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High-Speed Rail IDEA Program

MMW Obstacle Detection Radar for Highway Grade Crossings and Quad Gates

Final Report for High-Speed Rail IDEA Project 13

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"MMW Obstacle Detection Radar for Highway Grade Crossings and Quad Gates"

Prepared for:

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The concept developed under this project is the application of a low-cost 76.5 GHz radar sensor, incorporating the Spinning Grating™ Antenna, to highway-rail grade crossings for the detection of obstacles in the path of trains. The Spinning Grating™ Antenna is the key enabling technology provided by WaveBand Corporation. The antenna utilizes a principle of evanescent coupler, hence, it is also called evanescent coupled antenna. It provides agile scanning with simple reliable mechanics as opposed to bulky and slow gimbal mounting. At the same time, it is orders of magnitude less expensive than phased array antennas, which is crucial for the railroad sensor application. The sensor can also be used as a backup sensor to ascertain that the train has cleared the crossing. The sensor system has the ability to measure intrusions and near misses at crossings and a recording device can be added to provide a record of such information.

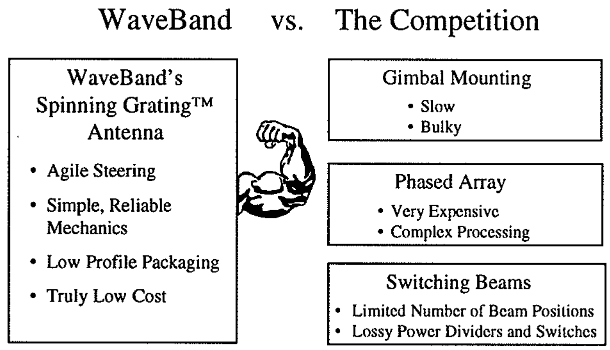
For evaluation of its effectiveness, the sensor was mounted at a railroad crossing. The outcome of this test and evaluation provided data that can be used to aid in the determination of how best to use this type of sensor to reduce collisions between trains and other vehicles at railroad grade crossings. Examples of such application include activation of additional motorist warnings when a vehicle is detected skirting the crossing gates or other signal device, and/or providing warning to the train engineer that there is a stuck vehicle on the tracks.

Use of an all-weather, low-cost millimeter wave (MMW) scanning radar sensor that has the ability to discriminate between obstacles located on the tracks and those that are not, can, in conjunction with current devices, dramatically improve the safety at highway-rail grade-crossings. MMW sensors are able to accomplish something that optical sensors cannot do, “see” under all-weather conditions.

1.0 INTRODUCTION

1.1 Concept and Innovation

The concept proposed for development under this project is the application of a low-cost 76.5 GHz radar sensor, incorporating the Spinning Grating™ Antenna, to highway-rail grade crossings for the detection of obstacles in the path of trains. The proposed sensor has also other applications that are expected to be of benefit to the railroad community. For example, it can be used as a backup sensor to ascertain that the train has cleared the crossing. The sensor system has the ability to measure intrusions and near misses at crossings, and a recording device can be added to provide a record of such information. A critical element of the sensor is a scanning antenna. WaveBand's Spinning Grating™ Antenna found a niche in the growing market of MMW systems, which require the antenna to provide fast scanning at a low cost (Figure 1-1).



WaveBand vs. The Competition

WaveBand's Spinning Grating™ Antenna
- Agile Steering
- Simple, Reliable Mechanics
- Low Profile Packaging
- Truly Low Cost

Gimbal Mounting
- Slow
- Bulky

Phased Array
- Very Expensive
- Complex Processing

Switching Beams
- Limited Number of Beam Positions
- Lossy Power Dividers and Switches

Figure 1-1. WaveBand's Spinning Grating™ antenna vs. three competing approaches.

The operating principles of the antenna are explained in Figure 1-2. A single-mode dielectric waveguide with an effective refractive index N_{eff} is used as a line feed. As a metal grating is placed in close proximity to the waveguide, it interacts with the evanescent tail of the propagating mode. The result of this interaction is a radiating mode whose direction in space is described by

$$\sin\varphi = N_{eff} - \lambda / \Lambda . \qquad (1\text{-}1)$$

It follows from Equation 1-1 that by varying the grating pitch Λ, one can steer the out-coupled radiation in various directions. Also, due to the antenna reciprocity, the incident radiation will be received only from the same angle φ, given the same Λ and the same feed geometry.

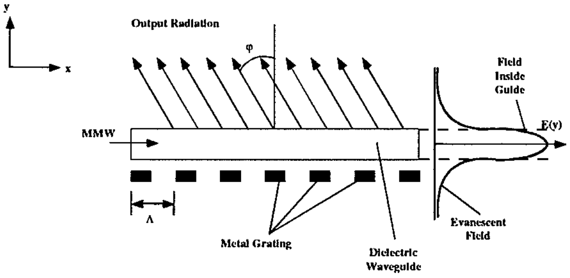


Figure 1-2. Spinning Grating™ Antenna: the Principle of Evanescent Coupling.

One way to accomplish scanning is to wrap a set of gratings with different values of Λ (or with a continuously varying Λ) around a drum as seen in Figure 1-3. By spinning the drum, beam-scanning in the yz plane is achieved. Due to its low fabrication cost – the grating is etched on a copper clad Duroid in a process similar to printed circuitry board fabrication – and fast, reliable scan that can produce video frame rates, the antenna fits uniquely the requirements placed on the railroad quad gate sensor.

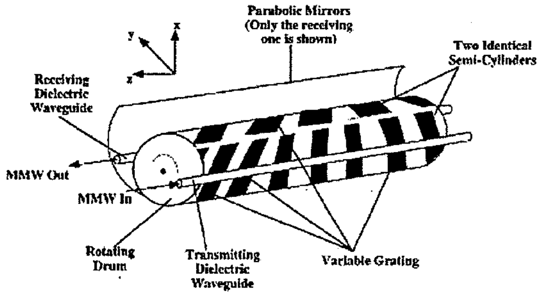


Figure 1-3. Antenna Design: A bi-static antenna is shown as an example.

For evaluation of its effectiveness, the sensor was mounted at a railroad crossing that is part of the Burlington Northern Santa Fe (BNSF) system. The outcome of this test and evaluation provides data that can be used to aid in the determination of how best to use this type of sensor toward the goal of reducing collisions between trains and other vehicles at railroad grade crossings. Examples of such application include activation of additional motorist warnings when a vehicle is detected skirting the crossing gates or another signal device, and/or providing warning to the train engineer that there is a stuck vehicle on the tracks.

The innovation here is the use of a low-cost millimeter wave (MMW) scanning radar sensor to monitor highway-rail grade crossings for the purpose of drastically reducing the number of accidents.

1.2 Potential Impact and Payoff in Practice

There are nearly 270,000 railroad-highway grade crossings in the U.S.[1] Of these approximately 164,000 are classified as "Public at Grade", i.e., the public physically cross the tracks, not overhead or under, but at the level of the track. The vast majority of the 164,000 have some sort of warning device and approximately 39% of these use some type of active warning such as gates, flashing lights, wigwags, bells, etc. Even so, in 1995 there were 4,416 motor vehicle accidents at U.S. highway-rail crossings resulting in 508 deaths and 1,825 injuries. Over the last six years the casualty rate per accident has been 51% or higher at public crossings.

Use of an all-weather, low-cost MMW scanning radar sensor that has the ability to discriminate between obstacles located on the tracks and those that are not, can dramatically improve, in conjunction with current devices, the safety at highway-rail grade-crossings. MMW sensors are able to accomplish something that optical sensors cannot do, "see" under all-weather conditions.

1.3 Product Transfer and Implementation

The MMW radar obstacle detection system would be deployed at most of the 164,000 grade-crossings in the U.S. The ultimate system would operate at low power levels and could operate from batteries recharged by solar cells, or from standard 110 volt AC lines. At grade-crossings with a history of problems, the recording and information gathering feature could be added.

To best implement such a system, the integration of the obstacle detection information into current warning systems will need to be accomplished. A combination of signage, gate control, train warning and communication to the dispatcher need to be considered and evaluated as part of the overall control system.

The system will be targeted at a selling price of $3,000 in quantities of several hundred.

2.0 PROJECT OBJECTIVES

The objective of this project was to demonstrate an integrated MMW obstacle detection radar system that could be used for grade crossing surveillance, including obstacle detection. The radar system should be capable of interacting with a gate crossing control system. A demonstration of the system was carried out at an operating quad gate crossing.

3.0 OPERATIONAL CONSIDERATIONS

3.1 Operational Scenario

The concept of a millimeter-wave radar sensor operating in the 77 GHz band presents a unique approach to the detection of obstacles at grade crossing. The millimeter wave band has been chosen, since it provides an excellent balance between spatial resolution, package size, all weather capability, and cost. The 77 GHz operating frequency has been selected to take advantage of the low-cost components that soon are going to be manufactured for the automotive industry.

The radar sensor can be integrated with quad gate controllers as one of the inputs used to insure that crossings are free of obstacles when a train is approaching. In this case, the sensor provides a digital output data stream that contains information with respect to obstacle detection, obstacle location, and sensor status. For the sensor's location, we have considered, as a possibility, mounting it ontop of a pole, at some distance from the crossing to be monitored. The field of view of the sensor must be compatible with the scene under scrutiny and this has a major bearing on the location of the sensor. For the purposes of this project, the selected test site is in Los Angeles, along the right-of-way of the Los

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[1] U.S. Federal Railroad Administration, March 26, 1996

Angeles Metro Blue Line. The 124th Street crossing is represented schematically in top view in Figure 3-1. The blue region describes the area monitored during the test and evaluation period. This area is contained within a set of quad gates located on each side of, and parallel to, the set of three tracks, and by the roadway boundary perpendicular to the tracks. A side view of the installation is shown in Figure 3-2 for an azimuth angle of zero degrees.

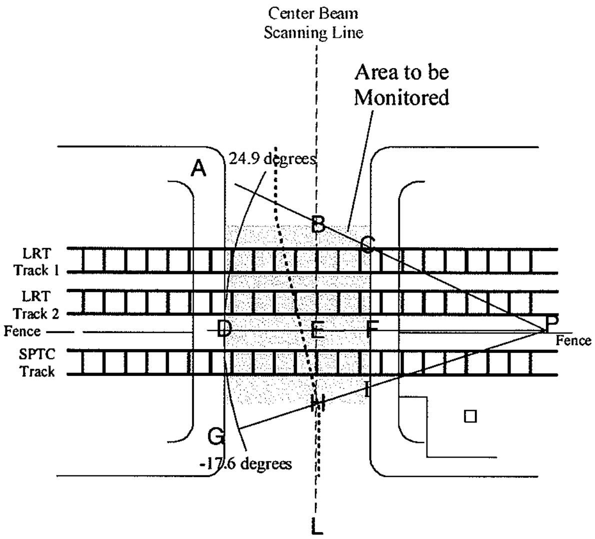


Figure 3-1. A schematic top view of the 124th Street crossing.

The antenna (point R in Figure 3-2) is placed on top of a pole, approximately 6 meters high, facing the crossing. The bottom of the pole is marked P in both figures. We have selected a beam width of 6.72 degrees in the elevation (vertical) plane and believe that it remains essentially constant as the beam is scanned in the azimuth (transverse) direction. The center of the beam is scanned along the dashed line marked L in Figure 3-1. This scanned path defines the angular scanning range of the antenna, which turns out to be –17.6 to +24.9 degrees relative to the antenna boresight.

Discussions with several members of the railroad community have aided us considerably in the development of our system parameters. Discussions included conversations with John Johnson of Amtrak, Vijay Khawani of Los Angeles Metro, Lorraine Paccoha of Massachusetts Bay Transportation Authority, John Haggerty of San Diego Trolley, Jonathan Chapman of the San Diego Coaster, and Jeff Twombley of Rail Safety Engineering.

The smallest obstacle to be detected for this project is a motorcycle. The radar cross section of a motorcycle is quite small and depends upon the motorcycle orientation and on scintillation. The radar cross section at this frequency can be as small as –10 dBsm. This is one of the criteria that must be met in the sensor design. Another is the antenna scan angle, which is controlled by the geometry described above. Spatial resolution defines the antenna beamwidth, which also defines the antenna gain and therefore the transmitted power. The spatial resolution required is that which is needed to clearly determine which lane of traffic an automobile is located in. With typical traffic lanes about 12 feet in extent, we need resolution of about 6 feet in azimuth.

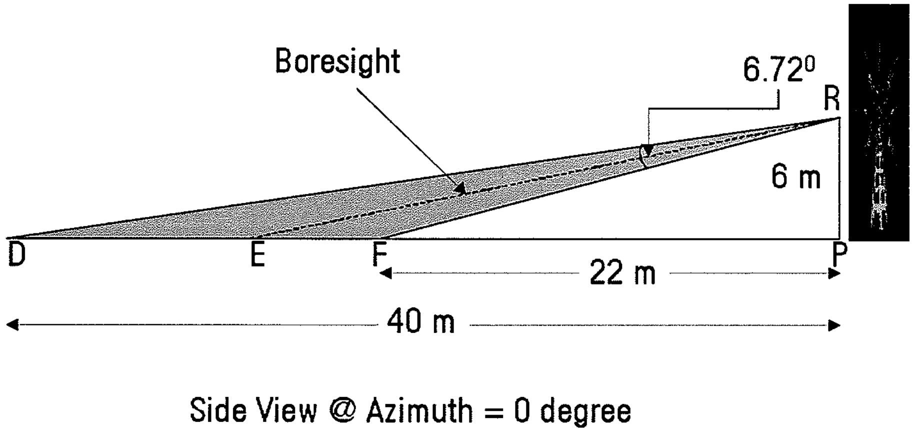


Figure 3-2. A side view of the 124th street crossing.

Range measurement resolution provides information as to where in a given lane a vehicle is located. It also acts as a discriminant for objects that are not considered in jeopardy. A range resolution of 0.5 meters is considered adequate at this time. Working from the basic radar range equation

$$P_D = P_o G^2 \frac{\sigma \lambda^2}{(4\pi)^3 r^4} \qquad (3\text{-}1)$$

we arrive at the sensor performance parameters given in Table 3-1.

Table 3-1. Radar Sensor Specifications.

Parameter	Value
Frequency, GHz	76.5
Transmitter power, dBm	10
Modulation	FMCW
Minimum detected power with 20 dB S/N, dBm	-102.2
Maximum range, m	50
Minimum range, m	20
Range resolution, m	0.5
Antenna scan angle, degrees	-17.6 to +24.9
Antenna polarization	linear
Antenna gain at boresight, dB	37.9
Antenna azimuth beamwidth, degrees	1.0
Antenna elevation beamwidth, degrees	6.72
Number of beam positions	45
Scan rate, Hz	1
Antenna aperture, cm	22.5 x 3.34

Using the Eq. (3-1), we can determine the expected radar return power from a motorcycle at various points located on the diagram in Figure 3-1. This data is summarized in Table 3-2. From it we can clearly see that there will be an excellent signal-to-noise ratio when compared to –102.2 dBm minimum detectable signal. There may even be enough excess signal to permit lowering the value of the transmitted power. This tradeoff can be made once we evaluate the "time on target" parameters. The antenna scan rate, FM sweep rate, and number of radar interrogations per beam position all influence the amount of detectable power from a given target. By choosing a probability of detection, we can then finalize the value of the transmitted power.

Table 3-2. The detected radar signal from a motorcycle located at various points in Figure 2-1.

Point	Detected Power (dBm)	Range (m)
A	-79.3	47.6
B	-66.5	32.2
C	-68.1	25.0
D	-75.6	40.5
E	-63.9	29.1
F	-65.6	22.8
G	-66.9	43.6
H	-65.0	30.3
I	-77.3	23.9

3.2 Inclement Weather Performance

The detected power calculated above will be minimally affected by inclement atmospheric conditions such as fog, smoke or dust. Both Figure 3-3 and Table 3-3 attest to that.

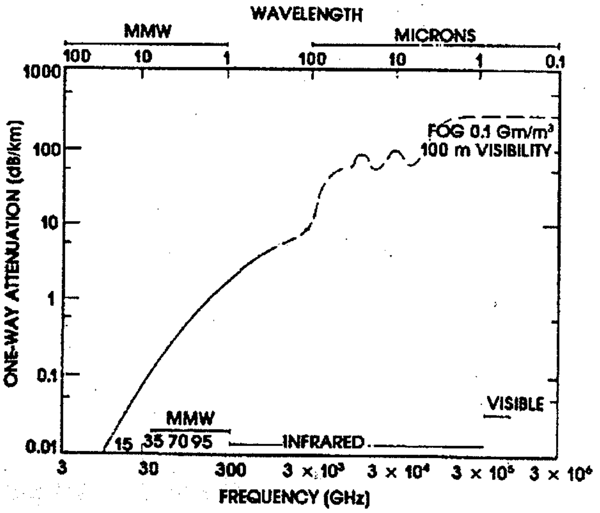


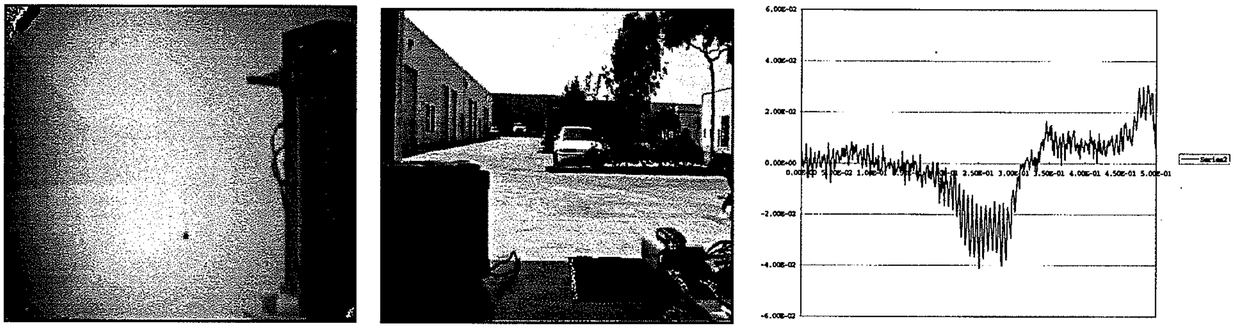
Figure 3-3. Foggy atmosphere attenuation spectrum.*

Table 3-3. Worst case attenuation for different obscurants.*

Max Attenuation dB/km			
Atmospheric Obscurant	Visible/IR	35 GHz	95 GHz
Fog	86	0.4	1.7
Snow	52	4	4
Dust	17	Negligible	

Notice that the MMW railroad sensor operates at up to 60 m range, so that even a worst-case 4 dB/km attenuation in snow translates into no more than a 0.3 dB loss. This small degradation does not affect very much the probability of detection as calculated in Section 6.2 (see Figure 6-9).

In addition, WaveBand has simulated a foggy condition using an artificial fog generator. As seen from Figure 3-4, MMW radar return from the target remains unhampered by the fog. The same is true for the MMW imaging through dust. The images in Figure 3-5 have been taken in the desert when a wind raised a cloud of dust. Both a person and a wire remain detectable.



IR Image | Scene | MMW Scan

Figure 3-4. Artificially generated fog obscures the IR image of the car, however, its MMW image (the dip at the center of the scan) remains unaffected.

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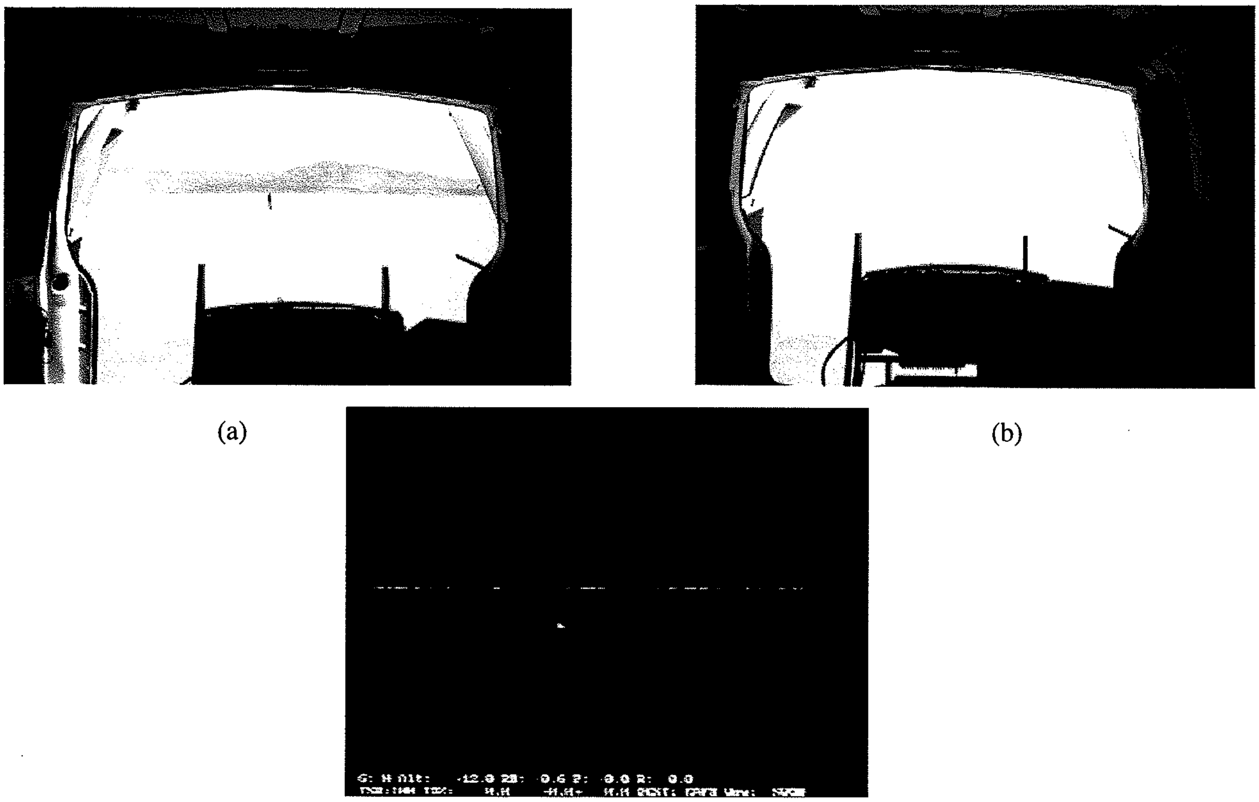
* L.A. Klein, *Millimeter-wave and Infrared Multisensor Design and Signal Processing*, Artech House, Boston, MA, 1997.



(a)

(b)

(c)

Figure 3-5. A MMW image of a 1 cm diameter wire at 500 m (c) is generated through a "no visibility" dust cloud, (b). The actual scene, with the power line at the foot of the mountain is shown in (a). There is a person at a distance of 300 m.

4.0 SYSTEM DESIGN

4.1 Antenna

In this section, WaveBand will provide some of the detailed analysis that went into converting system performance parameters into antenna requirements. The system parameters were presented in the previous section. A sensor system block diagram is provided for reference in Figure 4-1.

The antenna consists of a rotating drum that contains a grating designed to create a beam of the desired shape and scanning angles. Millimeter wave energy from the transmitter is coupled to a dielectric waveguide placed in proximity to the drum. Energy is coupled from the waveguide and directed toward a parabolic reflector that shapes the resulting beam in the elevation plane. The drum is rotated by a dc motor at a constant rate, which in turn causes the generated beam to scan in the horizontal plane. The constituent parts of the antenna are shown in Figure 4-2.

The detailed antenna analysis, much of which is proprietary and is included as Appendix A, provides the design criteria for the drum size and shape, the grating period and pattern, the spacing between the drum and dielectric waveguide, and the parabolic reflector size, shape and spacing. The resulting antenna beam pattern meets the requirements of the system performance. The results of the analysis are translated into a drawing package that is used in the manufacturing process.

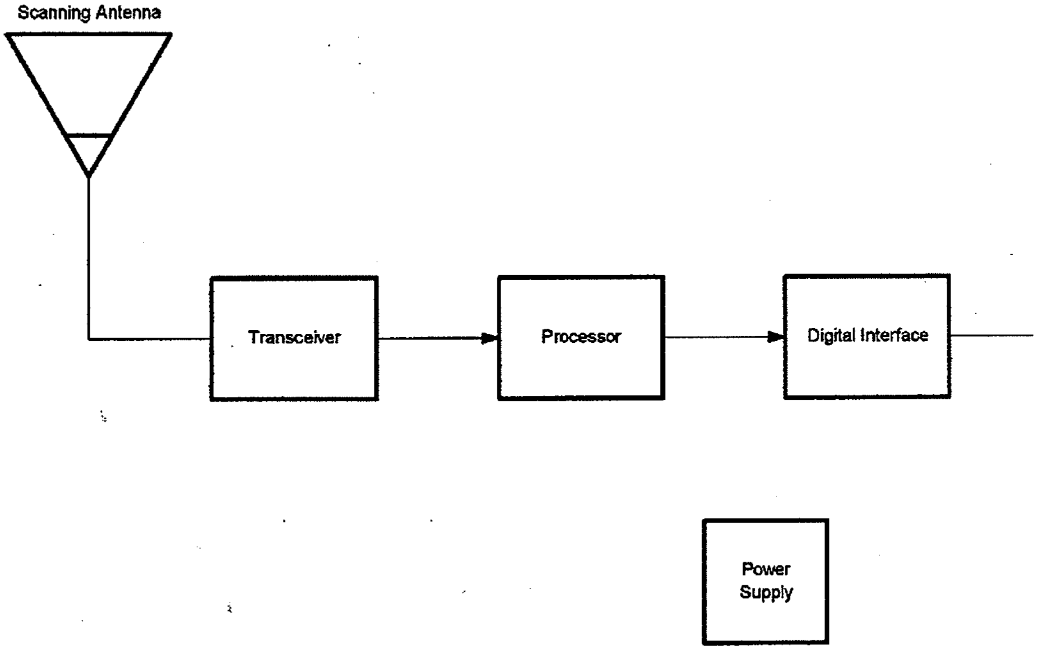


Figure 4-1. Sensor block diagram.

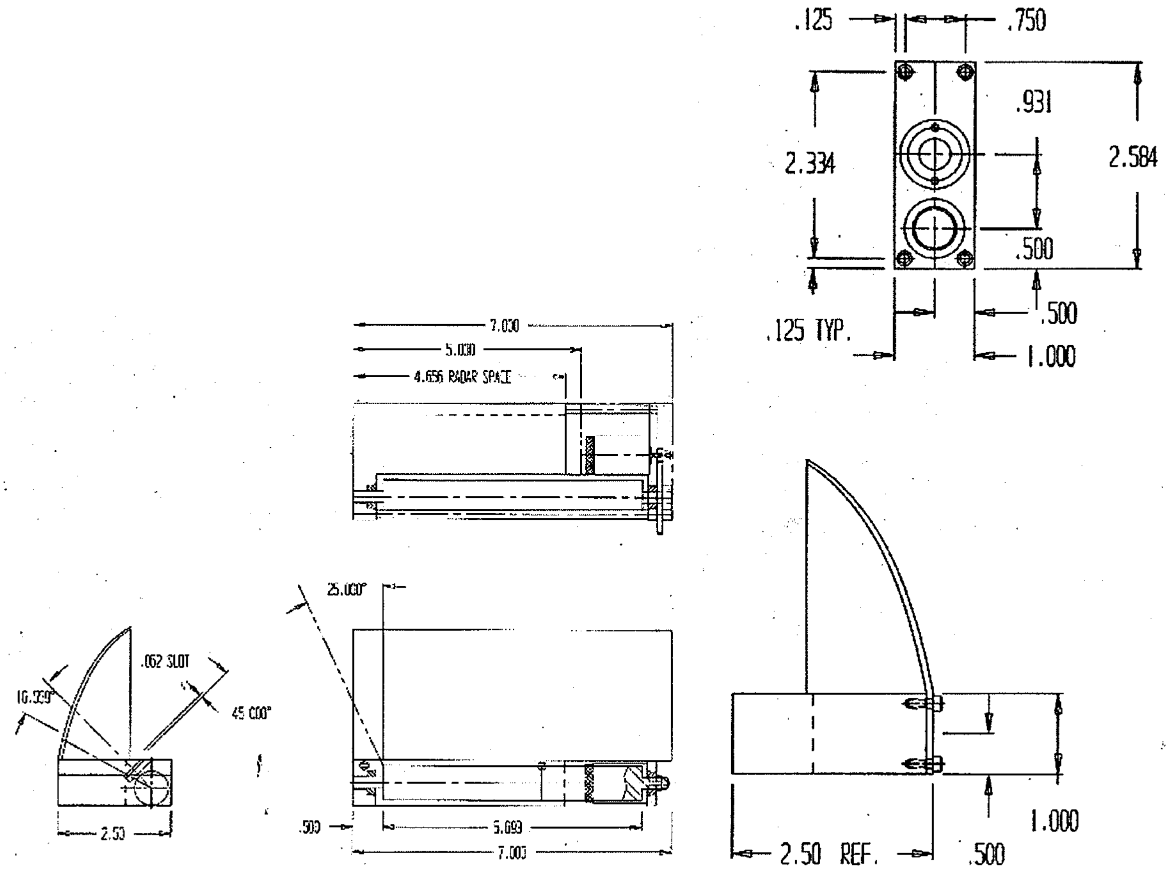


Figure 4-2Antenna drawing.

4.2 Transmitter/Receiver

The transmitter/receiver (transceiver), a key element in the sensor, has been designed, fabricated and tested. It is pictured in Figure 4-3.

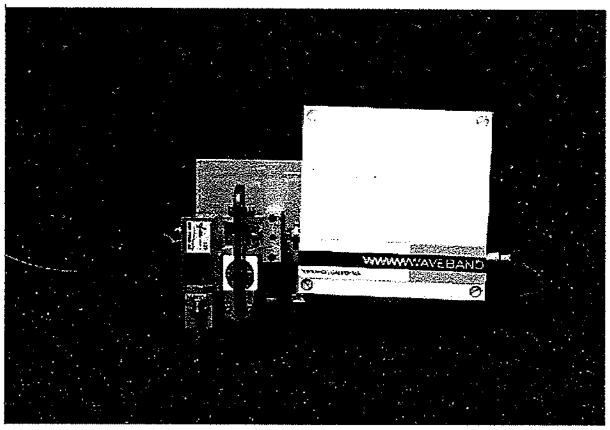


Figure 4-3. Photograph of the transceiver.

The transmitter, shown schematically in Figure 4-4, uses a Gunn diode oscillator operating at a nominal frequency of 76.5 GHz. The diode is frequency modulated with a triangular sweep signal. It is this modulation that allows the sensor to measure the range to an obstacle. In order to maintain the appropriate range resolution and accuracy, a linearizer is applied to the sweep signal. A coupled sample of the oscillator signal is mixed with a reference signal in a harmonic mixer to generate an error signal for the linearizer. The transmitter output is approximately 10 milliwatts.

The receiver, also shown schematically in Figure 4-4, is a balanced mixer that uses a sample of the transmitted signal as the local oscillator drive signal. The output of the mixer is the radar information containing range and velocity information on all obstacles detected in the antenna beam.

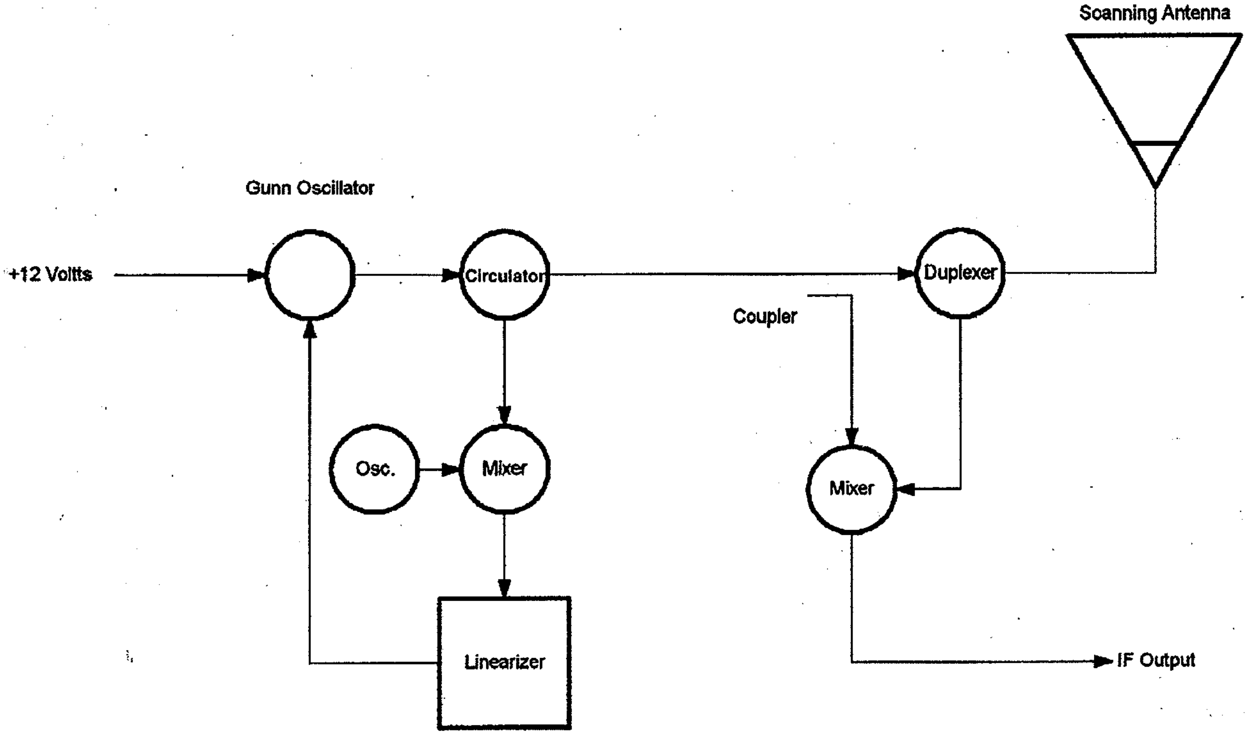


Figure 4-4. Transceiver schematic.

4.3 Processor

The processor has three basic functions: that of converting the raw radar data to computer usable information, of determining whether the resulting information represents an obstacle, and formatting the data for the interface board. While radar signal processors are not new or unusual, processors that can easily be packaged for use in an outdoor environment are not off-the-shelf. WaveBand's original intention for this program was to adapt a processor that was previously used in a Department of Transportation automotive radar test program. This processor, made by Sensor Technologies and Systems, Inc. (STS) is a perfect fit for this program. The only modifications needed are to reduce it in size from a 19" rack-mounted set of boards to a set that is compatible with a much smaller package while at the same time deleting functions that were peculiar to the automotive testing program. Unfortunately, our current funding could not support this effort.

As a result, WaveBand utilized a reduced throughput capacity processor from STS (see Figure 4-5 for a functional block diagram). WaveBand feels that the processor performs most of the required functions. The critical issue is the throughput. The ability to operate the system in a real-time environment may be marginal. If we used the processor originally intended, we feel confident the system could have performed in real-time.

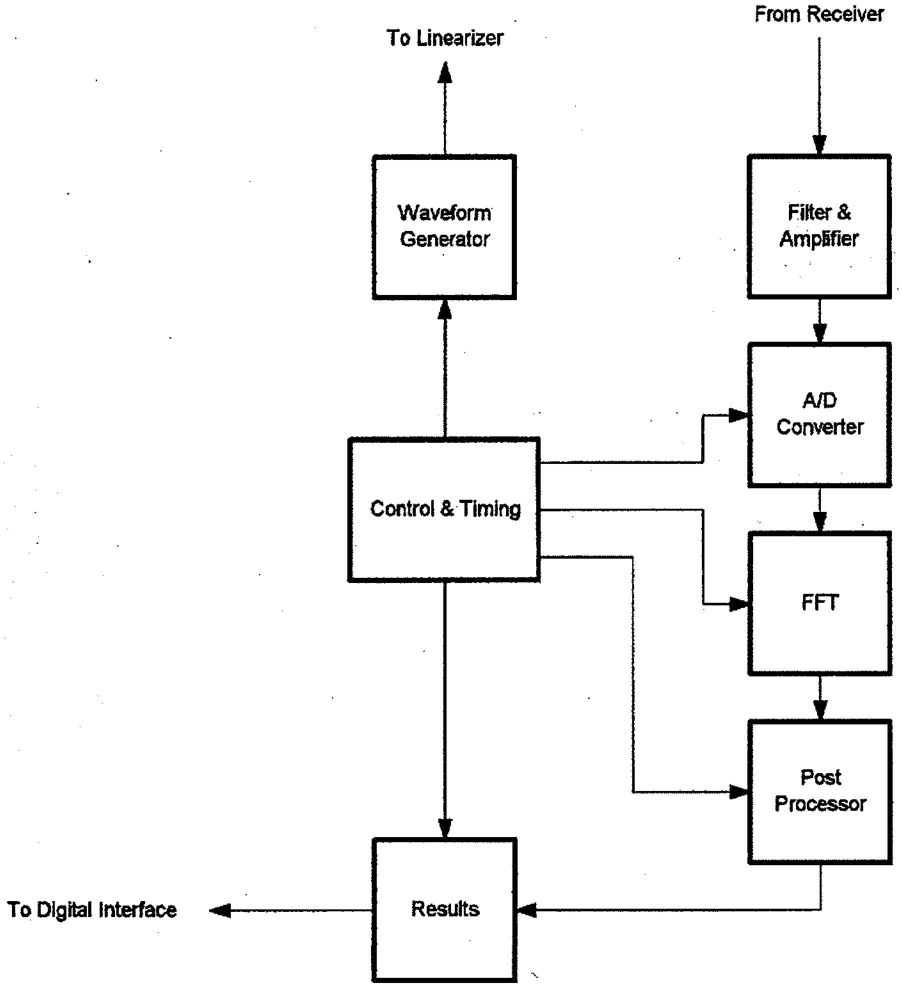


Figure 4-5. Processor functional block diagram.

4.4 Digital Interface

The digital interface is used to transfer data to the quad gate controllers such as the one designed by Rail Safety Engineering (RSE). The interface must also accept commands from the controller.

WaveBand has provided RSE with a "Vehicle Presence Status Is" message that was compatible with ITS standard digital interface (Table 4-1).

Table 4-1. Top-level message format.

Byte#	**Value(s)**	**ATCS Usage**
0	EEh	Source: Dest. Address length in Digits
1-6	00 00 00 00 00 00	Destination Address Digits #1 - #13
7	Valid range is 00h through 08h	Destination Address Digit #14
8-13	00 00 00 00 00 00	Source Address Digits #1 - #13
14	Valid range is 00h through 08h	Source Address Digit #14
15	00h	Facility Length Field
16	00h	Message Number
17	02h	Part number
18	03h	Message Length
19	00h	Message Label (High)
20	00h	Message Label (Low)
21	00h	Message Version Number
22-120	See QGC-iRS-2.1.3.2	Application Message Data
121-124	00h	Presentation (vital) CRC bytes
125-128	See QGC-IRS-2.1.3.3	Transport (vital) CRC bytes

The corresponding QGC-IRS lines are provided for reference.

QGC-IRS-2.1.3.2 Application Message Data General Format (Bytes 22-120)

- Byte 22 of the ATCS layer 4 packet begins the application message data. The general format of the messages is as follows:

!<Command>[~,Data>] <CR> <LF>

Where:

!	Is a header byte that identifies the start of a message.
<Command>	Is any of the valid 2-byte commands.
~	Is a field separator preceding every data field.
<Data>	Is a message-specific multiple byte binary data field, MSB first.
<DR><LF>	Is the message terminator (ASCII characters 0Dh and 0Ah respectively.

Any unused bytes following this application message shall be padded with 0's out to and including byte 120 of the ATCS layer 4 Packet.

QGC-IRS-2.1.3.3 Transport (Vital) CRC (Bytes 125-128) – A 32-bit vital CRC is stored in the last four bytes of the packet, most significant byte first. This code shall be calculated on packet bytes 0-120 and included in all packets. The polynomial for this code is:

$$1+x^{7}+x^{9}+x^{11}+x^{15}+x^{16}+x^{18}+x^{19}+x^{25}+x^{28}+x^{30}+x^{31}$$

The status message is specified in Table 4-2.

Table 4-2. Vehicle Presence Status Is Command Structure.

"Vehicle Presence Status Is" Field Name	Purpose	Byte Value(s) or Range
Header	Identifies the start of the message	! (21h)
Command	Instruction	SV (53h, 56h)
Separator	Field separator	~
Vehicle Present / Absent	Indicates the current presence or absence of a vehicle as detected by the device.	00h = Absent 01h = Present
Message Terminator	Carriage return / linefeed	0Dh, 0Ah

The developed message C-code is supplied in Appendix B.

5.0 FIELD DEMONSTRATION

The system needed for field demonstration included a radar from Marconi Astronics. This allowed us to do simultaneous video and MMW sensor recording. The demonstration was performed at a quad gate crossing in Los Angeles (Fig. 5-1).

Figure 5-1. Quad gate crossing at the intersection of Willowbrook and 124th Street.

The crossing layout is shown in Figure 3-1. It is heavily populated with metal constructions as partially seen in Figure 5-2 (posts, fences, manhole covers, etc.).

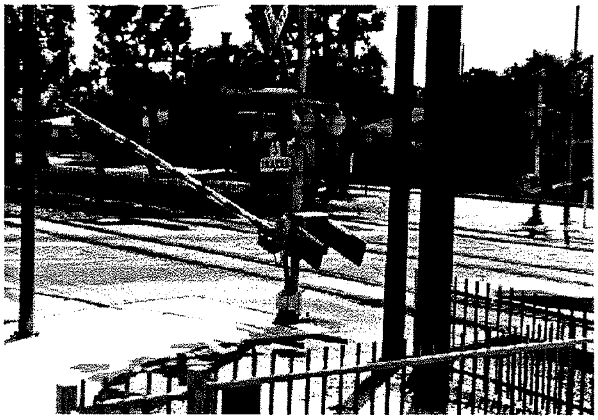


Figure 5-2. Quad gate crossing metal structures.

They generate stationary radar signal returns and were eliminated from the display using a novelty filter and a set of masks. Some of them can be used as reference points to calibrate the sensor and to establish its operational status.

The crossing was passed by trains from both directions (Figure 5-3).

(a) (b)

Figure 5-3. East (a) and westbound (b) trains passing through the crossing

Indeed, trains were the first targets to be detected as shown in Figures 5-4 to 5-6. Two items are important to note in evaluating sensor operation in this test. First, that the sensor was agile enough to build several images of a high-speed train (a total of six while the train was in the sensor's field of view). From these images one can estimate that the train speed was about 60 miles per hour.

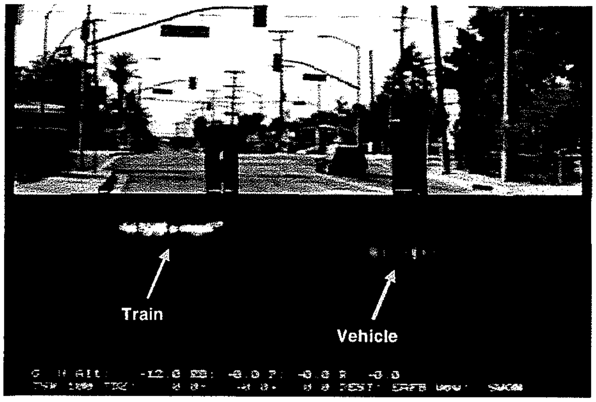


Figure 5-4. A train entering the crossing. The upper picture is the image of the scene, while the lower one is the processed radar display.

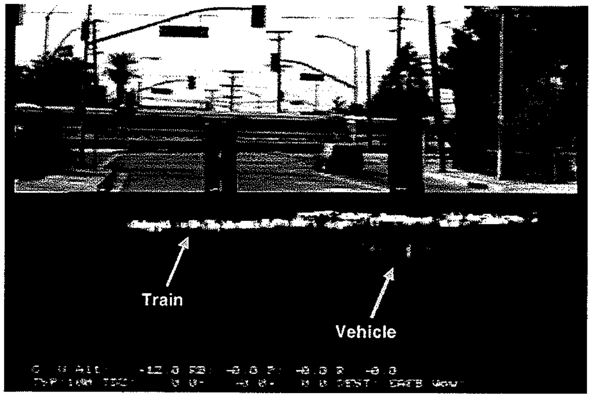


Figure 5-5. Full length of the train proceeding through the crossing.

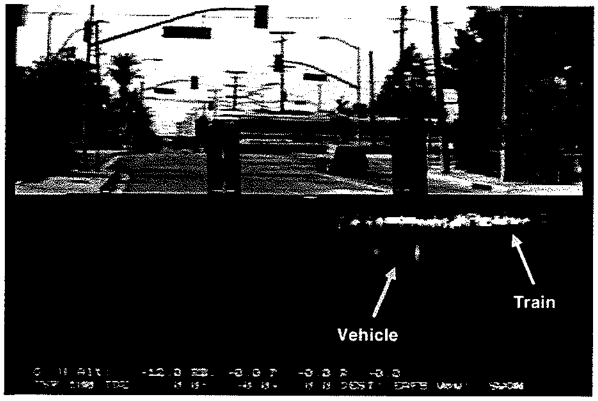


Figure 5-6. The train exiting the crossing.

The Doppler processor that was available with the test system was capable of determining the direction of the train movement. It was however, not activated this time. Second, is the large dynamic range of the sensor. Despite very large radar cross-section (RCS) of the train, vehicles stopped at the gate were well detected. This is partially due to a good range resolution available from the sensor (range is shown as a vertical coordinate on the radar display, while horizontal coordinate is the same as in the video image).

As suggested by the Project Manager, we looked at the detection of the gates themselves. Although characterized by a very low RCS they were detected in the process of being lowered, (Figure 5-7). The vertical coordinate indicates the range to the target. Thus, the gate being lowered and the gate completely lowered occur at about the same position on the display. The only observed difference was in the strength of the signal, which can eventually be used to identify the gate position.

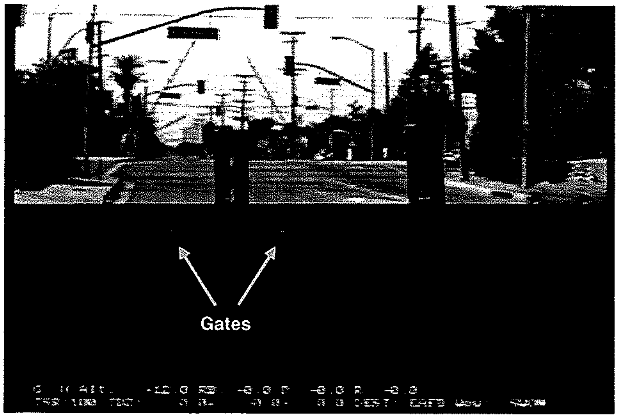


Figure 5-7. Detecting lowering of the gate by the MWW sensor.

The main goal of the field-testing was to demonstrate the detection of various vehicles at the crossing. We collected over 15 minutes of radar data, some of which have been digitized, combined with the corresponding synchronized video image and are presented with this report.

A large truck both at the crossing (Figure 5-8) and outside of it (Figure 5-9) gives an ample signal. Again as indicated before, the range from the sensor to the target displayed as the vertical coordinate of the display provides us with the exact position of the vehicle, so that its location in the danger area between the gates is determined (Figure 5-8).

Moreover, due to the high sensor resolution different parts of the truck are identified so even a partial blockage by the truck can be detected (Figure 5-9).

The same high resolution permits detection of multiple vehicles simultaneously as indicated by Figure 5-10.

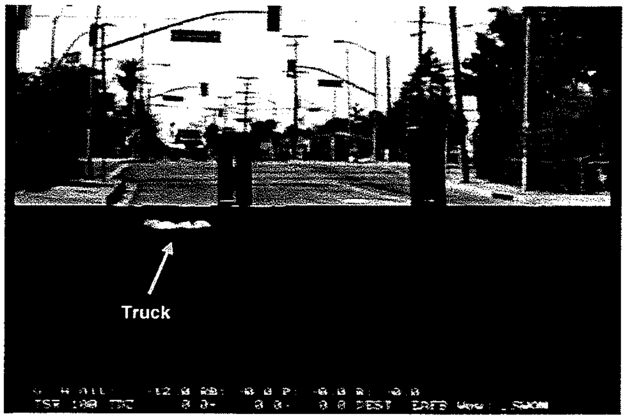


Figure 5-8. A truck is detected in the danger zone between the gates.

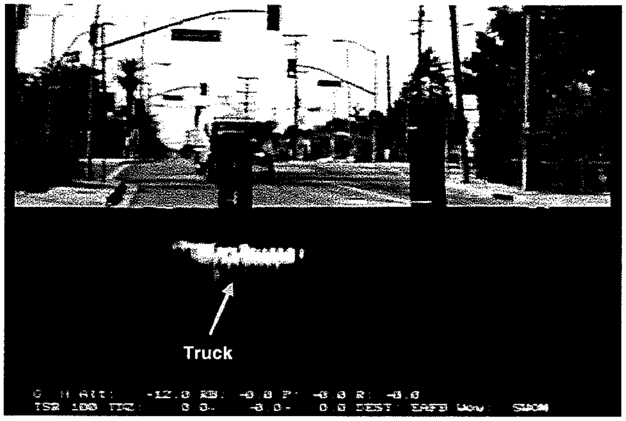


Figure 5-9. The rear of the truck is still in the danger zone while the rest is out.

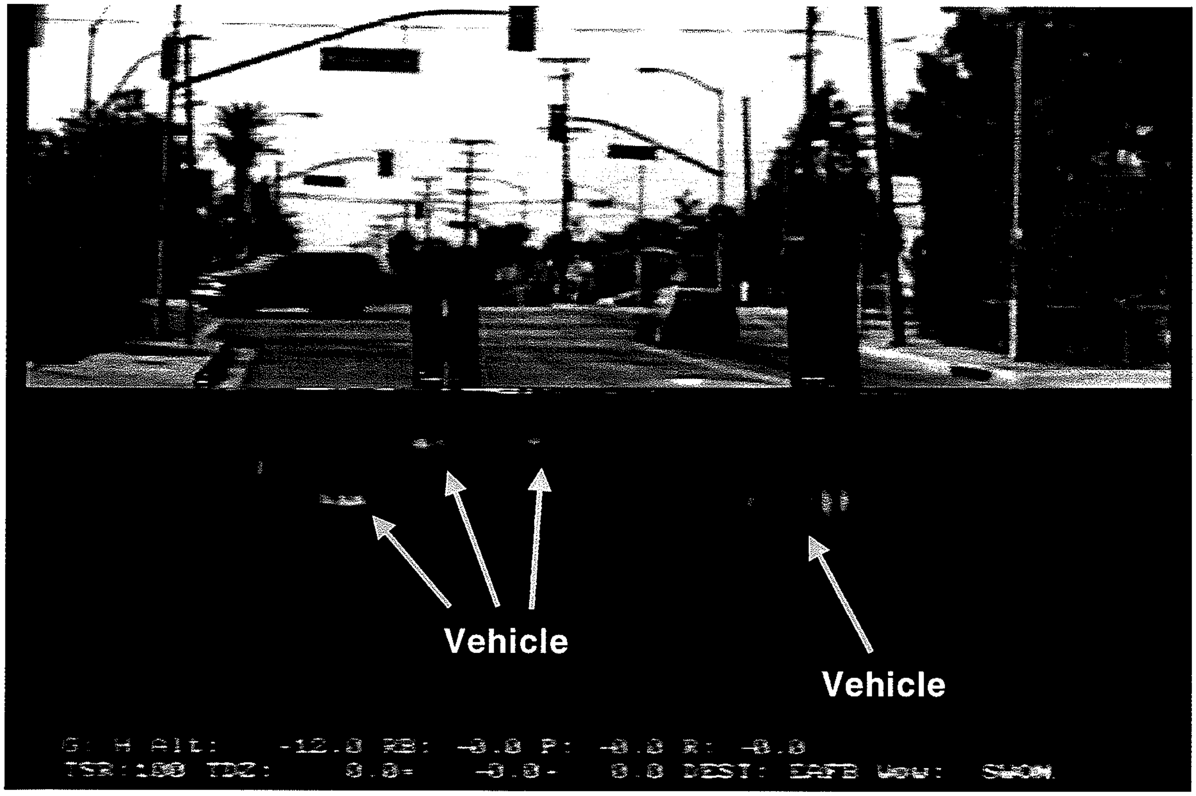
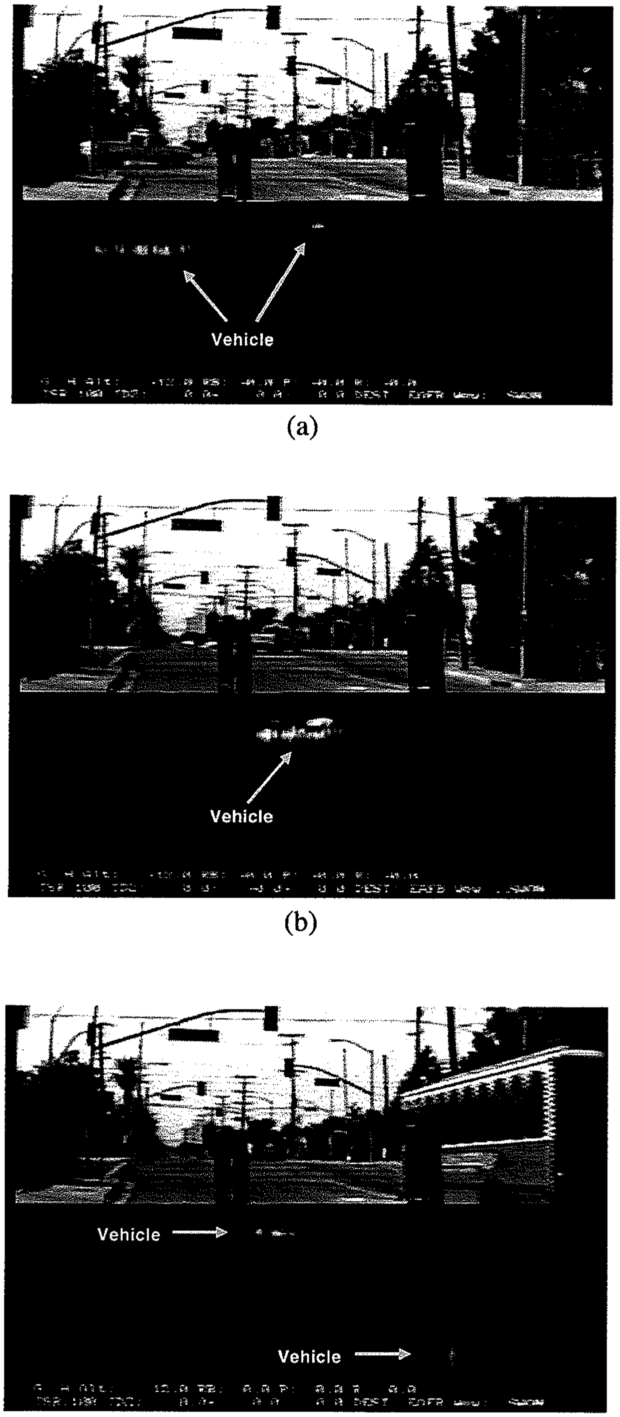


Figure 5-10. Multiple vehicle detection.

The same is true for the vehicle making a turn into the crossing. By comparing the vehicle RCS in the sequence of radar frames (Figure 5-11) the sensor's processor can potentially deduce the vehicle's orientation.



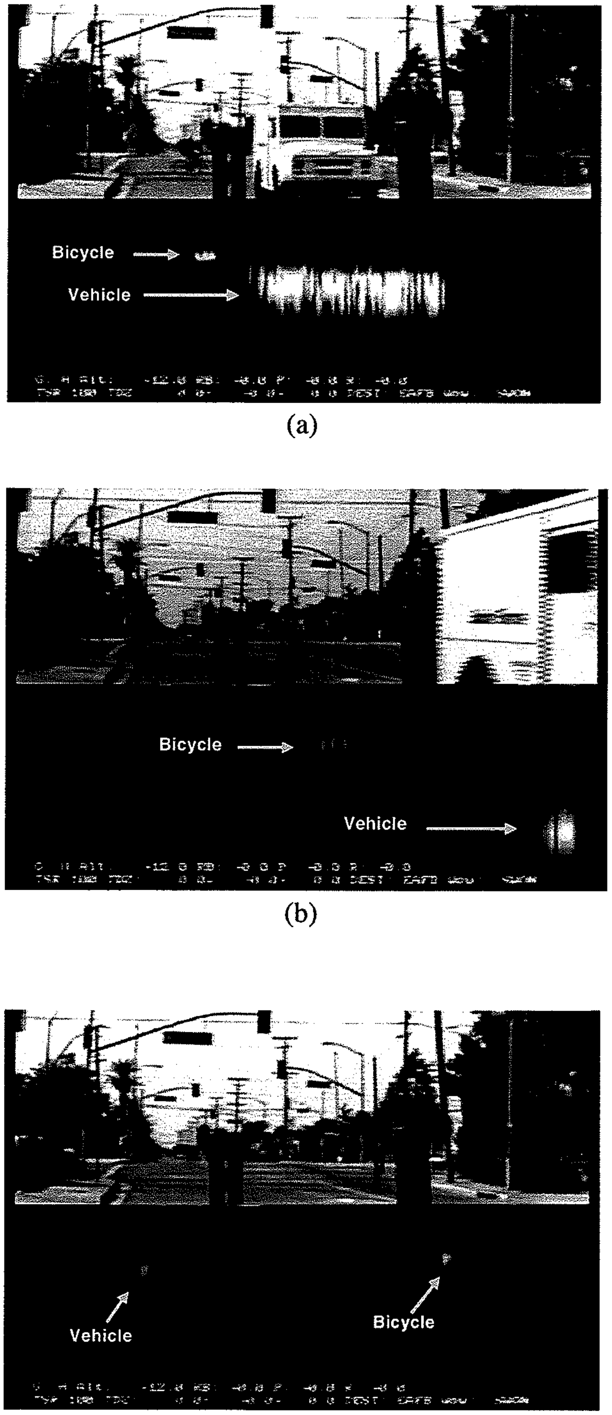
(a)

(b)

(c)

Figure 5-11. A vehicle turning left (a, b, c) at the crossing.

Finally a small target such as a bicycle can be reliable detected as seen from Figure 5-12. This is accomplished even in the presence of a large vehicle.



(a)

(b)

(c)

Figure 5-12. A bicycle is detected (a, b, c) at the crossing.

6.0 DATA ANALYSIS

6.1 Probability of Detection

As with any radar system it is important to identify the probability of detection (Pd) for the MMW grade crossing sensor. With the assumption of the system specified in Table 6-1.

Table 6-1. Target Radar Parameters

Radar Parameter	Value(s)	Units
Type	FMCW	
Frequency	76.5	GHz
Power	2	milliWatts
Target RCS	0.1, 1.0, 10.0, 100.0	meters^2
Antenna Gain	37	dBi
Clear Air Attenuation	0.6	dB/km
40 mm/hr Rain Attenuation	15.0	dB/km
Transmit Losses	1.0	dB
Radome Loss	0.5	dB (one way)
Receive Losses	1.0	dB
Bandwidth	300	MHz
Signal Processing Gain	12	dB
Noise Figure	8.5	dB
Pfa	10^{-6}	
Target Fluctuation Model	Swerling I	
Detection Method	M of N	

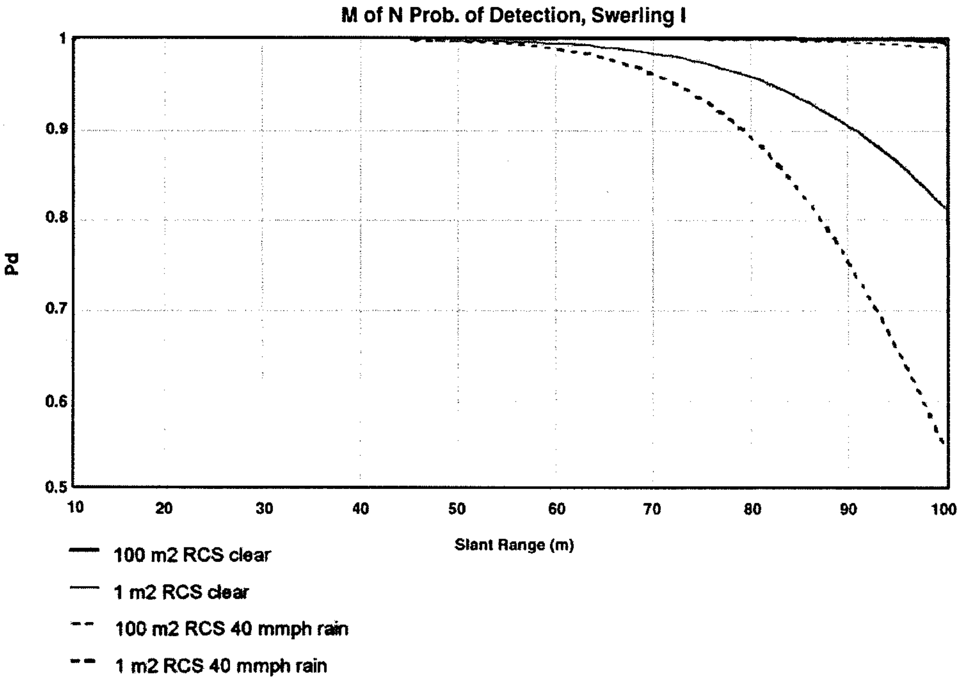


Figure 6-1. Detection performance of the proposed radar sensor.

The calculated probability of detection is shown in Figure 6-1.

It is seen from these calculations that within the 60 m range close to 99% Pd can be obtained even for a small CS target in adverse weather.

6.2 Field Demonstration Data Analysis

The probability of detection can be also estimated from the data collected during the demonstration. The signal processor described in Section 4.3 along with the embedded signal processing software generates a data file that contains coordinates (range and angle, or cross range) of all targets in the sensor's field of view. The file is updated with every scan or alternatively can be stored for further integration (comparison) with other frames. Figure 6-2 shows unprocessed one frame data arranged for the rectangular B-scope display.

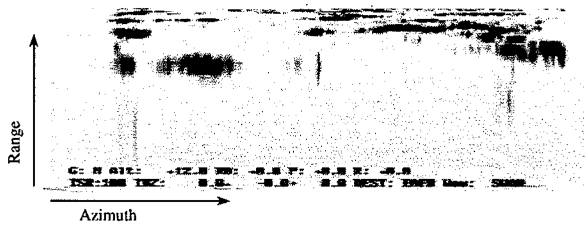


Figure 6-2. Unprocessed MMW image of the crossing. The gray scale (inverted) corresponds to the intensity of the radar return.

The inverted data can be conveniently used as a novelty filter to cancel out all radar returns from the crossing itself, so that only new targets (obstacles) will be considered. This has been done to obtain images in Figures 5-4 to 5-12. Prior to filtering, one can apply a simple masking to window out the monitored area only (see Figure 3-1). As this may vary from installation to installation such a digital mask can be adjusted based on the crossing geometry. Figure 6-3 shows a windowed out baseline image.

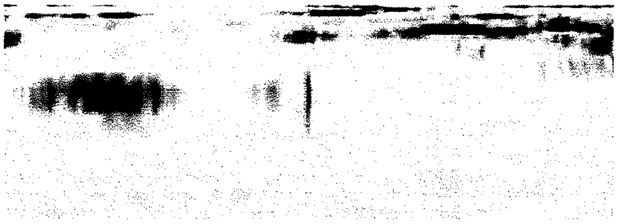


Figure 6-3. MMW baseline image (inverted) of the monitored area.

Its digital 3D plot is shown in Figure 6-4.

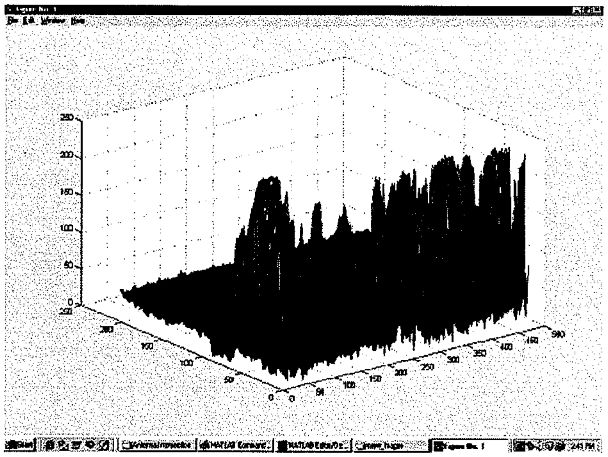


Figure 6-4. 3D intensity plot of the range/azimuth radar image.

This file can be used for any further data processing.

As an example, we consider the smallest RCS target we have detected during the test – a bicyclist (Figure 5-12). Once the novelty filter and the mask is applied the resulted MMW image and the corresponding 3D plot are as seen from Figure 6-5 and Figure 6-6 respectively.

Figure 6-5. Singled out MMW radar return from a bicyclist.

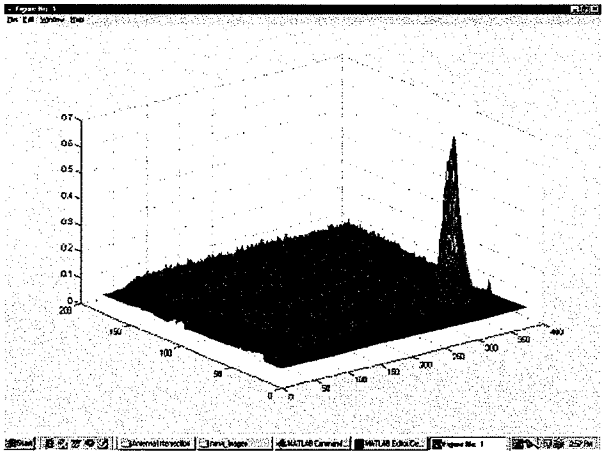


Figure 6-6. 3D rendering of a radar return signal as in Figure 6-5.

The available data file can be used to calculate signal-to-noise ratio (SNR). The nose figure can be derived from a single scan line as in Figure 6-7.

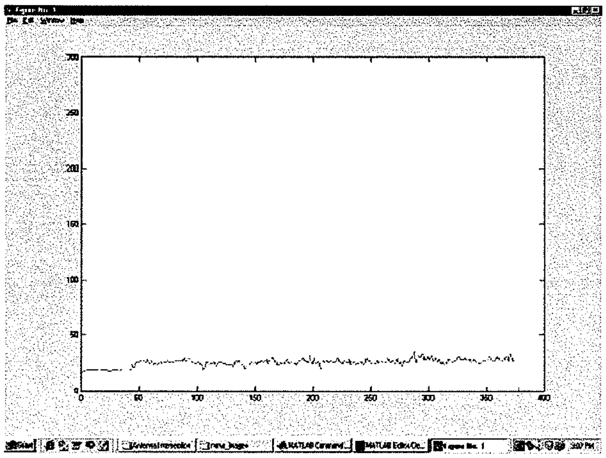


Figure 6-7. Noise level data.

At the same time a scan containing the target is used to estimate the signal (Figure 6-8).

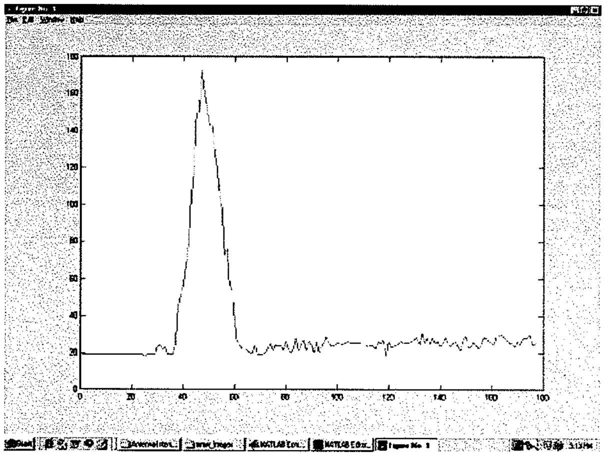


Figure 6-8. A line scan across the target (a bicyclist).

Resulting SNr = 17.5dB calculated as he signal peak value to rms noise ratio allows to achieve close to 99% probability of detection as seen from a diagram in Figure 6-9.

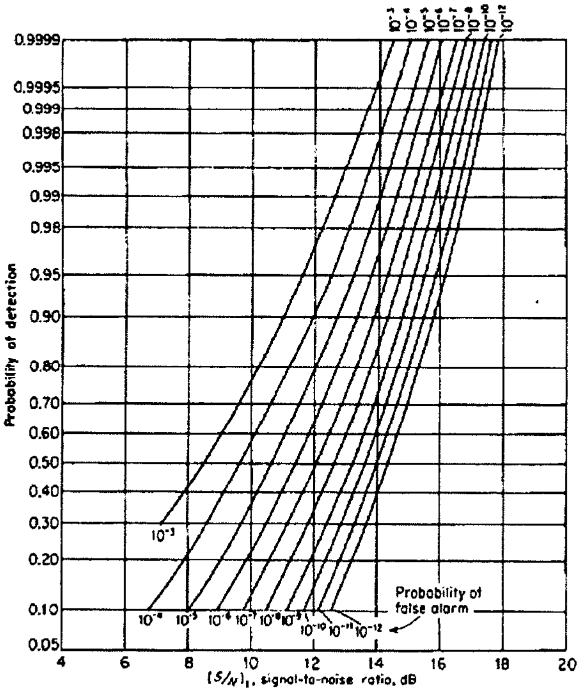


Figure. 6-9. Rise Curves for Single Hit, Non-Fluctuating Target (from M. Skolnik, 1980. McGraw Hill Company).

7.0 CONCLUSIONS

WaveBand has accomplished the project objectives by

- Introducing MMW radar as a grade crossing sensor
- Introducing a novel, fast scanning MMW antenna as the key element of the radar system
- Providing a radar system design amenable to cost-effective production
- Integrating the radar system with the antenna
- Providing the "Vehicle Status Is" signal generating code according to RSE requirements
- Demonstrating the MMW radar system capability to detect:

- Vehicles and bicycles in the danger area of the crossing (area to be monitored as in Figure 3-1)
- Vehicular motion through the crossing, including vehicle orientation
- Multiple vehicle situation
- Large trucks partially in the danger area
- Passing high-speed trains
- Lowering or lowered gates

Determining the eventual system requirement as summarized in Table 7-1.

Table 7-1. Requirements

Requirement Item	**Specification**	**Comments**
Frequency Band	W-band	76.5 GHz +/- 200 MHz desired in order to benefit from automotive radar development
EIRP	Max 10 W	10 W max for detection of 1 m^2 RCS target at 50 m
Useful Range	40 meters	For 1 m^2 RCS with 3 out of 4 detection schemes. Probability of detection (P_d) is > 99% at 50 meters. Range performance increases with increasing RCS.
Range resolution	0.8 meter	Linear frequency modulation bandwidth of 400 MHz provides 0.8 m resolution
Range accuracy	+/- 0.4 meter	Linear frequency modulation bandwidth of 400 MHz provides 0.8 m resolution
Search Area	20 m x 40 m 3 detections of an object in 4 seconds	Provides 90 degree scan width and 90 deg/sec scan rate allowing 4 independent detection opportunities within a 4 second decision interval
Target RCS	Physical size = 0.125 $meter^2$	Parametric analysis indicates range and P_d specifications met for 1 m^2 and greater RCS targets.
Angular resolution	0.8 degrees	0.8 degrees both ways
Angular Accuracy	+/- 0.4 degrees	+/- 0.4 degrees
Az/El Beamwidth	2 degrees	Az BW = 1 deg, El BW = 2 deg
Adverse Weather	Minimize effects of rain, hail, snow and fog	Range and Pd performance met in 40 mm/hr rain. Hail, snow, and fog conditions are generally not as demanding as heavy rain.
Maximum Power Consumption	25 W	Within specification.
Input Voltage	12 Vdc or 36Vdc	12 Vdc
Interface	Ethernet	1 Mbps Ethernet supported
Software Items	External Interface Requirements from RSE	The latest available Rev. 1.0, July 1999

In the future, the sensor could be configured to provide an inexpensive in-vehicle alert signal for high occupancy and priority vehicles. This would permit a signal to be broadcast to vehicles equipped with simple inexpensive detection circuits, analogous to the transponders now being put into use for toll roads, and alert the driver that the crossing is active.