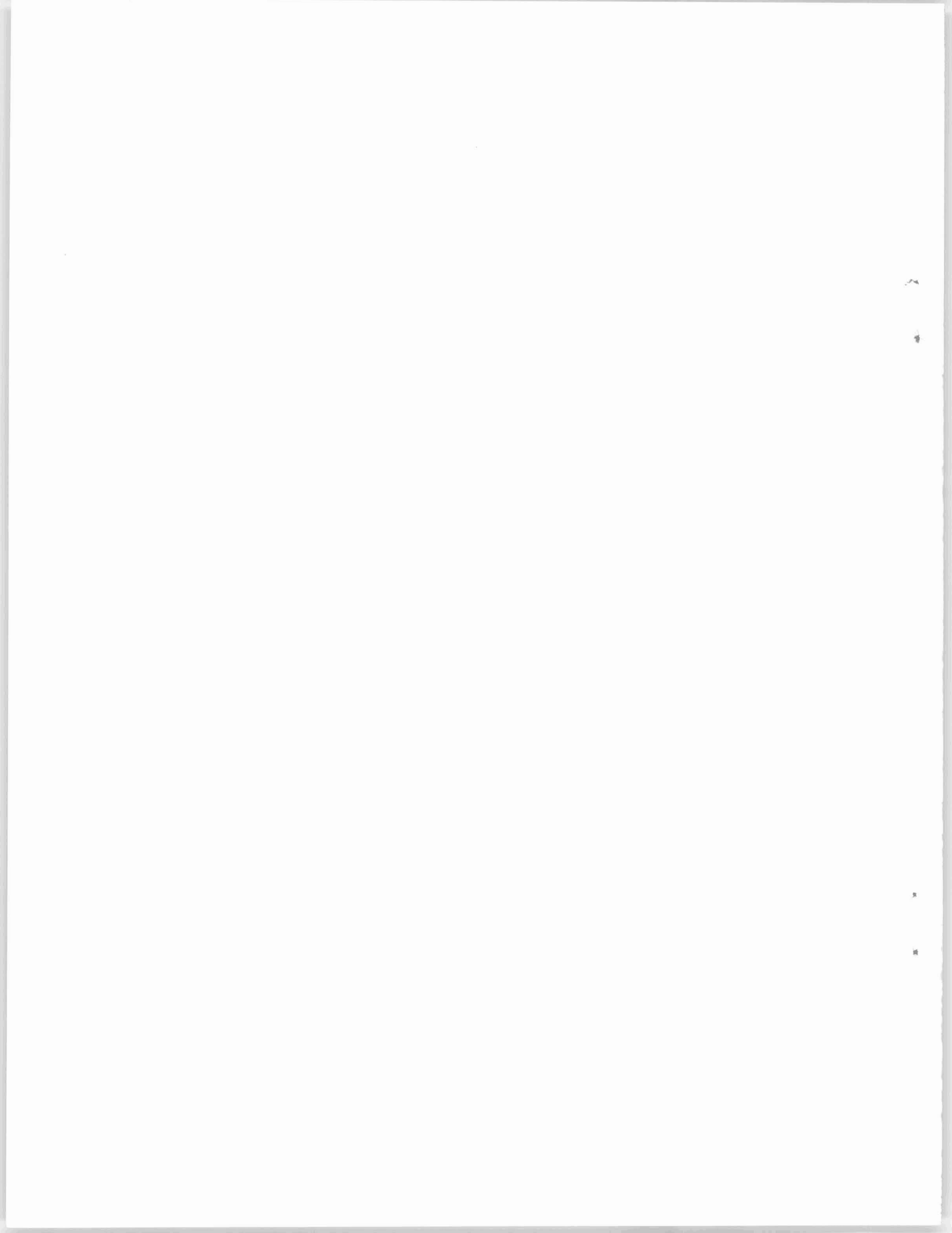
As the fundamental means of warning actuation, radar has been found to raise a number of very challenging questions of technical feasibility. Meeting the conflicting requirements of very low false-alarm rate and zero train-detection failures, within the basic constraints of high reliability, fail-safe operation, infrequent operation, infrequent and low-cost maintenance, and insensitivity to a notoriously harsh environment, may be possible; but the cost is likely to be far beyond that which is acceptable. Radar may offer considerably greater promise when used merely to provide constant warning time, the basic train detection being accomplished independently. The necessary information can be derived far more directly from a radar echo than with an impedance-based track circuit. However, it is not clear that this apparent simplicity will, in fact, lead to lower cost; much of the expense associated with track-circuit hardware is required by demands of reliability and hardening against environment, and radar would be subject to the same constraints.

8.3 DIRECTIONS FOR FURTHER RESEARCH

The major limitation of existing technology lies in the train-detection portion of the system. Although several approaches could yield a practical system, none are truly satisfactory. Rail-mounted and buried detectors are vulnerable to damage during track maintenance, dragging equipment, etc., and limit the degree of independence. Beam-breaking and radar approaches appear to be relatively expensive and of limited reliability (as measured by the normal standards of rail safety and operations). The many ways in which an object such as a locomotive might be detected suggest that valuable research could be carried out in this area.

Beyond this, advanced development and large-scale test of the entire system must precede any possibility of adoption either by railroads or public bodies. If the merits of a perfected system warrant a developmental effort of this scope cannot be determined at the present time. However, selection of a preferred means of train detection and development and test of several second-generation systems will be necessary to provide cost and reliability estimates adequate for realistic benefit/cost comparisons.

The relatively unpromising results of the radar investigation suggest that this area does not, at present, warrant substantial investment. However, use of radar as a constant-warning-time subsystem, possibly in parallel with conventional track-circuit actuation, appears to be possible, if very difficult. Continuing advances in microwave and electronic technology may also, at some point, bring radar train detection into the realm of economic as well as technical feasibility. Thus, this area should not be foreclosed.



9. REFERENCES

1. A Program Definition Study for Rail-Highway Grade Crossing Improvements. D.W. Schoppert, Prepared for FRA by Alan M. Woorhees, & Assoc., Inc., Oct. 1969, NTIS # PB-190401.
2. Report to Congress. Railroad-Highway Safety. Part II: Recommendations for Resolving the Problem. Staff of FRA and FHWA. Aug. 1972. NTIS # PB-213115.
3. Technical Innovation in Grade Crossing Protective Systems. J.B. Hopkins and M.E. Hazel, Final Report DOT-TSC-FRA-71-3, June 1971. NTIS # PB-201624.
4. Train-Activated Rail-Highway Protection. J. Moe, Proceedings of the 1972 National Conference on Railroad-Highway Grade Crossing Safety, Ohio State University, Columbus, Aug. 29-31, 1972.
5. Development and Evaluation of Anticipatory Crash Sensors for Automobiles. J. Hopkins, R. Holmstrom, M. Hazel, and R. Abbott, Final Report DOT-TSC-NHTSA-73-6 (HS-801036), Feb. 1974.
6. Monopulse Azimuth Measurement in the ATC Radar Beacon System, B. Kulke, B. Rubinger, and G. Haroules, Final Report DOT-TSC-FAA-72-6, Dec. 1971.
7. Electronic and Radio Engineering, 4th Ed. F.E. Terman, McGraw-Hill, N.Y., 1955, pp. 808-823.

APPENDIX
DETAILED DESCRIPTION OF EXPERIMENTAL SYSTEMS

A.1 RANTEC TELEMETRY SYSTEM

A.1.1 Introduction

The Rantec telemetry system is based upon low power MSI/MOS integrated circuitry -- both linear and digital. It is a one-frequency system, with the modulation mode being used to carry information. The system is basically digital, but linear circuitry is used for amplification, filtering, and automatic gain control. System specifications are summarized in Table A-1.

All circuitry, except the Gunn oscillator, is powered by an unregulated +5 or -5 volt source, the output of which varies with the voltage of the external battery. (All the integrated circuitry is specified by the manufacturers to be able to withstand the kind of voltage fluctuations anticipated.) It should be noted that in a digital system power conditioning is not as important as it is in linear circuitry.

The inputs to both the transmitter and the receiver are not failsafe. A train is represented by a 5 volt signal level on the input terminals, while a no-train-present condition is denoted by a 0 volt signal level. The outputs, however, are failsafe.

A.1.2 Transmitter

Figure A-1 is a block diagram of the transmitter; the actual circuitry may be seen in Figure A-2.

The Rantec transmitter uses two power conditioning circuits. At the input, the external battery drives a 400 kHz oscillator. The oscillator output is the master clock for the transmitter circuitry and also serves as the driver for a counter/divider IC. The counter, through a flip-flop, puts out a 20 kHz square wave which then drives a transformer, rectifier, and filter circuit. The filter circuit produces unregulated outputs of +5 volts dc, +5 volts dc, -5 volts dc, and +22 volts dc. The unregulated 5-volt outputs drive all the circuitry while the unregulated 22 volts

TABLE A-1. SYSTEM SPECIFICATIONS-RANTEC

	<u>Requested Design Goal</u>	<u>Proposed Design Goal</u>	<u>Engineering Model</u>
<u>Transmitter Unit</u>			
Power consumption	<150 mw	48.5 mw	100 mw
X-band power output	100 mw	50 mw	150-250 mw
Maximum VSWR	6:1	6:1	>6:1
Frequency stability	<u>+25 MHz</u>	<u>+25 MHz</u>	<u>+30 MHz</u>
<u>Receiver Unit:</u>			
Power consumption	<300 mw	90 mw	108 mw
Average current drain	25 ma	8 ma	9 ma
Maximum VSWR	6:1	6:1	6:1
Signal-Noise Ratio	>20 db	23 db	>23 db
<u>General:</u>			
Size	<0.3 ft ³	0.04 ft ³	<0.04 ft ³
Weight	<10 lbs	2 lbs	2.5 lbs Tx 5.8 lbs Rx
MTBF (false alarm)	20,000 hrs	28,785 hrs	21,906 hrs
MTBS (missed de- tection)	100,000 hrs	107,296 hrs	155,279 hrs

A-3

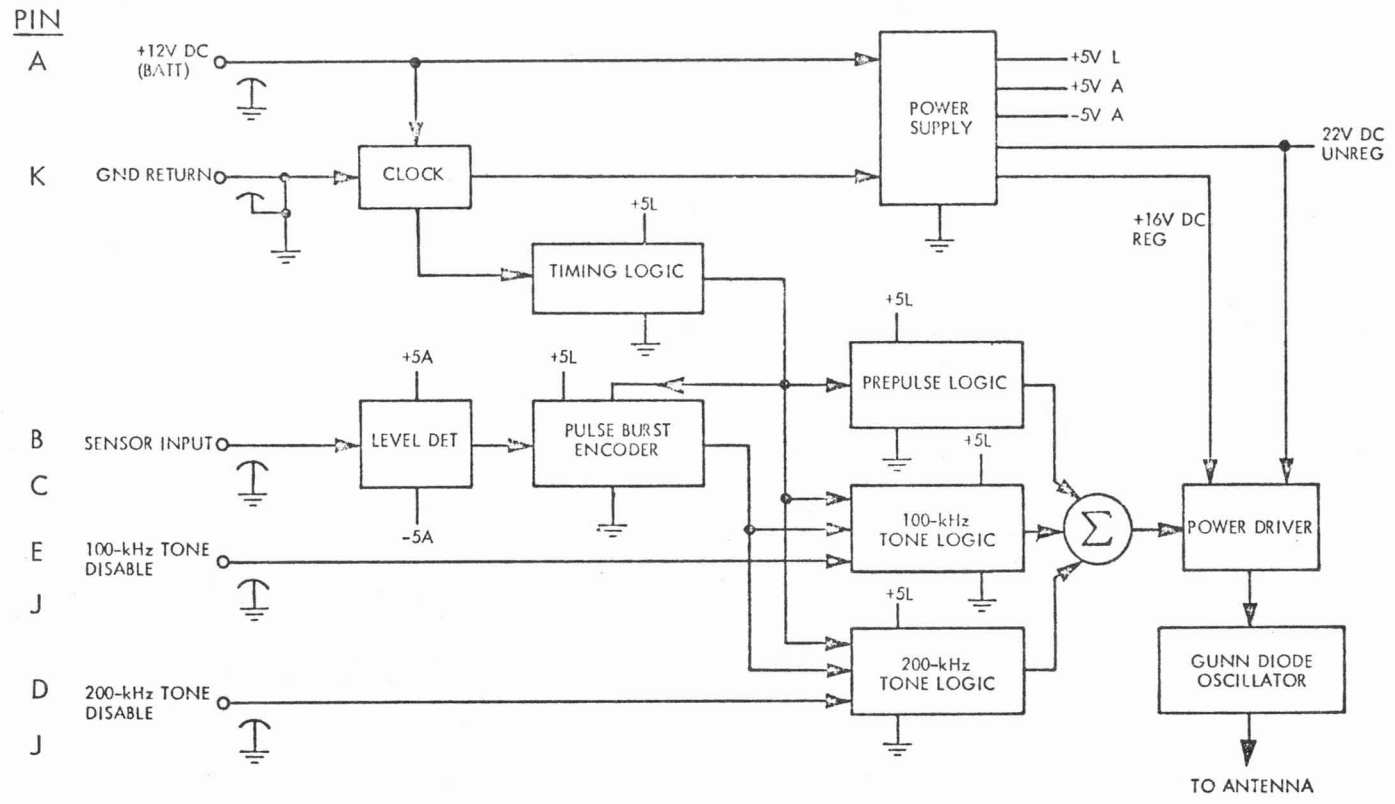


Figure A-1 Block Diagram of Rantec Transmitter

A-4

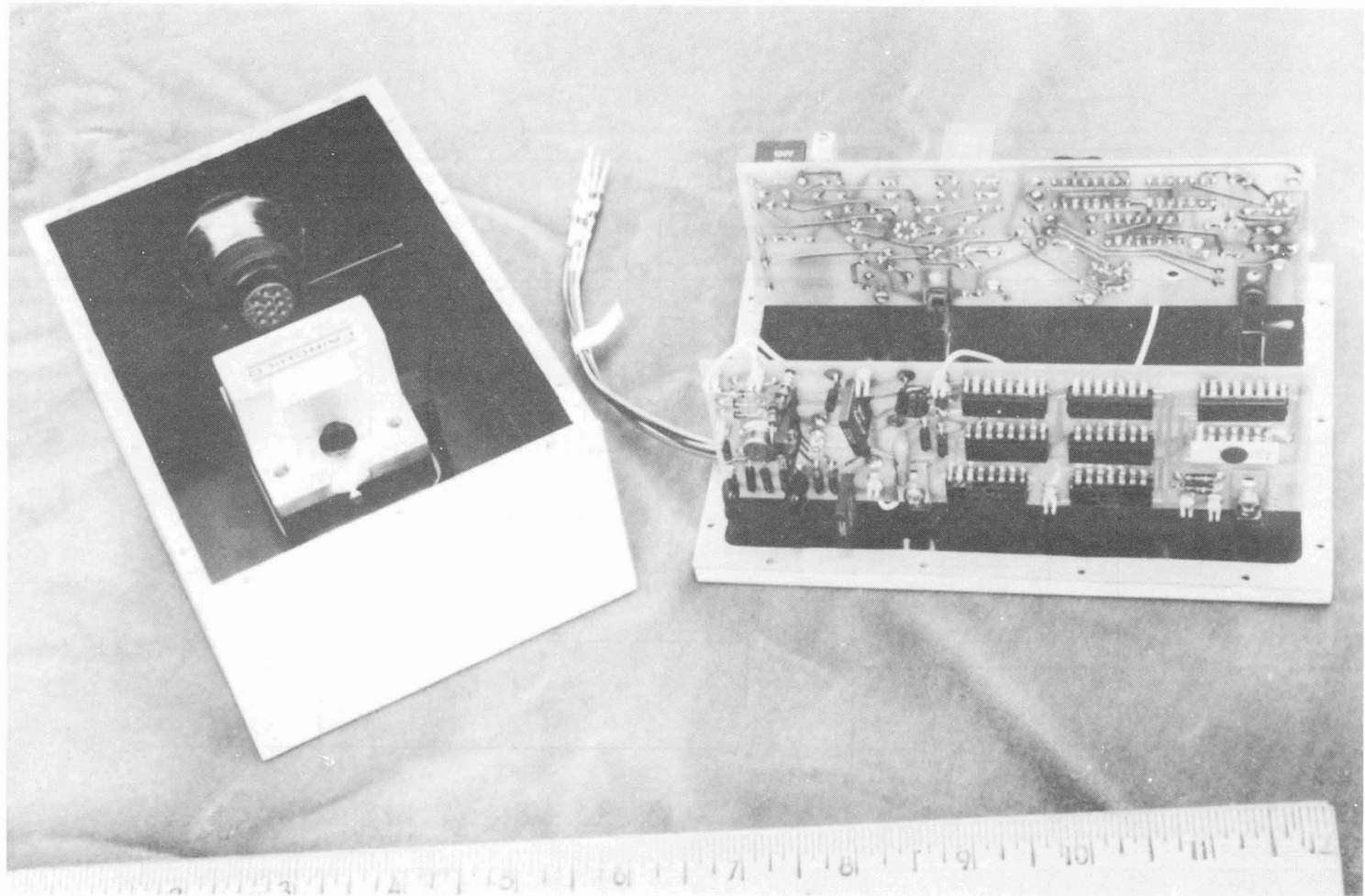


Figure A-2 Rantec Transmitter

drives the voltage-regulator circuit. The heart of the regulator circuit is an AGC amplifier IC, the current output of which is held constant by a feedback loop. The constant-current output of this amplifier drives a series of transistors. The last stage is a power transistor which drives the Gunn oscillator with a regulated +16.0 volts. One of the transistors in the series serves as an on-off gate for the regulator circuit; the diode is modulated by use of this gate.

The heart of the transmitter logic circuitry is two counter/divider-integrated circuits wired in series and driven by the 400-kHz clock. With this arrangement periods of oscillation from 5 microseconds to 0.3 seconds, in 5-microsecond increments, are available. Every 0.3 seconds the counter puts out a 5-microsecond pulse, which sets two latches. The first latch is reset after 20 microseconds, and is on for the purpose of applying a 20-microsecond heating pre-pulse to the Gunn oscillator. The second latch then becomes operative after the first latch is reset. When this second latch is in the set position, the modulating waveform is allowed to pass to the modulation gate of the regulator/driver circuit. The modulating waveform is either a 100-kHz or 200-kHz square wave; either waveform is available at the counter output. The waveform that is to be used is selected by grounding one of two leads at the output connector. The second, or burstwidth, latch is reset at either intervals of 120 microseconds for a "clear" condition, or 260 microseconds for a "train present" condition, as determined by the train sensor circuit.

The train-sensor circuit is not operated in a failsafe mode, in the sense that a train is represented by a -5-volt signal level and a no-train condition is represented by a 0-volt signal level applied at the train-sensor input terminals. These terminals are connected to an operational amplifier, which in turn drives a filter circuit. (The purpose of the filter circuit is to provide immunity from pulses of 10-millisecond duration or less.) Surge protection is provided with a zener diode. If a +5-volt pulse of duration longer than 10 milliseconds enters the train-sensor input, a latch is set. The latch in the set position causes the

burstwidth latch to be reset in 260, instead of 120, microseconds. The train-sensor latch is then reset three seconds after the input signal level returns to ground by use of still another counter. The transmitter will then return to a no-train condition with the burstwidth equal to 120 microseconds.

A.1.3 Receiver

Figure A-3 is a block diagram of the receiver circuit, with a prototype unit shown in Figure A-4.

The Rantec telemetry receiver uses the same type of unregulated voltage supply as the transmitter, with unregulated outputs of +5 volts DC, and -5 volts DC. The external battery drives a 40 kHz oscillator which serves as the master clock for the receiver logic, and through a flip-flop, drives the transformer, rectifier, and filter circuit.

After the microwave signal is detected with a Schottky barrier diode, it enters a three-stage band-pass amplifier. Each stage of amplification is a band-pass, Tschebyscheff, one-pole, LC-type filter with automatic-gain control. Each stage contains one integrated circuit and two transistors for buffering. Rantec specifies the three-stage amplifier to have an AGC range of 30 dB, corresponding to an RF-input signal level of -50 dBm to -20 dBm. The center frequency of each of the three band-pass filters is different -- 95 kHz, 100 kHz, and 105 kHz for 100-kHz operation, and 195 kHz, 200 kHz, and 205 kHz for 200-kHz operation. The center frequency of each stage can be electronically switched from one mode to the other by connecting a lead on the output connector to either the +5-volt dc or to the -5-volt dc output pin. The bandwidth for all three stages is 10 kHz, which corresponds to the reciprocal of the shortest possible burstwidth -- 100 microseconds. With this filter there exists 18 dB of channel rejection for a 100 kHz signal in the presence of a 200-kHz mode.

At this point, the burst of pulses of normalized amplitude passes through a second detector. The second detector is a single IC which puts out a pulse with width equal to the burstwidth of the input waveform.

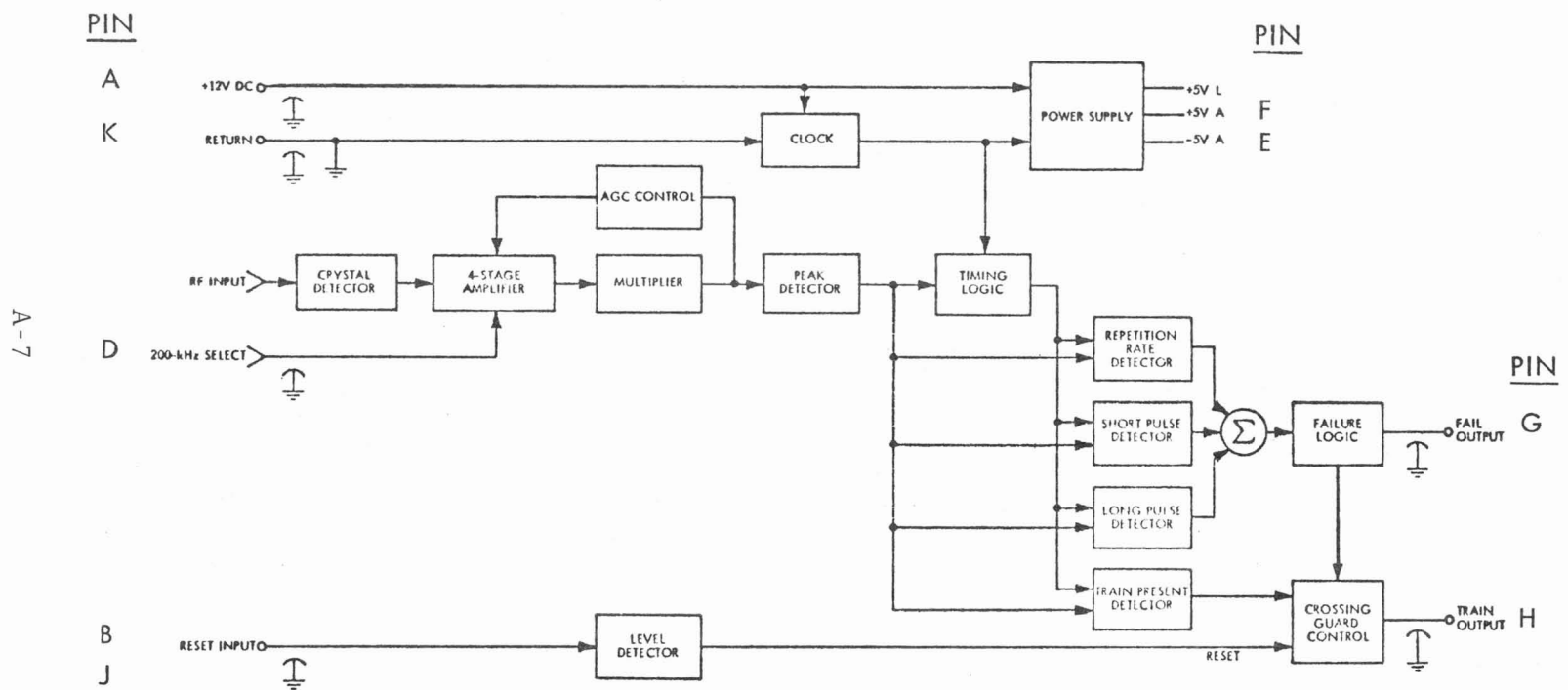


Figure A-3 Block Diagram of Rantec Receiver

A-8

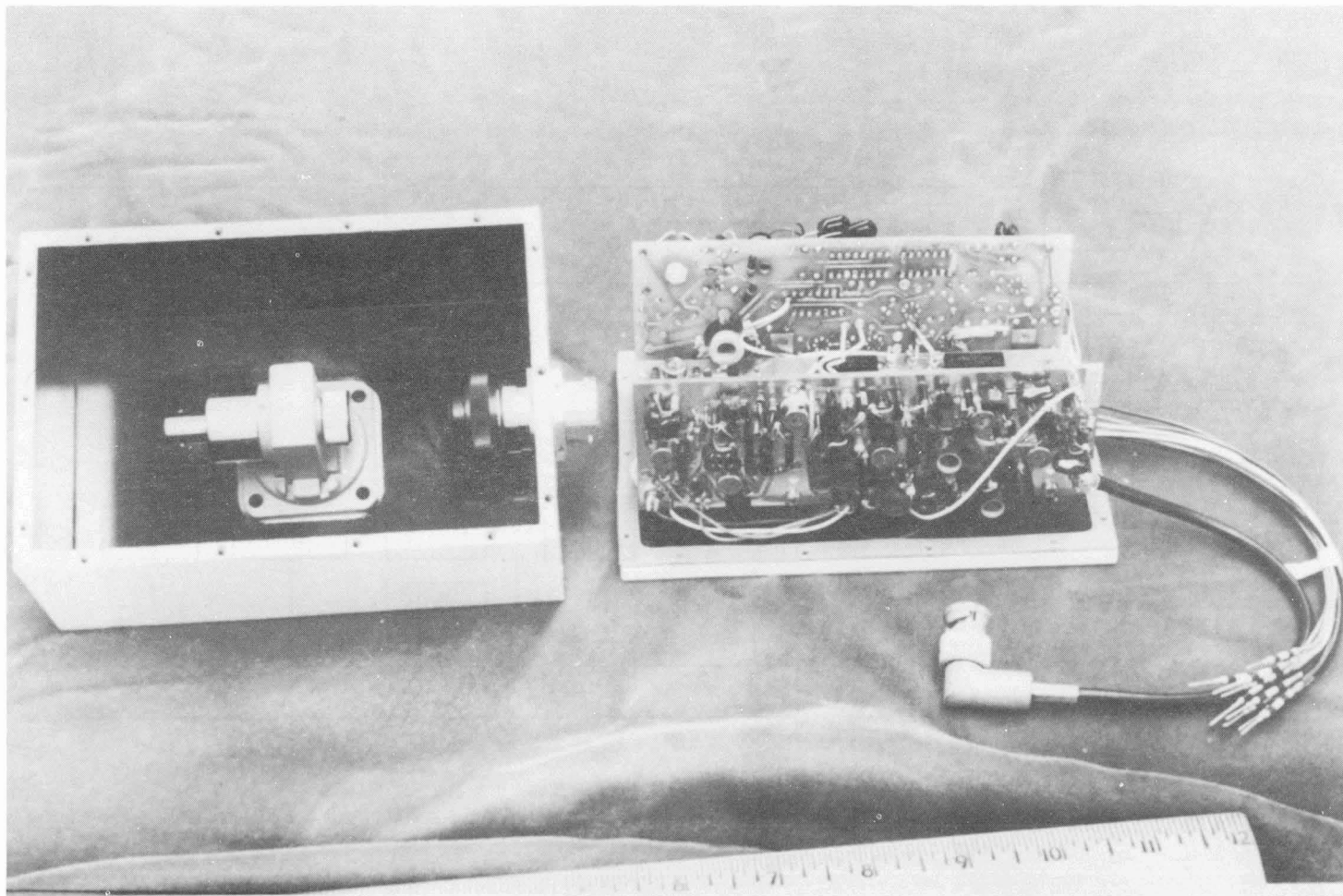


Figure A-4 Rantec Receiver

This pulse is applied to two different points. The pulse is peak-detected and the resulting dc waveform is sent back, through some buffering, to the AGC input of the band-pass video amplifier. It is also sent to a comparator where it is tested for amplitude, reshaped, and processed.

The heart of the information-processing circuit is three shift registers wired in series and driven by the 40 kHz clock. With this arrangement, time delays from 25 microseconds to 0.5 seconds are available, in 25 microsecond jumps. The long pulse is now tested. The receiver expects to see one pulse every 0.3 seconds, the pulse being either 100 or 250 microseconds. Both the on-and-off times of the pulse are tested for conformity. Six tests are performed in parallel operation. If four consecutive pulses of width greater than 150 microseconds, or one pulse of width greater than 600 microseconds, is received, the crossing protection activation output is driven from +12 volts DC to 0 volts. Both the malfunction and activation outputs are operated in a failsafe mode in the sense that the -12-volt level represents the "non-failure" and "no-train" conditions, respectively. A level of 0 volts denotes the system failure, or train-presence conditions, respectively. Neither of the above situations, not even the 600-microsecond burst, is regarded as a system failure by the receiver. The system-failure output remains at -12 volts DC, while the activation output will be held at 0 volts. The activation output remains grounded until the receiver is reset by a pulse across the train-sensor input terminals. The receiver also tests for four possible failure conditions: a pulsewidth less than 50 microseconds, a pulsewidth greater than 375 microseconds, a pulse-off time less than 0.2 second, or a pulse-off time greater than 0.4 second. If four consecutive failures are detected by the receiver, the malfunction output is driven from +12 volts DC to 0 volt whenever the malfunction output is low. However in this mode, one conforming pulse will reset both the system failure latch and the gate activation latch, and both outputs would return to +12 volts DC.

As for the transmitter input, the receiver input is not operated in a failsafe mode. A train present condition is represented by a -5-volt level on the input terminals. The train-sensor input terminals are connected to an operational amplifier and then to a filter, which provides immunity from pulses of duration of 10 milliseconds or less. Surge protection is provided with a zener diode. If a -5-volt pulse wider than 10 milliseconds is applied to the train sensor input terminals, a capacitor is allowed to discharge. The capacitor begins to charge slowly after the input returns to 0 volt. Three seconds after the last train-sensor pulse, the capacitor is fully charged and resets the train-presence latch. This latch in the reset position causes the warning activation output to return to +12 volts DC.

A.1.4 Reliability and Cost

Rantec's reliability analysis shows a predicted mean time to failure of 21,906 hours (over two years) with malfunction indication, and 155,279 hours for a non-failsafe failure mode. Their estimated production cost for a simplified production design, in lots of 1000 per year, is \$290 for materials plus 15.3 hours per transmitter/receiver pair. (It should be noted, however, that these experimental units represent a significantly less-sophisticated design than would be utilized in an actual application. See Section 2. At the same time, further design effort could yield further improvement, particularly in MTBF.)

A.2 SAFETRAN TELEMETRY SYSTEM

A.2.1 Introduction

The Safetran system is based upon discrete components, and uses only two integrated circuits in the entire transmitter/receiver pair. There are 55 transistors, plus bias resistors and blocking capacitors associated with each transistor. This high parts count makes challenging the achievement of satisfactory MTBF, and contributes to high power consumption (~300 mW).

A.2.2 Transmitter

In the transmitter unit (see Figures A-5 and A-6) Safetran uses two voltage-regulator circuits. The first is a combination static inverter/regulator. It takes a 9-to-15 volt DC battery voltage and puts out a constant 15.0 volts DC. The circuit consists of an oscillator, transformer, rectifier, filter, and zener diodes. The regulated 15.0 volts is then used to drive all the logic circuitry plus the second integrated circuit voltage regulator which provides highly stable voltage regulation and has an electronic shut-off capability. This IC drives the 50 milliwatt Gunn oscillator directly, the diode being modulated by use of the electronic shut-off switch in the chip. All the logic circuitry thus drives a high-impedance, low-capacitance load -- the shut-off gate on the IC chip. Safetran also places a 'draw-down' circuit in parallel with the diode. The purpose of this circuit is to short-circuit the diode to ground at the end of each pulse.

The modulation circuit uses three simple RC-type oscillators. The first is the duty-cycle oscillator which once every 0.5 seconds supplies the V_{CC} voltage to each of the other two for 10 milliseconds. These latter oscillators, which specify train presence or absence, are in a parallel mode of operation and feed a two input-frequency selecting gate.

The frequency select circuitry is failsafe, in the sense that 12 volts at the sensor-input terminals denotes a no-train condition, while less than 4 volts represents a train-present condition. When the train-sensor input is grounded, a timing capacitor is allowed to discharge. A pulse duration of tens of microseconds is required. The zero potential across the timing capacitor causes a frequency selector gate to switch and allow the 2.2-kHz signal to pass to the voltage regulator and not the 1.0 kHz. After the train-sensor input returns to a high, 12 volt state, the timing capacitor begins to charge. After 3-5 seconds, when the capacitor is fully charged, the frequency-select circuit switches back and allows the 1.0 kHz signal to pass to the regulator.

A-12

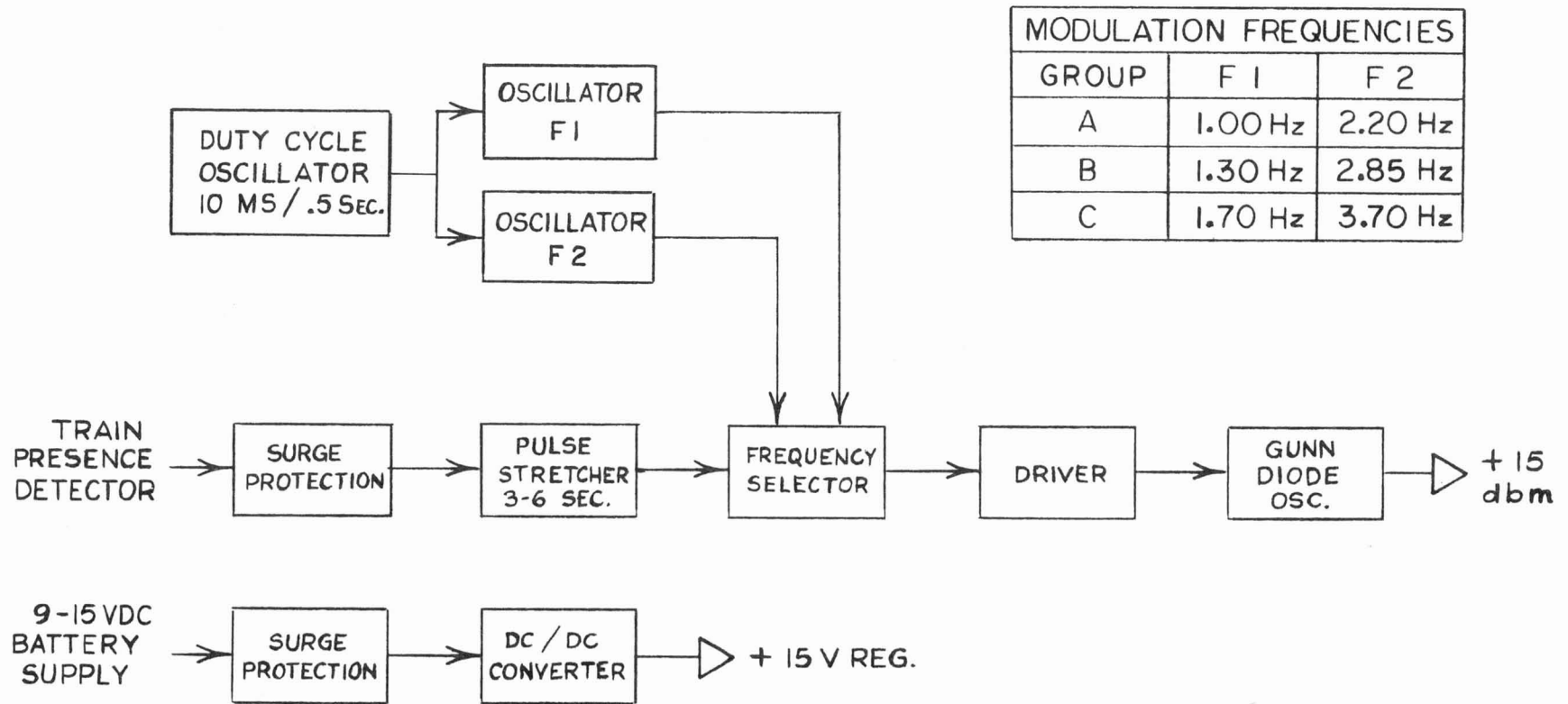


Figure A-5 Block Diagram of Safetran Transmitter

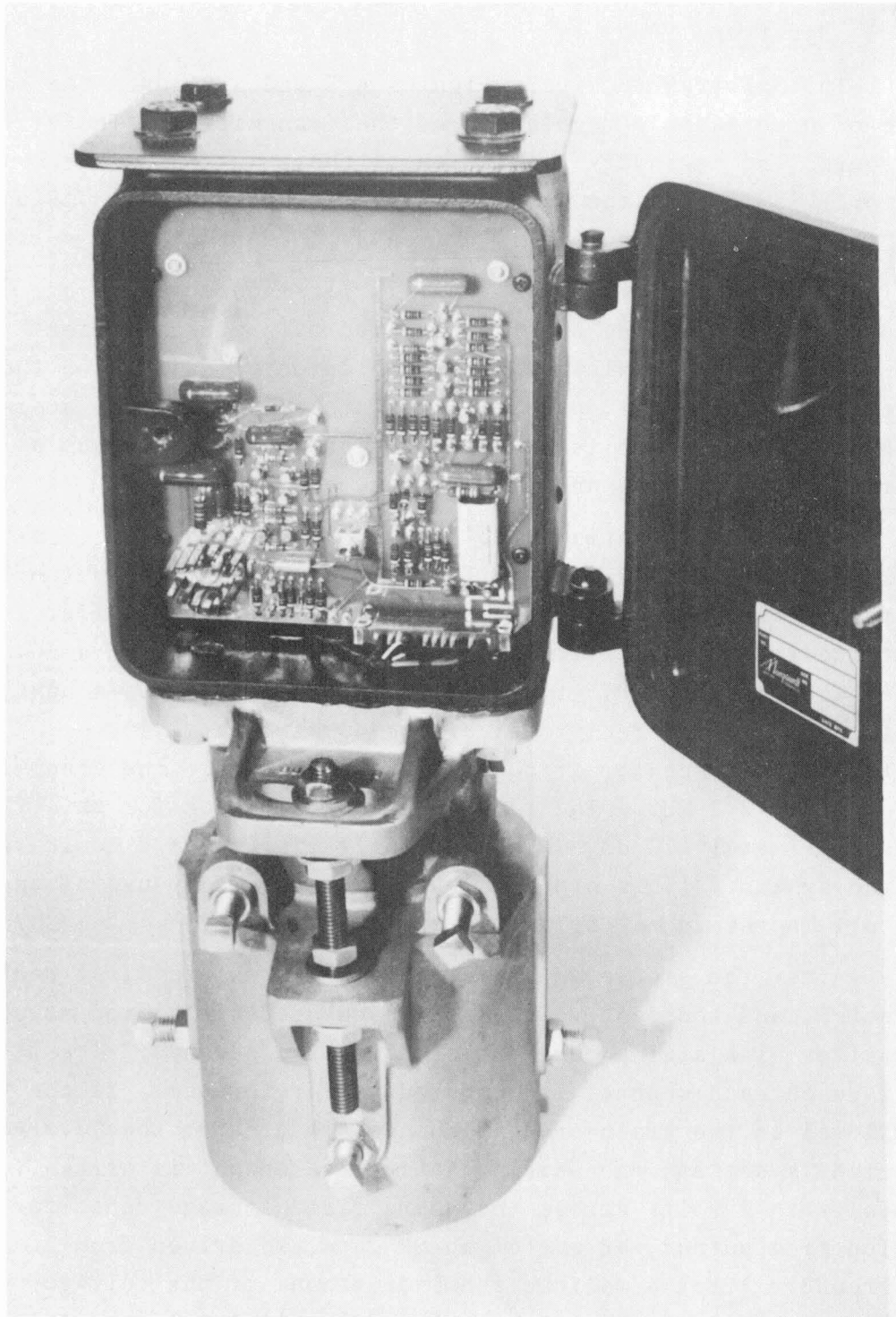


Figure A-6 Safetran Transmitter

A.2.3 Receiver

The Safetran receiver (Figures A-7 and A-8) uses the same type of power supply regulation as the transmitter. There is, of course, no secondary regulation as there was in the transmitter. As long as the supply voltage is between 9 and 15 volts DC, the receiver circuitry is driven by a constant 13.7 volts DC.

The received microwave input is first detected by a Schottky-barrier diode and then applied to a pre-amplifier. The waveguide-to-coaxial adapter, the detector diode, and the 4-stage, 5-transistor, pre-amplifier are all mounted in a single package. The pre-amp is an all transistor design and has a voltage gain of 80 dB and a noise figure of about 5 dB.

After amplification, the signal is fed onto the circuit board and into two parallel filters. The separate output of each filter is then amplified in a two-channel stereo amplifier integrated circuit. The filters used are band pass and of a LC, two pole, Tschebysheff, "T" type design. Each filter has a bandwidth equal to the reciprocal of the burstwidth -- 100 Hz. One filter has its center frequency at 1.0 kHz while the other filter has its at 2.2 kHz. The cross-channel rejection for this filter is approximately 12 dB, which seriously limits the dynamic range of the system. (This problem could be lessened by use of an AGC circuit in the receiving amplifier.)

After the stereo amplifier, the waveforms are first peak detected, and the peak voltages of each are then stored across a capacitor with a time constant of about two seconds. The DC voltage on each channel is compared to a reference. If the voltage level on the train-present channel is greater than 2.5 volts, a latch is set and the warning activation output is driven from 12 volts to 0 volts across the appropriate storage capacitor, the malfunction output, by use of an OR gate, is driven from 12 volts to ground. After a malfunction indication, if the voltage on either channel returns to above the 2.5-volt level, the malfunction output returns to 12 volts DC.

A-15

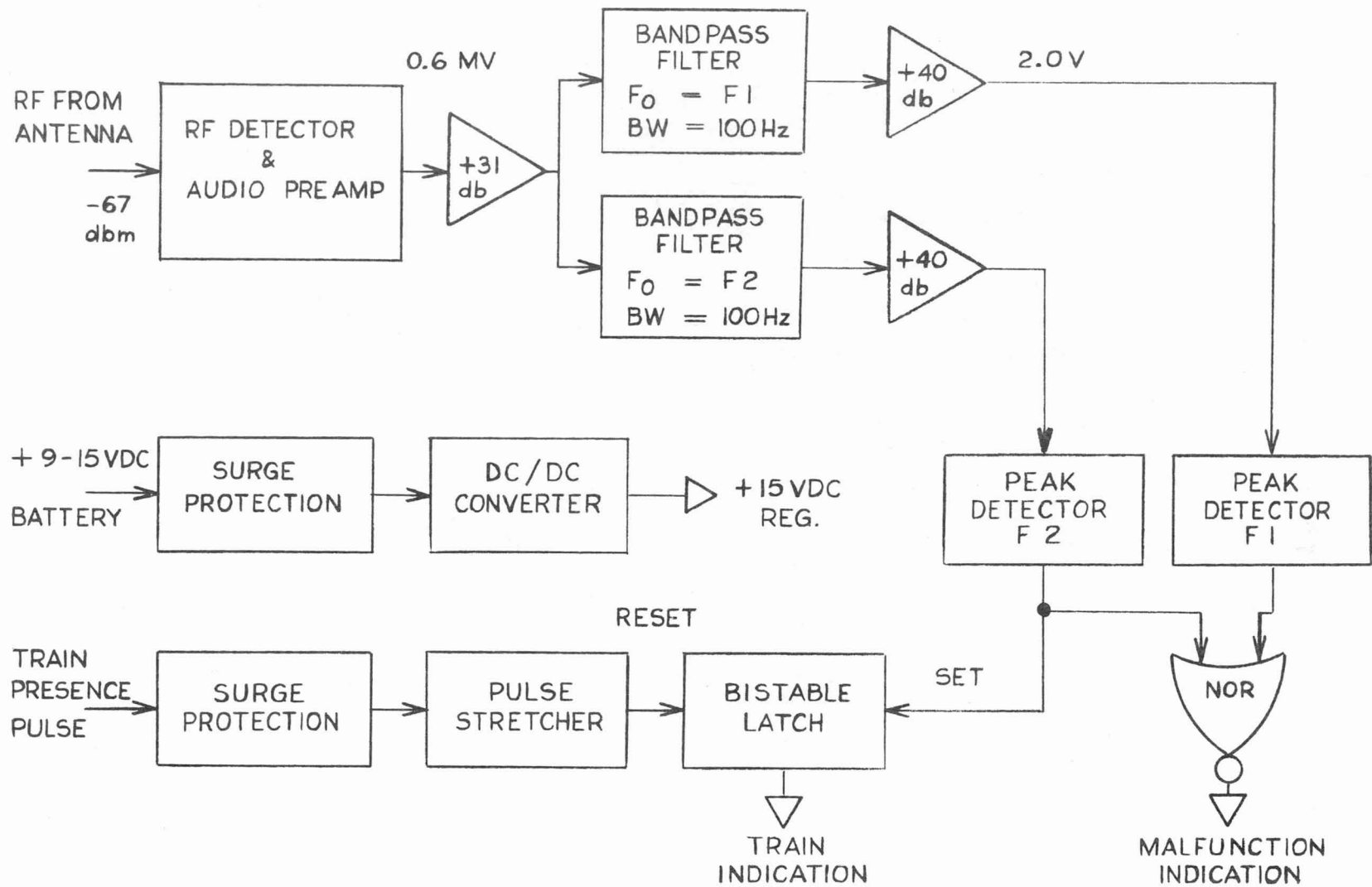


Figure A-7 Block Diagram of Safetran Receiver

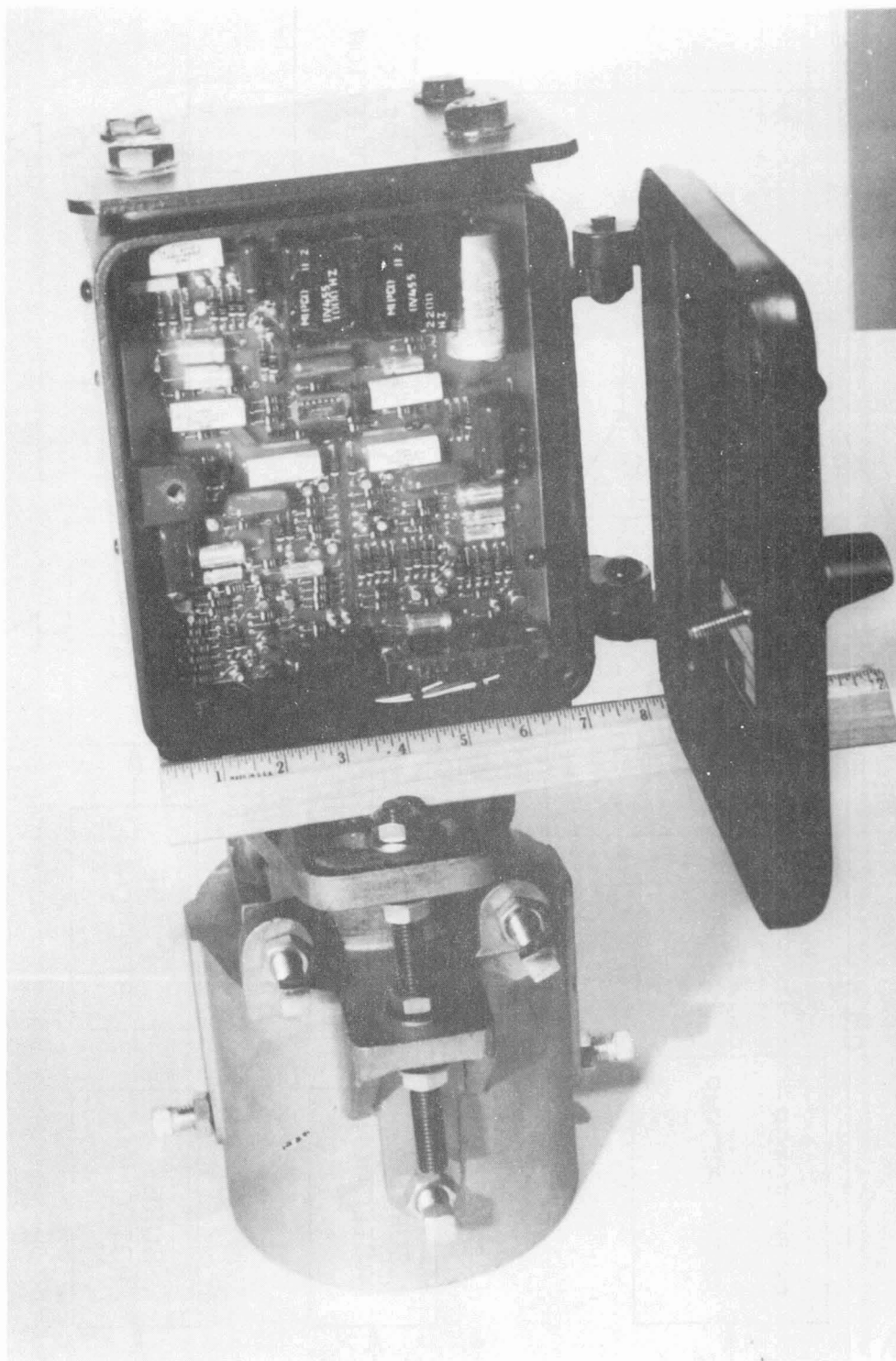


Figure A-8 Safetran Receiver

The receiver inputs, like those of the transmitter, are operated in a failsafe mode in the sense that a no-train condition is represented by 12 volts on the sensor-input leads, and a train-present condition is represented by 0 volts. The train sensor circuit produces a pulse five seconds after the last train sensor pulse is applied to the input terminals. This pulse resets the gate-activation latch and thus resets the receiver to a no-train condition.

A.2.4 Reliability and Cost

Safetran estimates a price of \$1200 per transmitter/receiver pair in 1000 lots. No detailed failure-mode analysis was undertaken, but they report estimates based on experience with existing systems utilizing similar components and circuits. Their predicted reliability is a MTBF of 5 years, given sufficient operating and manufacturing experience with a particular system.

