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ABSTRACT

For high speed intercity or low speed intracity operation, communications and surveillance are important aspects in the design of control systems for advanced ground transportation. New technological approaches in communications and surveillance can provide improvements in system capacity, operational economy, safety and passenger convenience.

A dielectric waveguide for communications and surveillance of vehicle characteristics (position and velocity) has been under experimental and analytical investigation for use along fixed guideways for ground transportation. This communication concept is nonradiating, has a broad bandwidth and provides a high rate of information transfer. Another important aspect of guideway surveillance is the detection of foreign obstacles that may cause vehicle damage or compromise passenger safety. For this application, an optical concept using a set of laser beams along the wayside is under investigation. The operating characteristics and method of deployment along TACV and railway guideways are presented.

INTRODUCTION

Many new concepts of ground transportation are under consideration because of the increasing demand to efficiently transport people and goods. The success of many of these new approaches are contingent upon timely improvements in communications and surveillance.

In this context, communication is the means of linking all elements of a transportation system for the exchange of information as distinguished from the control function which processes information and develops responses. The information transmitted over communication links includes all necessary commands and data for the operation, supervision and safety of all vehicles. However, information transfer should not be limited to command and control functions. If economically feasible, channels of communication should also be available to the passengers while traveling between cities. Methods that provide this broad band capability are feasible and can be implemented without infringement on the electromagnetic spectrum.

Surveillance refers to the techniques of sensing the vehicle state (position and velocity) and guideway conditions. A control policy based only on position of forward vehicles is inadequate and other parameters must be made available for high capacity transportation systems. In addition, the prevention of catastrophic accidents caused by guideway conditions is in need of concentrated study and the development of surveillance concepts.

The purpose of this paper is twofold: (1) to review the benefits from improvements in communications and surveillance for transportation along an exclusive guideway and (2) to present some promising technological concepts. With adequate communication, the quality and economy of service should be improved for both advanced and conventional transportation. Implementing communication improvements on conventional transportation should provide benefits in 3 to 5 years whereas benefits which await the development of new transportation systems will be delayed one or two decades.

Two concepts of communications and surveillance that are currently under experimental and analytical investigation are described. One of the concepts, the dielectric waveguide, provides many of the needed improvements in communications and is applicable to existing or advanced ground transportation. Also, the dielectric waveguide has surveillance capability for determining the vehicle state variables, position and velocity. The second concept under investigation is a method of surveillance for obstacles on the guideway using lasers located along the wayside. The optical sensor scans the guideway surface, senses the presence of obstacles, and transmits alarms to a control center.

BENEFITS FROM IMPROVED COMMUNICATION AND SURVEILLANCE

Any new technical concepts in communication and surveillance must provide improved transportation for the passengers and/or enhanced operational and maintenance characteristics of the transportation system. Most certainly, the implementation of new concepts is costly, and at the outset, the functional benefits should be identified. Toward this end, four benefits from improvements in communication and surveillance can be identified:

- capacity
- safety
- passenger convenience and comfort
- operational economy

Capacity - By improving the communication in a transportation system, the capacity of the system can be increased and more vehicles or traffic can be handled. Distance between vehicles can be minimized, delays reduced and an overall optimization of equipment achieved.

It must be emphasized that increased capacity is possible in existing systems as well as advanced systems. As shown in Figure 1, existing control and communication for trains consists of a series of isolated blocks. The detection or surveillance equipment determines the presence or absence of a train in each block. The presence of a vehicle in a block is communicated to the wayside equipment which alerts the manual or automatic controller on the following vehicle to take appropriate action. As shown by the literature(1),(2),(3),(4) the control policy implemented by the following vehicle varies rather widely depending upon the installation and application. However, all these systems provide a very substantial safety factor by maintaining a headway that is large with respect to the maximum stopping distance or time. For example, the vehicles on the Bay Area Rapid Transit System will maintain a minimum headway of 90 seconds and will operate at a maximum velocity of 80 mph. Assuming a constant deceleration of 0.12g, the stopping time is approximately 30 seconds which is substantially less than the prescribed headway.

In the above example the ratio, s, for the minimum headway to safe stopping time is 3. If s is reduced to 1, (the marginal value where a train would just avoid a collision), an increase in capacity can be achieved. This behavior is shown in Figure 2, where the minimum time interval between vehicles (reciprocal of capacity) is plotted as a function of vehicle velocity for various values of s.(1),(5)

Safety - By reducing s (Figure 2), any increase in risk of a vehicle collision must be offset with adequate communication and control. The addition of an effective communication link can provide the vehicle operator (manual or automatic) with more complete information with respect to other vehicles, and in this way the safety of the operation can be increased.

Operating with greatly reduced headways ($s < 1$) is not uncommon as illustrated by the standard automobile at a typical speed of 60 mph. Theoretically, such a vehicle has a stopping time of 12 seconds, yet the operating headway is only 2 seconds ($s=1/6$). These small values of s are possible because the driver of an automobile has sufficient information about events ahead of his vehicle. Hence, corrective or preventive action can be imposed to avoid collisions.

Another aspect of safety is the vehicle damage caused by foreign obstacles on the guideway. Approaching vehicles must be informed of the presence of such obstacles, and appropriate control policies must be implemented. If the obstacle is large enough to warrant an emergency stop, considerable advanced notice must be given to the vehicle controller. For high speed intercity vehicles, the advanced warning is particularly large. At 300 mph with a deceleration of .12g, the stopping distance is about 5 miles. A method of surveillance to provide such advance warning is discussed in the subsequent section.

Passenger Comfort and Convenience - With the implementation of improved communications, the benefits to the passengers can be expected to be manifold. With increased capacity and service, the delays the passengers must endure should be substantially reduced. The increased amount of information, that is made available to the operator as well as the passengers, should provide accurate scheduling of vehicles and should keep passengers well informed of train arrivals, departures, and progress. Because the system is under constant surveillance, greater dependability in the operation can be expected and the confidence of the users enhanced. All of these benefits can be achieved with existing transit systems.

From the viewpoint of advanced systems, transportation concepts which are competitive with the automotive mode of transportation become feasible. Many people have investigated the reasons behind the success of the highway network and how other systems might effectively compete. Examining the long range possibilities, one can envision competitive concepts using a dual mode which provides the door to door service of the automobile. One mode operates from the user's origin and efficiently connects to a network of transportation links which automatically handle the dual mode vehicle. If such personalized service is to be achieved in the future, improvements in existing communication techniques for ground transportation are required.

Operational Economy - An important objective of existing systems as well as advanced systems is operational economy. This objective implies that vehicles must be run in some optimal manner to achieve high utilization of capital equipment, use minimum energy for propulsion, and avoid unnecessary vehicle operation which entails increased maintenance. This optimization requires the availability of sufficient information through modern communication and surveillance concepts.

All of the above types of benefits are dependent upon improved communication and surveillance in the transportation system. At this time it is not possible to accurately estimate the cost to achieve the benefits through new technology. However, several concepts, which are now under study, will soon be available for development and demonstration. At that time, the trade-off between benefit and cost can be made, and control systems defined for implementation.

COMMUNICATIONS WITH A DIELECTRIC WAVEGUIDE

The benefits of the preceding section are possible with a wayside communication link consisting of a dielectric waveguide. As shown in Figure 3, the dielectric waveguide is mounted along the guideway and appears as an open channel with a dielectric rod. For the purposes of continuous communication, the main waveguide must extend the entire length of the guideway. However, since the operating characteristics of the system permit high transfer rates, it is also possible to use short lengths of waveguide that are spaced along the wayside. The seperation between these lengths of waveguide could vary depending upon the application and the specified time period between transfer of information. The concept of the dielectric waveguide is sufficiently flexible to satisfy a wide range of such requirements.

The transfer of information from the main waveguide to the moving vehicle is accomplished with a dielectric coupler which is a short section of waveguide mounted on the vehicle (Figure 3). With this coupler, information can be transferred to and from the vehicle across the air gap.

Experimental Facilities

Extensive analytical and experimental investigation of this communication concept has been performed and recently reported.(6) The experimental results are from two different facilities. The laboratory bench (Figure 4) is an indoor facility with a main waveguide approximately 20 feet long. The moving coupler, which is a section of waveguide about 4.5 feet long, is mounted on a carriage that moves parallel to the main waveguide. The mounting of the coupler provides for changing the relative position of the coupler with respect to the main waveguide. The facility is used to measure the propagation properties of the waveguide, the coupling properties between the main waveguide and the moving coupler and the system behavior across a simulated repeater station.

The other facility is an outdoor test site which has a main waveguide which is 80 feet long. The coupler is mounted on a carriage which is driven over tracks along the length of the main waveguide. This facility is used for investigation of performance under environmental conditions and external electromagnetic noise.

System Characteristics and Geometry

The geometry of the main waveguide and coupler are illustrated in Figure 5. Tha main waveguide is the upper element and has the cross section of an inverted channel with a continuous tang along the top of the channel. The tang is used to attach the waveguide to its supports and provides rigidity by increasing the moment of inertia. This portion of the waveguide, which is called the metallic shield, is constructed from aluminum. On the underside of the metallic shield, a polyethylene dielectric rod is mounted. The coupler, which is mounted on the vehicle, is identical in cross section to the main waveguide. The length of the coupler is z_o and the two waveguides are separated by a distance r_d.

Simplicity of construction and the lack of critical requirements in the shape and dimensions of the dielectric element is a most appealing feature of this type of waveguide. In addition, this system does not require any contact between the moving vehicles and the wayside components. Consequently, conventional rail transportation as well as advanced concepts such as track air cushions, can be effectively serviced by this communication concept. A problem of critical importance for deployment of the waveguide is the sensitivity of coupling properties to increases in the distance r_d between the coupler and the main waveguide. This problem was systematically investigated and a summary of the results of the investigation appear in Table I for operation in the C-S band and the X-band regions. Although the C-S band operation is substantially less sensitive to changes in r_d, both operating frequencies permit substantial variations in r_d without detrimental effects upon the communication link.

The performance of the dielectric waveguide as a communication technique must be evaluated with respect to many parameters. Four characteristics of major importance are frequency bandwidth, radiation loss, vulnerability to external interference, and radar capability. Each of these characteristics have been investigated for the dielectric waveguide, and the results are discussed below.

Frequency Bandwidth - As shown in Table I, the dispersion and attenuation of the propagated signal is small in both the X-band and C-S band. In the case of the C-S band, a 40 db attenuation between repeaters is reasonable and would require a repeater about every 5 miles. As a consequence of the small dispersion and attenuation effects, a broad bandwidth (500 MHz) can be propagated over long distances, permitting the transfer of large amounts of data between the wayside and the vehicles.

This broad band capability can readily accomodate control information for many vehicles, TV displays or voice channels for operators or supervisors, transmission channels between leading and following vehicles and channels for transmitting guideway conditions to vehicles or a control center. The preceding communication applications are of value to both interurban and intraurban transportation. Also, for interurban travel, the dielectric waveguide has ample capacity for telephone communication channels to service the needs of passengers.

Radiation Losses - In the selection of a free space communication link, a most important consideration is the allocation of an operating frequency as regulated by the FCC. Since the available operating frequencies are severely limited,(7) the bandwidth described above would not be possible if the communication system had radiation properties under the jurisdiction of the FCC.

The dielectric waveguide does not exhibit radiation losses or cause interference with other communication systems operating at the same frequency. In Figure 6 the amplitude of the electric field component is plotted as a function of the ratio of the radial distance from the axis of the dielectric rod to the radius r_o of the rod. One observes that the field amplitude decreases monotomically and much more rapidly than the amplitude

TABLE I

SUMMARY OF CHARACTERISTICS FOR THE DIELECTRIC WAVEGUIDE

Band	X	C-S
Nominal Frequency	9 GHz	4 GHz
Change of Coupling With Distance r_d	10 db/inch	3 db/inch
For 10 db Coupling, z_o	48 inch	60 inch
r_d	~ 4 inch	~ 7 inch
Velocity Ratio	$1.01 < \frac{c}{v_p} < 1.02$	$1.01 < \frac{c}{v_p} < 1.02$
Dispersity $\frac{d}{d_f}\left(\frac{c}{v_P}\right)$	$.016\ (GHz)^{-1}$	$.02\ (GHz)^{-1}$
Bandwidth	> 500 MHz	~ 500 MHz
Attenuation	12 db/km	4 db/km
Shield Width	2.5 inch	5.5 inch

of a radiation field shown as a dashed line on Figure 6.

Vulnerability to External Interference - The operating environment for ground transportation has several sources which tend to degrade the performance of a communication system. For example, electromagnetic noise is a common and particularly important cause of communication degradation.(8) This type of interference is generated by other communication systems which illuminate portions of the guideway, power collection apparatus for catenary or contact rails and propulsion and control systems onboard the vehicle. Hence, an important aspect in the evaluation of a communication system is its vulnerability to such external interference.

For the selected operating frequencies, the interference from external electromagnetic noise can be neglected if the waveguide is free of geometrical distortions or physical imperfections. The effect of curvature of the waveguide has been studied, and for typical applications this effect can be ignored. Typically, the radius of curvature must satisfy the following condition for negligible interference:

$$\rho >> \frac{\lambda}{\pi}\left(\frac{c^2}{v_p^2} - 1\right)^{-3/2}$$

where ρ is the radius of curvature and λ is the wavelength of the communication system. Similarly, physical imperfections are unimportant when normal fabrication and installation procedures are maintained.

Extensive tests were preformed to determine the effect of critical components, such as transition sections or the vehicle coupler, which may be vulnerable to electromagnetic interference. Maximum coupling occurred at an incident angle of 7° with respect to the axis of the waveguide. The coupler, which is 5 feet long, had an effective area of only $10\ cm^2$ as a receiving antenna over the entire frequency range. Based upon these studies, the dielectric waveguide is practically invulnerable to electromagnetic noise.

Radar Capability - Capacity of a transportation network can be increased as the information about the state of each vehicle is refined. The state of the vehicle is defined by its position, velocity and acceleration. Existing controllers utilize a block technique which determines the presence or absence of a vehicle in each block without an indication of vehicle velocity. In contrast, the dielectric waveguide can be used to propagate an interrogating signal which is reflected by the moving vehicles. As a consequence, the waveguide becomes a one-dimensional radar capable of determining position and velocity of the moving vehicles. With the wide band capability, the position of a vehicle can be determined within a range of 10 meters.

In principle, a conventional radar or radar-beacon system could be used to determine position and velocity of the vehicles, and a conventional microwave communication system could be used to transfer the required information to and from the moving vehicles. However, in addition to the noise and interference problems, a serious difficulty would arise with the scattering and multiple reflections of the microwave beam from the objects surrounding the guideway. This problem does not arise in the dielectric waveguide where the electromagnetic wave is guided and confined to a predetermined region.

Method of Deployment

Methods of deploying the dielectric waveguide are illustrated in Figure 7 for railway and TACV guideways. In a conventional railway, the dielectric element of the main waveguide is facing downwards. The main waveguide is supported with columns at intervals of approximately 20 feet as indicated in Figure 7a. The waveguide of the moving coupler is positioned in the same vertical plane as the main waveguide. To protect the moving coupler from the environmental conditions, a radome type of cover is shown in Figure 7a. To increase the protection of the main waveguide against the environmental conditions, an independent cover is recommended as shown in the figure, rather than an increase in dimensions of the waveguide shield. A thin mylar sheath may be attached to the cover to provide added protection.

For the TACV application (Figure 7b), the main waveguide can be mounted beneath the side supports in the guideway. The coupler may be mounted at several locations on the vehicle. For example, the support cushions, which are designed for vertical motions of ± 1 inch, would provide suitable mounting surfaces. Depending upon the secondary suspension between the vehicle and the air cushion, other locations on the vehicle itself may be appropriate.

SURVEILLANCE FOR OBSTACLES

Analytical and experimental investigations are being performed on the obstacle surveillance technique illustrated by Figure 8. As shown, a light source and receiver are located at Station A. The light source transmits a collimated beam across the guideway to the retroreflector (Station B), which reflects the light along the same path as the incident light, and the intensity is measured by the receiver at Station A. If an obstacle is located in the path of the light, the intensity of the light is reduced at the receiver, and an alarm registers at the control center.

The basic concept can be extended for the surveillance of an entire area by permitting the transmitter-receiver at Station A to scan over a prescribed angle (Figure 8). The retroreflector then must be deployed as a surface or fence on the opposite side of the guideway.

For this application the transmitter is a laser diode (9) which has a very narrow frequency range allowing the removal of ambient radiation, the high reliability of solid state devices, and a low operating voltage. The characteristics of the transmitter used for the experimental studies are summarized in Table II. As shown, the laser diode transmits low power and is within the no-protection level for safe operation. (9) With an optical system, the small emitting surface of the laser diode is collimated to the desired size (~ 1 inch) for transmission across the guideway.

The retroreflector is an entirely passive device formed by a combination of mirror-like surfaces which reflect all radiation in a direction parallel to the incident light. Standard types of retroreflector materials are suitable for this application and are fabricated in long lengths with a width of about 2 1/2 inches to capture the full height of the laser beam.

The receiver consists of two main elements; an optical system which collects the light from the retroreflector and a solid state photodetector for measuring the intensity of the light. The receiver, which is mounted coaxial with the transmitter, has a large optical aperture in order to compensate for the divergence of the beam from the retroreflector.

A second generation laboratory model of the scanner is shown in Figure 9 with the transmitter and receiver elements identified.

TABLE II

CHARACTERISTICS OF LIGHT SOURCE

Type	RCA TA2628 Pulse laser diode
Peak Power	3 watts
Wavelength	9050°A at peak emission (near infrared - not visible)
Pulse Width	.15 µs
Repetition Rate	2 kHz
Size of Emitting Surface	.003 x .00008 inch
Radiation Angle	.1 Steradian

The design of this optical sensor for ground transportation applications is dependent upon a comprehensive evaluation and balance of numerous parameters. Three important parameters, which are selected for discussion in this paper, are scanning angle, range and retroreflectors.

Scanning Angle - In the specification of a scanning angle, θ, two basic objectives must be balanced; namely, the region of surveillance for each sensor must be large and the electronic design of the sensor should be made as simple as possible.

By operating the sensor with its beam almost parallel to the guideway, the region of surveillance is greatly increased within the limitation imposed by range. As shown in Figure 10, the region of surveillance is characterized by the length x along the retroreflector fence and the minimum distance, L, between the sensor and the retroreflector. In this example, a typical value of range is assumed (600 ft.), L = 10 feet, and the centerline of the guideway is at $^{L}/2$. As the scan angle increases from 0 to 70°, the value of x increases from 0 to 27 feet or includes approximately 5% of the total range. In contrast, the next 19° of angular rotation covers the remaining 95% of the total range. Hence, a simple scanning procedure, which provides surveillance over a large portion of the guideway, is an alternate clockwise and counter clockwise movement in the interval $70^\circ \leq \theta \leq 89^\circ$. This small angle can be rapidly scanned in both directions with a minimum of dwell time.

The second generation sensor in Figure 9 was designed and built on the basis of the interval (70° , 89°). As a consequence, a simple mechanical design is possible. In addition, the associated electronics can be simplified in comparison to the earlier model (9) since the retroreflector fence can be designed to substantially reduce fluctuation in the intensity of the returned beam.

Range - The maximum range between the sensor and the retroreflector fence is influenced by the following factors:

- power
- diameter of the receiving window, D_r
- safety
- obstacle size
- temperature gradient
- weather

Range is influenced primarily by two parameters with respect to the design of the sensor; namely, power and D_r . The value of D_r is limited by the practical dimensions for the sensor, and the upper value of power is constrained by safety requirements. The laser diode (Table II) is safe for operation along guideways and has a maximum operating range of 600 feet under good environmental conditions.

The obstacle size imposes a range limitation that is related directly to the temperature gradient of the air immediately above the guideway. This temperature gradient produces a gradient in the index of refraction, and consequently the laser beam tends to bend upwards. On a typical clear day, the maximum beam bending occurs in early afternoon and obstacles with vertical dimension that are small compared to these beam displacements can not be detected.

The beam bending phenomena was experimentally and analytically investigated using different operating ranges for the laser over simulated guideways with various temperature gradients. For railway surveillance, results to date show that an operating range of 600 feet is feasible for obstacles the order of one inch since the gradient of temperature at the height of the rail head is small. For TACV applications, the laser beam is always in close proximity to the guideway surface where the temperature gradient can be severe. Consequently, the operating range must be considerably less than 600 feet for obstacles the order of one inch.

The weather conditions (rain, fog and snow) which can introduce additional attenuation and scattering of the laser beam, impose limitations on the range of the sensor. Various wavelengths in the optical range have been examined as a possible method of overcoming this constraint, but only minor improvements are possible. As of this time, adverse weather conditions still cause an operating constraint on optical sensors for unprotected guideways.

Retroreflector - The purpose of the retroreflector fence is to reflect the beam radiated from the transmitter in a direction parallel to the incident beam. In the absence of an obstacle, the receiver senses the bright background of the retroreflector. An obstacle will appear as a dark region due to the much lower reflectivity of its surface, and the receiver senses the presence of an obstacle.

The important parameters affecting the retroreflector design are:

- available materials
- angle of incident
- edge effect
- beam size

There are numerous types of materials available to provide a reflecting surface, but for this application, only materials that reflect the light parallel to the incident light are of interest. This requirement is adequately satisfied using corner-cube surfaces.

Ideally, the incident light should be nearly normal to the surface, but as the sensor rotates over large scanning angles this condition is difficult to satisfy. By operating with the small scanning interval (70° , 89°), the problem is not severe, and the design shown in Figure 11 is feasible. In this design, a mounting structure or frame is installed parallel to the guideway and rectangular retroreflectors are mounted perpendicular to the frame. The critical dimensions in this design are a, b, the size of the corner-cubes of the retroreflector (edge effect) and the size of the laser beam. At very large scan angles, the retroreflectors appear as a finite number of edges, one behind the other. Since each edge has a number of corner-cubes that are destroyed (Figure 11), the dimensions must be selected to minimize the area of ineffective edges with respect to the total reflecting area that is illuminated by the laser beam. Studies of these parameters have been performed and typical optimum values of a and b are 4" and 12" respectively.

CONCLUSIONS

Communication and surveillance are important components in conventional or advanced transportation systems. Improvement in these components is warranted by benefits such as increased capacity, safety, passenger comfort and operational economy.

The dielectric waveguide has many features which can provide practical improvements in communications and vehicle surveillance for the control of ground transportation. In addition, the dielectric waveguide is broad band and has sufficient capacity for other communication needs. Feasibility of the concept has been demonstrated under laboratory conditions and future emphasis should be in field demonstrations under actual operating conditions of a railway or TACV.

The detection of obstacles on the guideway of high speed vehicles is an important problem requiring additional research. Surveillance with optical sensors involves numerous parameters which must be carefully balanced to achieve an operational system. For outdoor guideways, adverse weather conditions (rain, fog and snow) can introduce operational problems for obstacle surveillance systems. The effective range of the optical sensor is reduced under such conditions.

NOMENCLATURE

c	speed of light
D_r	size of the receiving window
L	minimum distance from the sensor to the retroreflector
r	radial distance from the axis of the dielectric rod
r_d	separation between the main waveguide and coupler
r_o	radius of the dielectric rod
s	minimum headway/safe stopping time
v_p	phase velocity
z_o	length of the coupler
θ	scanning angle
ρ	radius of curvature

ACKNOWLEDGMENT

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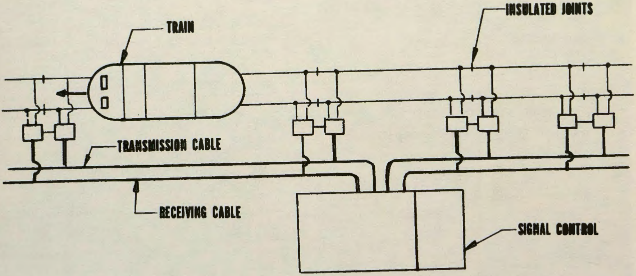


FIGURE 1 LAYOUT OF COMMUNICATION AND CONTROL FOR RAIL SERVICE

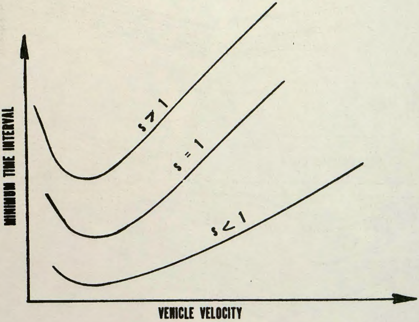


FIGURE 2 MINIMUM TIME INTERVAL vs VEHICLE VELOCITY

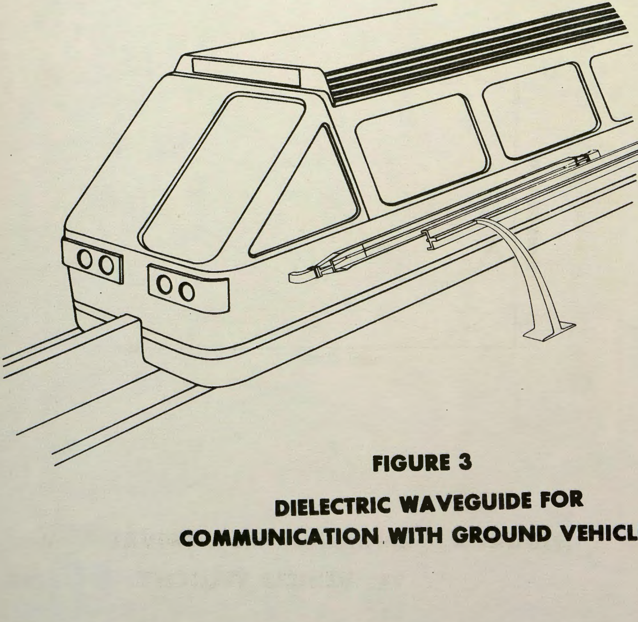


FIGURE 3

DIELECTRIC WAVEGUIDE FOR COMMUNICATION WITH GROUND VEHICLES

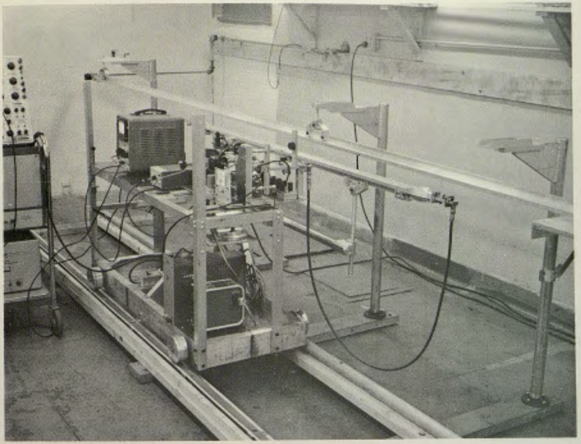


FIGURE 4 LABORATORY TEST FACILITY

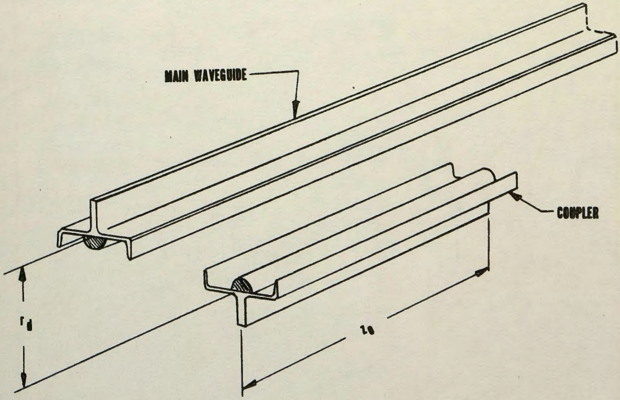


FIGURE 5 DIELECTRIC WAVEGUIDE AND COUPLER

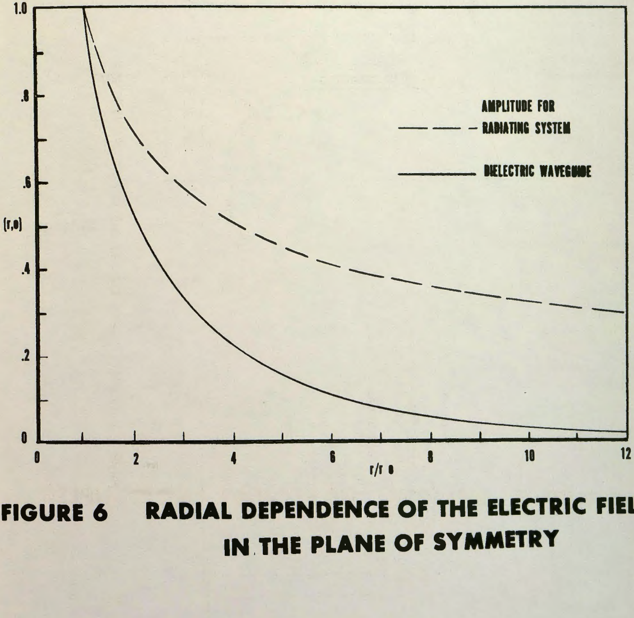
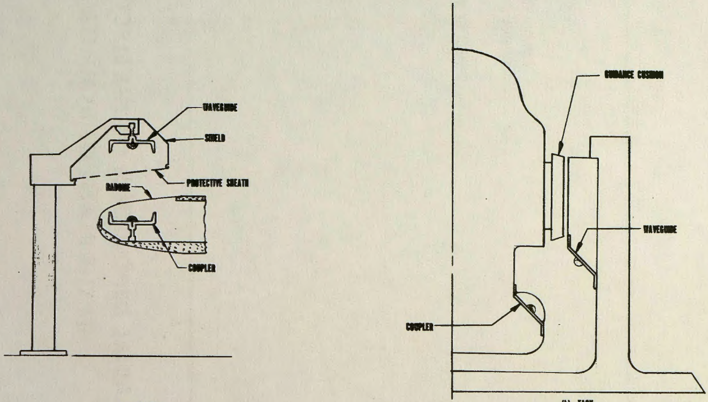


FIGURE 6 RADIAL DEPENDENCE OF THE ELECTRIC FIELD IN THE PLANE OF SYMMETRY



(a) RAILWAY

(b) TACV

FIGURE 7 DEPLOYMENT OF THE DIELECTRIC WAVEGUIDE

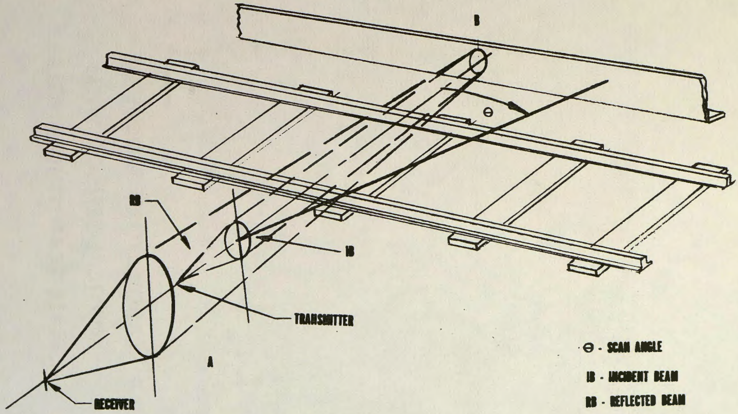


FIGURE 8 OBSTACLE DETECTION

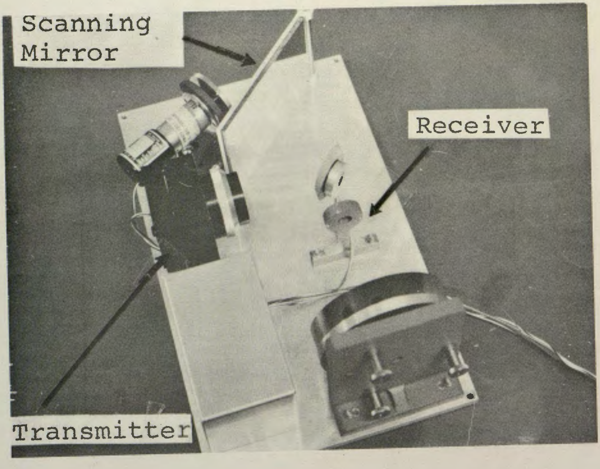


FIGURE 9 LABORATORY MODEL OF OPTICAL SENSOR WITH SMALL SCANNING ANGLE

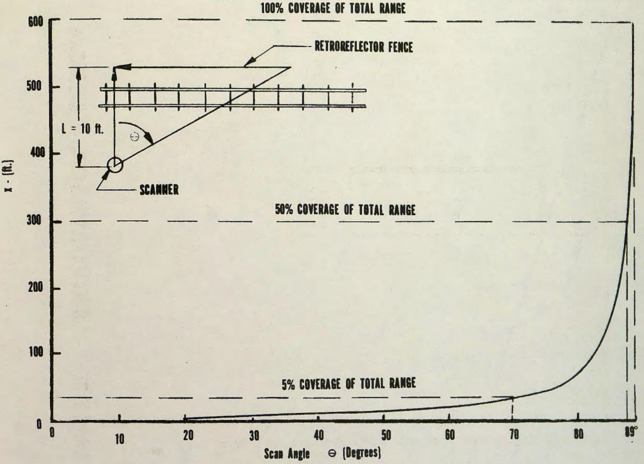


FIGURE 10 RELATION FOR TRACK COVERAGE VERSUS ANGLE OF SCAN

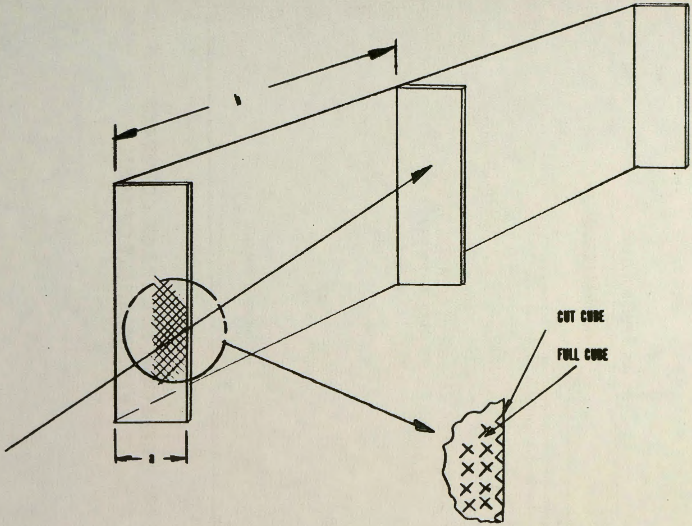


FIGURE 11 RETROREFLECTOR DESIGN.