

High-Speed Rail IDEA Program

Innovative Scanning Antenna Systems for Advanced Recognition of Rail Collision, Obstacle Detection and Automobile Collision Avoidance

Final Report for High-Speed Rail IDEA Project HSR-1

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**IDEA Program Final Report
for the Period October 1995 Through October 1996
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**“Innovative Scanning Antenna Systems for Advanced Recognition
of Rail Collision, Obstacle Detection and
Automobile Collision Avoidance”**

**Prepared for
the IDEA Program
Transportation Research Board
National Research Council**

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EXECUTIVE SUMMARY

The innovative Spinning GratingTM Antenna developed as a result of this project is a low-cost millimeter wave (MMW) antenna that can be applied to collision avoidance systems for both railroads and automobiles. The antenna is unique in that it uses the optical phenomenon of diffraction to define and steer a beam of MMW energy. Unlike electronically steered antennas and more traditional gimballed antennas, the Spinning GratingTM antenna (see Figure ES-1) is both low in cost and reliable, ideal features for the transportation market. This technology was first developed for radar imaging systems for aircraft autonomous landing guidance.

FIGURE ES-1. Spinning GratingTM Antenna for application to the transportation industry.

In the rail industry, the focus of the project was on the application of the antenna to MMW sensors that can reliably detect the presence of an object in the path of a train resulting in action that can be taken to prevent a collision. One application of this nature is shown in Figure ES-2.

FIGURE ES-2. Obstacle detection radar for application to grade crossings.

In the automotive industry, MMW sensor systems used for collision warning functions and intelligent cruise control are already available for limited markets. Low-cost scanning antennas are expected to hasten the acceptance of these systems to the automotive consumer.

Spinning GratingTM antennas operating at 76.5 GHz were designed and manufactured for tests with radar systems in applications relevant to both the rail industry and the automotive industry. Since the automotive industry has been studying methods of reducing automobile collisions for several years, through the Intelligent Transportation Systems program and others, a stronger consensus on system needs and requirements was available to work with. Therefore, an antenna was designed to meet those requirements and then provided to Frontier Engineering Sciences for use on their DOT sponsored collision avoidance, intelligent cruise control test bed vehicle. Test data from the Frontier program is expected to become available in mid 1997.

For the railroad industry, our attention was turned to the issue of collisions at grade crossings. Both active and passive sensors were evaluated and limited tests were conducted on an active radar system using a Spinning GratingTM antenna. The data indicates that detection of vehicles and other objects at grade crossings is feasible. This promising approach should be investigated further with a more mature sensor system.

An important producibility study for high volume, low cost manufacture of the Spinning GratingTM antenna was conducted. The results are very encouraging.

IDEA PRODUCT

The unique millimeter wave (MMW) scanning antenna developed as a result of this IDEA project will result in the ability to provide low-cost radar and/or radiometric imaging systems for obstacle detection in the rail and automotive applications. Two antennas of the Spinning Grating™ type depicted in Figure 1 were produced, respectively, for the rail and automotive obstacle detection markets. One antenna was provided to Frontier Engineering Sciences for application to Automotive Collision Avoidance Radar testing sponsored by the Department of Transportation. The second antenna was integrated with a simple radar system and tested under conditions similar to those expected at a railway crossing.

FIGURE 1. Spinning Grating™ Antenna.

CONCEPT AND INNOVATION

There has been a growing interest in applying systems under development for the automotive industry to the railroad industry. Among the systems of interest are those that have the ability to detect obstacles on the right of way of the nations rail network.

To provide the spatial resolution required for obstacle detection applications, a narrow beam scanning antenna must be used with the radar. Traditional electronically steered antenna concepts are not a good solution because of their very high cost. Mechanically gimbaled antennas are unreliable, bulky and are subject to acceleration problems. For these reasons, the Spinning Grating™ antenna developed by WaveBand Corporation is ideally suited to this type of application; the antenna is inexpensive, reliable, and not bulky. The Spinning Grating™ antenna is unique in that it uses the phenomenon of diffraction to define and steer a beam of MMW energy in a very cost effective manner (see Figure 2). This technology was first devised for imaging radar systems for aircraft autonomous landing guidance systems. Reducing size while retaining performance and low cost was the major challenge during this project.

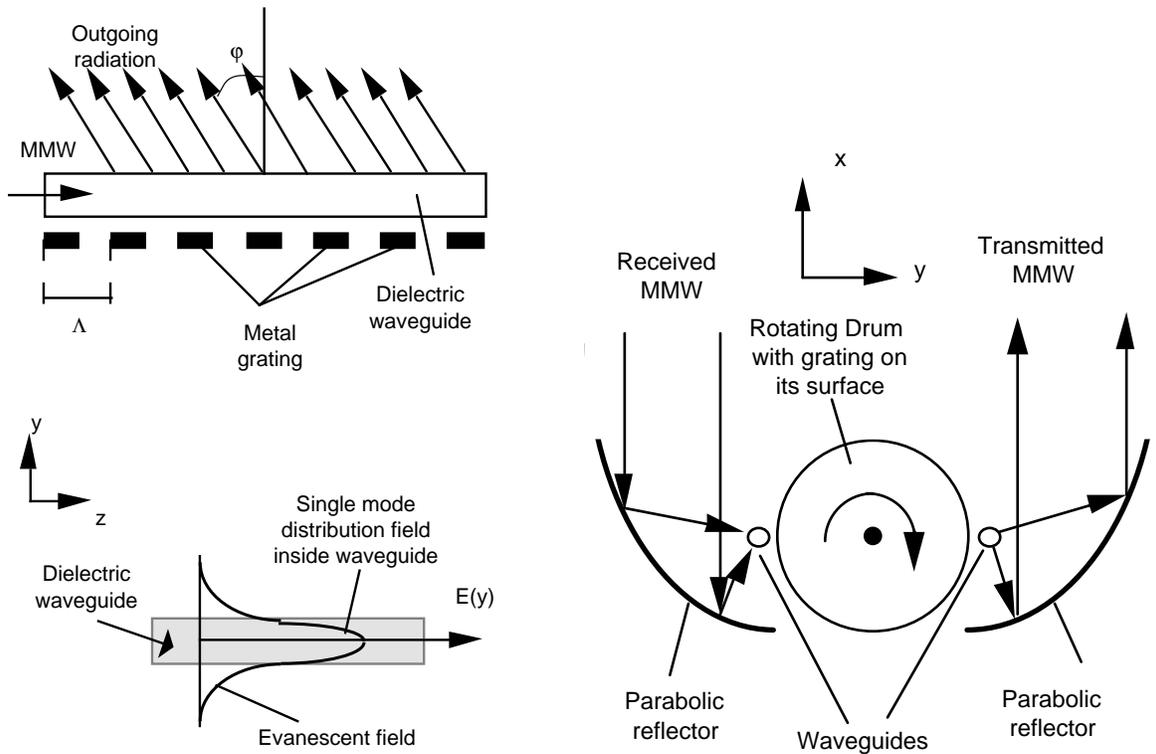


FIGURE 2. The Principles of the Spinning Grating™ Antenna.

An electromagnetic wave is propagated in a TEM mode down a dielectric waveguide. The evanescent field that extends outside the waveguide is perturbed by the presence of a metal grating. This perturbation results in energy being radiated out of the waveguide into free space. The radiation angle ϕ depends upon the grating period Λ according to the equation $\sin\phi = \beta/k_0 - p\lambda/\Lambda$ where β is the propagation constant, λ is the wavelength in free space, $k_0 = 2\pi/\lambda$, p is an integer. The direction of the radiated beam can be controlled by variation of Λ . If the grating period is made to change in a prescribed fashion as a function of time, then the direction of the radiated beam will change as a function of time. By placing the grating on the surface of a drum and rotating the drum, one or more full scan of the beam can be accomplished for each revolution of the drum. A parabolic reflector is used to provide gain and the elevation beamwidth.

INVESTIGATION

The Project started with a review of applications of millimeter wave (MMW) sensors to the general problem of detection of obstacles in the path of trains and automobiles. Considerable work had been done by several companies and Government agencies on the problem of collision avoidance for automobiles. Less had been done for the railroad industry. However, as a result of our initial review, it seemed clear that in terms of scanning MMW antennas, a common design approach could be used. As it turns out, the sensor characteristics are somewhat different for the two applications, but the antennas remain very similar. We will discuss each field separately beginning with rail applications.

APPLICATIONS OF THE SCANNING ANTENNA TO RAIL COLLISION OBSTACLE DETECTION

The initial sensor concept was a train-mounted FMCW radar operating at 76.5 GHz that would use a scanning antenna to sweep the path in front of the train and detect objects on the right-of-way in time for the engineer to take action to prevent or mitigate a collision. Meetings and conversations held with knowledgeable parties within the Department of Transportation and the industry convinced us that this would not be a suitable solution. Two compelling reasons were given: 1) It is not unusual for a freight train to weigh 6 to 10 thousand tons. With pneumatically operated brakes, stopping distances can be as much as two miles. For a large number of locations, the line of sight down the track is not that far. 2) Even if one had a long straight stretch of track, how do we determine whether or not the object detected will still be

on the track before the train arrives at that location? In other words, will we cause the crew to apply brakes needlessly in a large number of obstacle detection occurrences? In the railroad industry, as in most of the transportation industry, time is money and needless braking could be very disruptive to schedules.

As a result of this investigative work, we arrived at two other potential uses for a MMW radar sensor. The first is associated with the Advanced Train Control System (ATCS) concept. Accurate location and tracking of trains can be accomplished with the use of the Global Positioning System (GPS). However, in many cases trains are running for some appreciable time on one of a set of parallel tracks. GPS is not able to easily resolve which set of tracks a train is on under those conditions. Therefore, there is a potential for a conflict for the right of way. By using a train mounted radar, we can determine which track, of a set of parallel tracks, the train is actually on and that information could be blended with the GPS position data for reliable location of the train at any instant in time (see Figure 3). Since the radar would, in this case, be train mounted it could also measure true train speed (via Doppler measurement) and be used to calibrate the trains speedometer.

FIGURE 3. Use of MMW radar with scanning antenna to locate train on correct track.

The second concept is an “offboard” approach. Low-cost MMW radar sensors could be mounted at grade crossing locations and automatically monitor for obstacles that would be in danger of being hit by a train. The resulting information could be communicated to the train crew and/or to a crossing warning system to alert the trespasser that the arrival of a train is imminent (see Figure 4). As an additional benefit, the system would be able to ascertain that a train is still in the crossing even though the shunt circuits may indicate otherwise (which they evidently do on occasion).

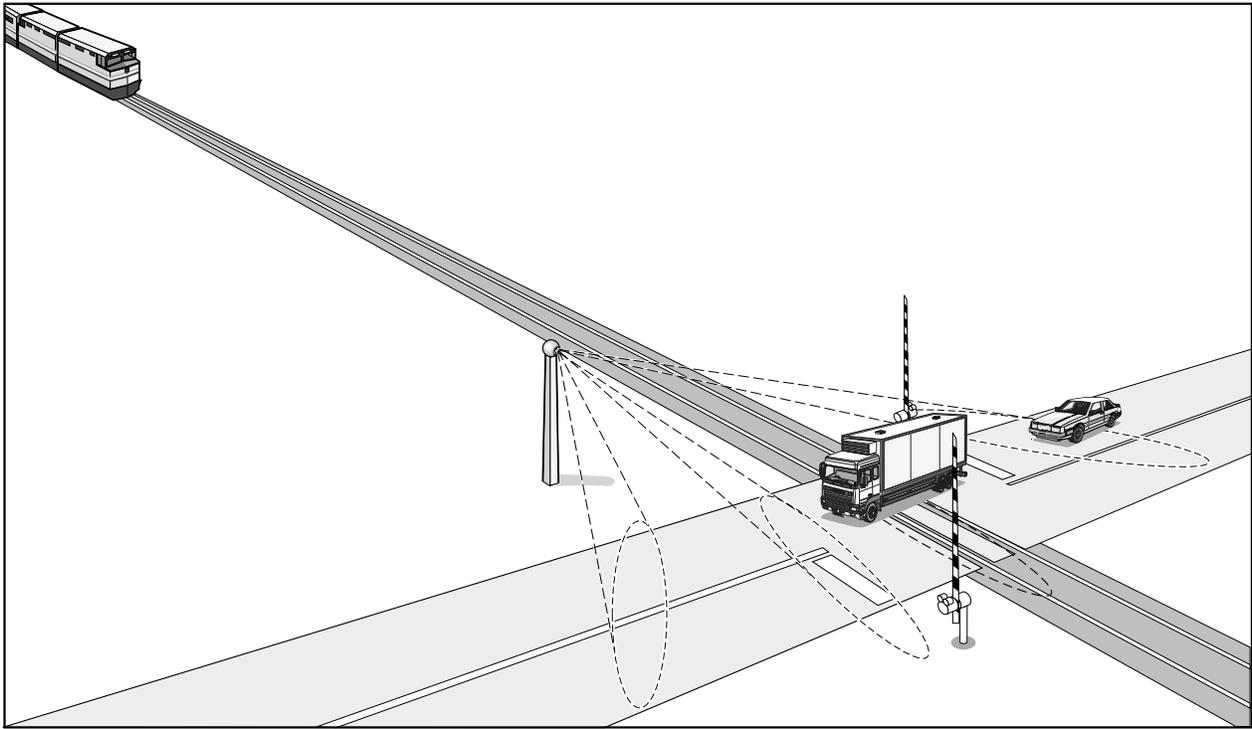


FIGURE 4. Obstacle detection radar concept for application to railroad grade crossings.

While both of these concepts were of interest to the railroad community, the grade crossing obstacle detection concept has received the most interest. While our tests indicate that radar detection of obstacles at grade crossings is feasible (discussed later in this report), the actual use of the information needs more analysis and study.

An additional sensor concept has been explored, that of using a passive MMW radiometer to image the grade crossing. There are compelling reasons for such an approach. First, the sensor has the potential of being lower in cost, a transmitter and associated power supply are not required. Second, a radiometer detects items by their apparent difference in temperature. Vehicles, in particular, have very high temperature contrasts compared to the background presented by roads, tracks, buildings, etc. Third, a passive sensor is much less susceptible to multipath and specular reflections that can be troublesome to radars. Passive sensors, however, for a given antenna size have poorer spatial resolution when compared to a radar. Data has yet to be taken with a passive sensor, but we expect that such a device would provide excellent information with respect to obstacles in the crossing.

APPLICATIONS OF THE SCANNING ANTENNA TO AUTOMOBILE COLLISION WARNING

The automotive industry has been working on the collision warning, intelligent cruise control system concept for a number of years. A weak point in systems to date has been the lack of a low-cost, reliable scanning antenna that operates in the now standard frequency band of 75 to 77 GHz. The concept for this portion of the project is to integrate a WaveBand Spinning Grating™ antenna with an automotive radar, conduct tests, and evaluate the effects on the collision warning function.

While briefing the National Highway Traffic Safety Administration, we were made aware of a DOT funded project that has as its goal the development of requirements and specifications for automotive collision warning and intelligent cruise control systems. The contractor, Frontier Engineering Sciences, is assembling a test bed using a van as the test vehicle. Frontier will install a radar system in which they have complete control of all the major parameters which influence the performance of the radar for those applications. By careful testing under a variety of controlled conditions, they will be able to define requirements for both collision warning and intelligent cruise control. From the requirements, specifications for the subsystems that make up the system can be written.

A major subsystem of either radar sensor is the scanning antenna. The WaveBand Spinning Grating™ was chosen for this important test bed application and was delivered to Frontier in early August, 1996. Tests are currently under way and the test program is scheduled to run through 1997. As a result of the selection of our antenna for the DOT test bed, WaveBand did not need to construct a radar and conduct collision warning tests.

MMW SCANNING ANTENNA

During the course of the project, two Spinning Grating™ antennas were manufactured for application to the obstacle/collision warning issues. The antennas were similar in performance, the only difference being that the unit used in the automotive application was monostatic (the transmit and receive functions share the same aperture) while the one used in the railroad application was bistatic (independent transmit and receive functions). The design parameters for the antennas are shown in Table 1.

TABLE 1. Spinning Grating™ Antenna Parameters

Parameter	Value
Center Frequency	76.5 GHz
3 dB Bandwidth	1 GHz
Azimuth Beamwidth	1.6°, Max.
Elevation Beamwidth	2.5° to 3.5°
Azimuth Field of View	+/- 8°, Min.
Azimuth Scan Rate	20 Hz
Sidelobes	<-20 dB
Transmit/receive isolation (bistatic)	>90 dB

Railroad MMW Scanning Antenna

A bistatic antenna was designed and fabricated for application to the railroad grade crossing scenario (see Figures 5 and 6). The bistatic concept selection was prompted by the need for a low-cost system, one that could get the transmit and receive function isolation by use of separate apertures. This allows the use of FMCW radars without the need for expensive duplexers and switches required by pulse radars.

FIGURE 5. Photograph of the bistatic scanning antenna designed for the railroad application.

FIGURE 6. Bistatic antenna outline drawing.

Scanning Antenna Design Considerations

The main element of the antenna is the dielectric waveguide that is loaded by a metal grating located on a spinning drum. The antenna is designed to radiate (or receive) a narrow beam with low sidelobes. These requirements suggest that the radiating element must be of sufficient length and that the intensity of the incident radiation must vary along the radiating element in a prescribed way. By computer simulation we determined the required radiation profile and the resulting beam shape (see Figures 7 and 8). The desired radiation profile can be achieved by changing the distance between the waveguide and the grating or by varying the fill factor (duty cycle) of the metal grating along the length of the waveguide.

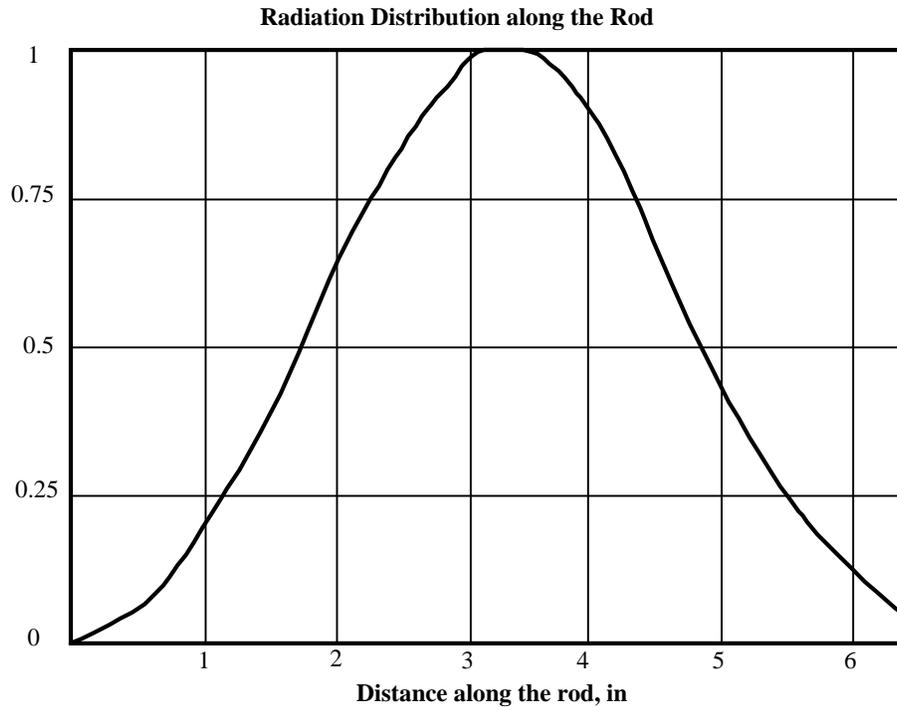


FIGURE 7. Computer simulation of the required radiation profile along the dielectric waveguide.

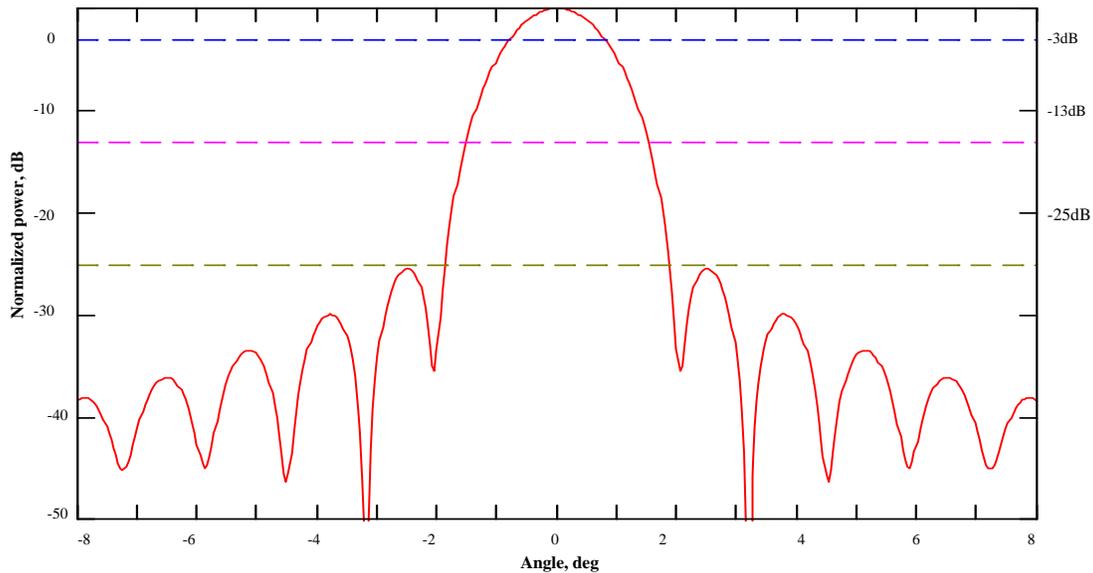


FIGURE 8. The resulting radiation pattern from the profile of Figure 7.

To choose the parameters of the grating one needs to know the propagation constant of the dielectric rod and its behavior when it is disturbed by the presence of the grating. One also needs to know the coupling efficiency as a function of the grating fill factor. Experiments were conducted to determine these parameters using the set-up shown in Figure 9. The radiating element was fed by a Gunn oscillator coupled to a 0.98 mm dielectric rod through a special low reflection transition. The other end of the dielectric rod was wrapped in absorptive foam. A grating was formed of copper on one surface of a thin Duroid sheet. The other surface was plated with solid copper to increase the antenna the efficiency. The grating period selected was $\Lambda = 2.7$ mm with the distance between the rod and grating, d , a variable parameter. Another variable was the width of the copper strip, w , that directly relates to the grating fill factor, FF , by the relationship $FF = w/\Lambda$.

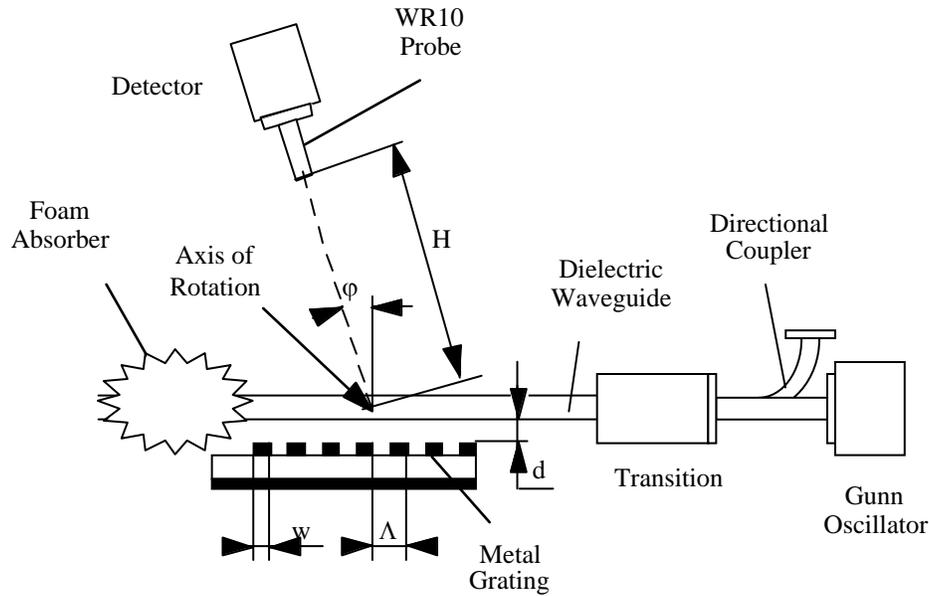


FIGURE 9. Experimental set-up for determining various antenna parameters.

The dielectric rod was set on a rotating platform with the platform's axis passing through the rod. A MMW Schottky diode detector was attached to an open WR10 waveguide that was used as a probe. The probe was located 46 cm from the rotation axis to assure that we were in far-field conditions. A directional coupler was inserted between the Gunn oscillator and the transition to monitor reflected energy (which was never more than 5%). The Gunn oscillator was modulated at 1 kHz and a lock-in amplifier was used to measure the detected signal.

A typical beam pattern is shown in Figure 10, the dependence of the radiated power on the grating fill factor is shown in Figure 11, and the dependence of the propagation constant on the grating fill factor for different gaps is shown in Figure 12.

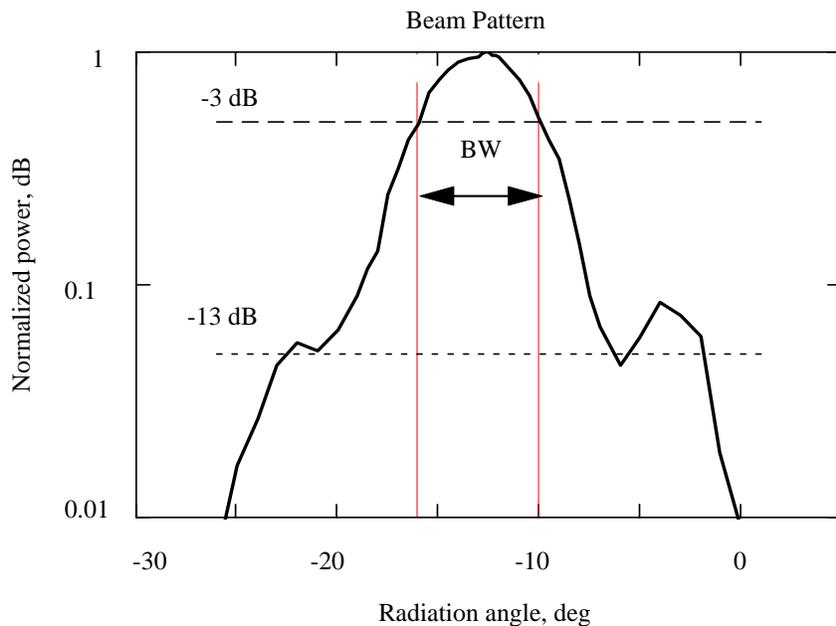


FIGURE 10. Typical beam pattern.

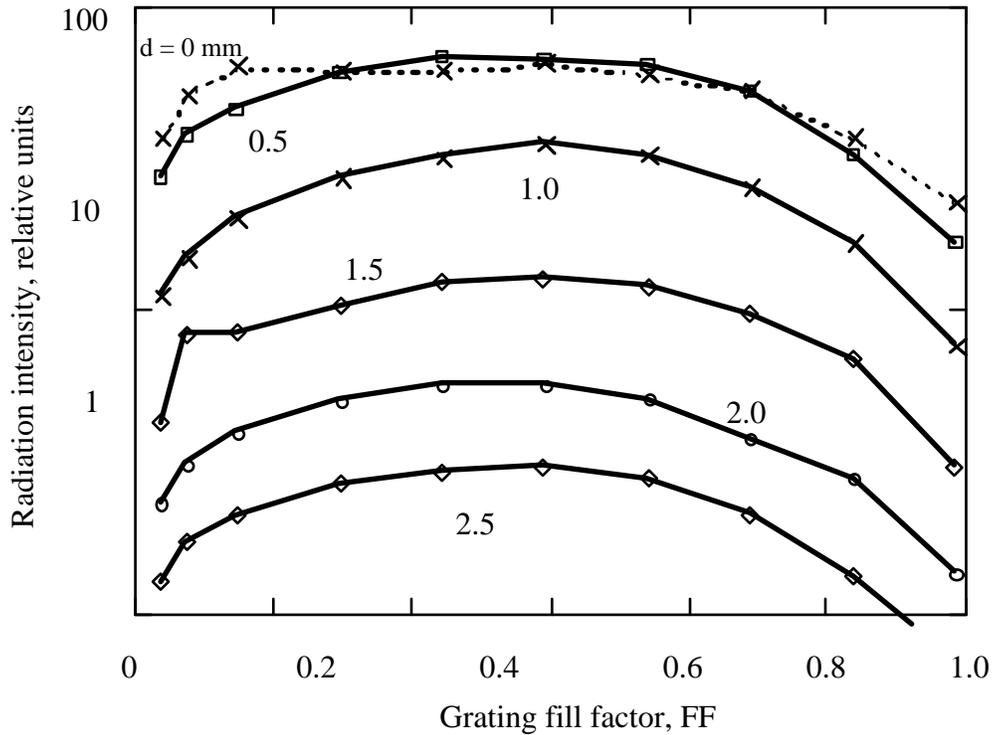


FIGURE 11. Dependence of radiation on grating fill factor for different gaps, d.

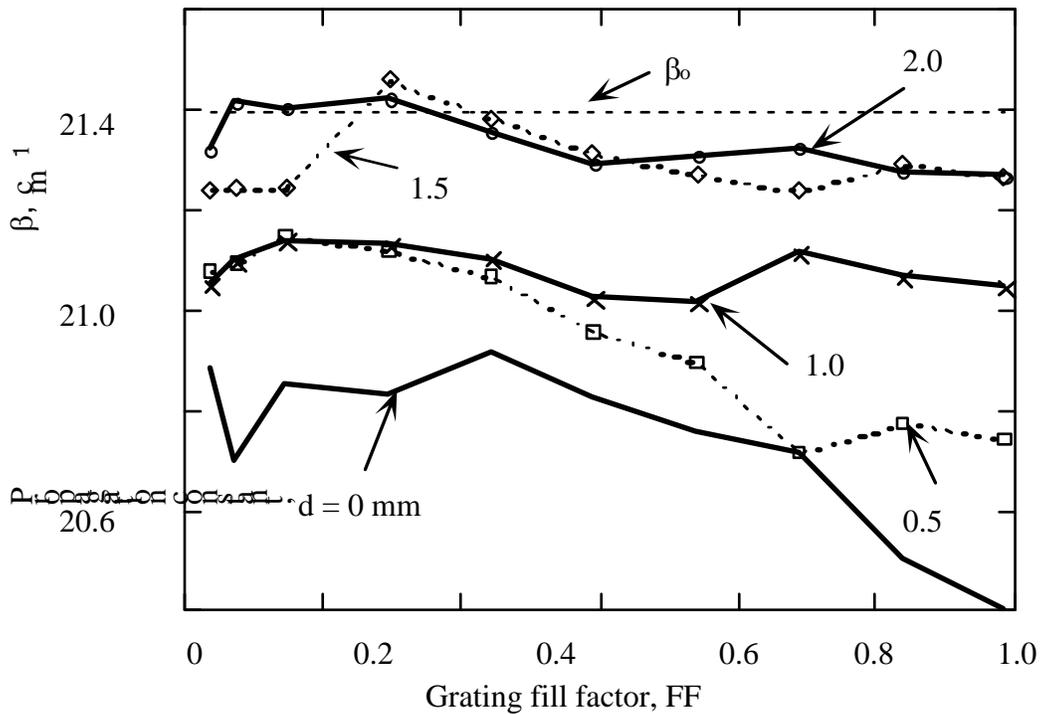


FIGURE 12. Propagation constant as a function of the grating fill factor for different gaps, d.

The design of the grating determines the direction of the beam as it is scanned. Software was developed at WaveBand that generates the desired grating pattern on a PC platform using C⁺ code. The software allows us to vary all grating parameters, thus enabling effective control of antenna performance (gain, beamwidth, and sidelobes). Figure 13 shows three antenna beam patterns as measured in the laboratory; one at each end of the scan range and one in the middle of the

scan range. The angular beam positions are distributed uniformly throughout the scanning range as shown in Figure 14. As can be seen in Table 2, the antenna gain and sidelobe levels are very consistent throughout the scanning range.

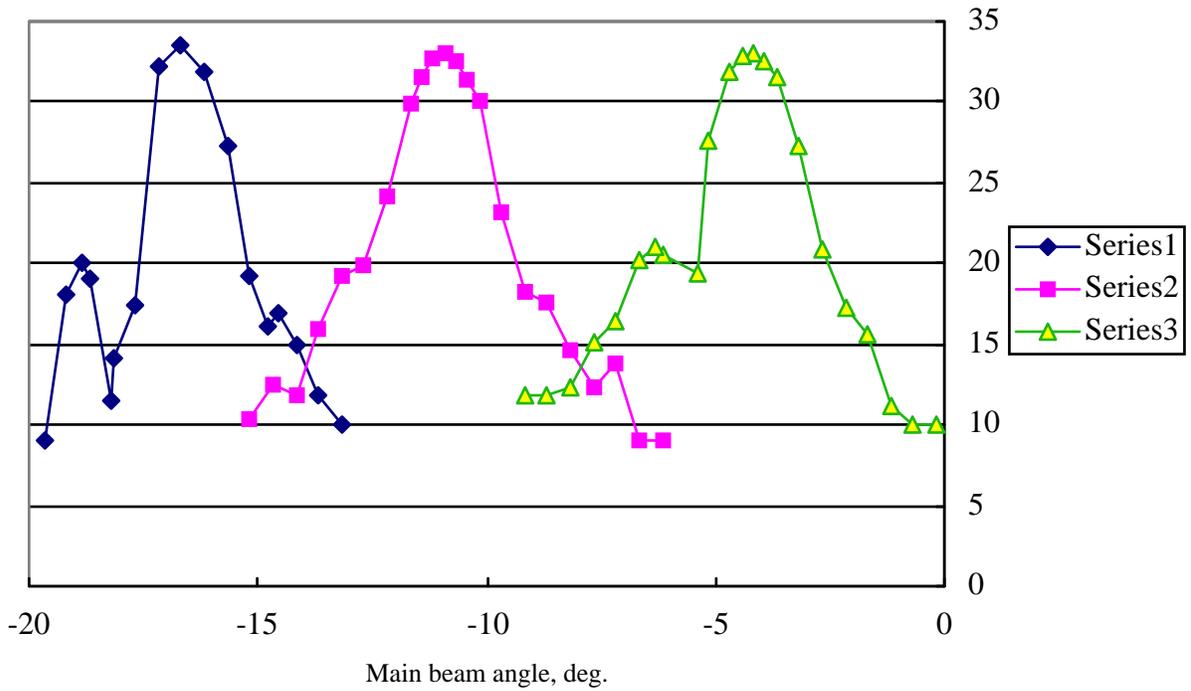


FIGURE 13. Beam patterns in the azimuth scanning plane.

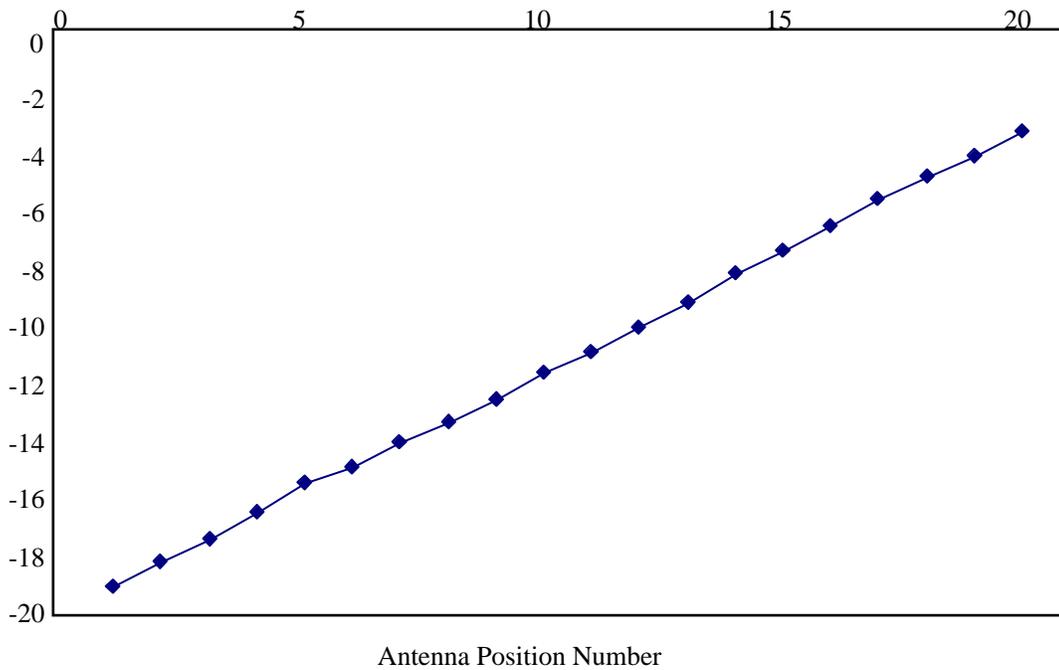


FIGURE 14. Scanning angles corresponding to the antenna's beam position.

TABLE 2. Scanning antenna's characteristics as a function of scan angle.

Antenna Position Number	Peak Angle (degrees)	Maximum Power (dB)	Average Sidelobe (dB)
20	-2.98	33.0	-18.0
19	-3.86	32.9	-15.8
18	-4.56	32.8	-17.1
17	-5.39	32.8	-17.8
16	-6.33	32.6	-16.5
15	-7.19	33.1	-17.0
14	-7.98	32.9	-17.1
13	-8.96	33.6	-19.0
12	-9.83	33.8	-18.2
11	-10.7	33.8	-17.5
10	-11.39	33.7	-18.0
9	-12.39	33.7	-17.4
8	-13.14	33.4	-16.2
7	-13.89	33.7	-16.8
6	-14.71	33.7	-18.1
5	-15.31	33.5	-17.2
4	-16.33	33.9	-18.0
3	-17.23	33.6	-17.4
2	-18.06	34.0	-17.4
1	-18.86	33.9	-18.1

The elevation beam pattern is determined by the design of the parabolic reflector and is subject to somewhat less stringent constraints due to the much broader beamwidth allowed. The elevation plane pattern is shown in Figure 15.

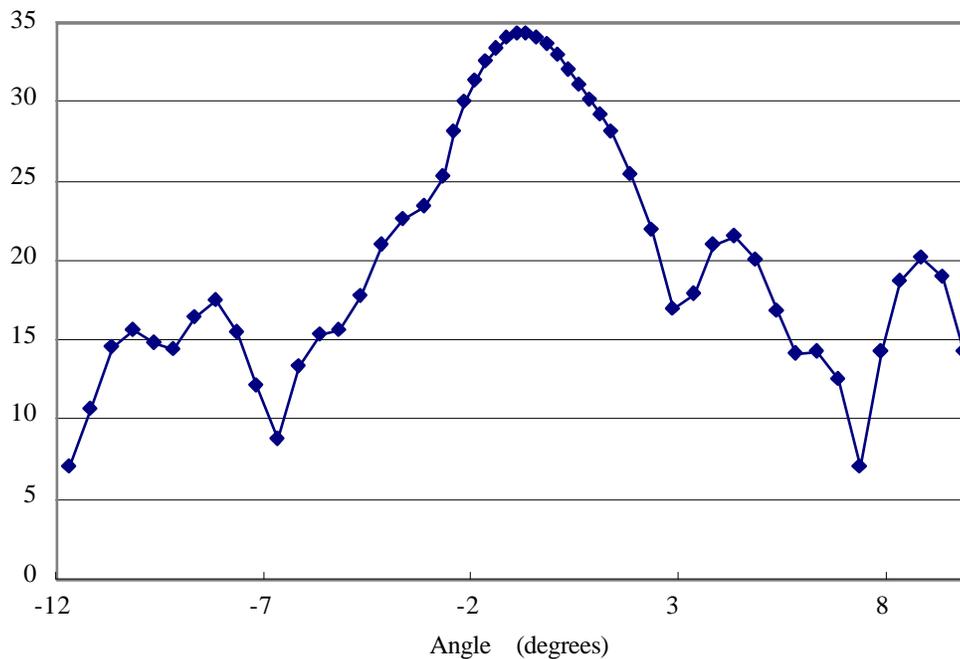


FIGURE 15. Elevation antenna beam pattern.

One of the challenges in the antenna design was the development of a reliable, low-cost transition from a standard WR10 rectangular waveguide to a cylindrical dielectric waveguide. The design of the transition is shown in Figure 16. Very low reflection losses are required to support operation of the system at close ranges on low-speed targets. A VSWR better than 1:1.1 was achieved with this design.

FIGURE 16. Drawing of the rectangular to circular waveguide transition.

Automotive MMW Scanning Antenna

A monostatic antenna was designed and fabricated for the automotive collision warning application (see Figures 17 and 18). The antenna parameters are those listed in Table 1. The antenna is designed to be used with an interrupted FMCW, hence the monostatic concept. Frontier Engineering Sciences received the antenna in August and tests to date have been satisfactory. The design issues described above are essentially the same for both antennas. Data collected from both the monostatic and bistatic antennas met the design requirements for the applications.

FIGURE 17. The monostatic version of the Spinning Grating™ provided to Frontier Engineering Sciences for automotive testing.

FIGURE 18. The monostatic antenna outline drawing.

SENSOR CONCEPTS

The initial sensor systems were assumed to be radar. In the course of our investigation, the possibility of using a passive radiometric sensor came to light. An aerospace company (TRW) was willing to lend a radiometric receiver to WaveBand for evaluation. In the meantime, a simple radar sensor was constructed and tested against simulated railroad grade crossings situations. Each of these sensors will be discussed in this section.

Radar Sensors

For both the railroad and automotive applications, the low-cost radar choice is one based upon a frequency modulated sensor (FMCW). Evaluation of the requirements as viewed by the automotive industry provided us with a sensor that would, for the most part, perform in either application. The most stringent requirement is associated with the need to discriminate between obstacles that represent a potential danger and those that do not. Some of the discrimination can be made by virtue of relative velocity or by range differences. An FMCW radar sensor can meet these discrimination requirements at relatively low costs. Additional discrimination, however, is required in angular position as measured in the direction of travel. It is this discriminant that forces the need for a narrow beam scanning antenna such as the Spinning GratingTM antenna. The system parameters for a sensor that meets the need of both the automotive and railroad applications are provided in Table 3. These parameters are consistent with those thought to be optimum by Frontier Engineering Sciences for the automotive collision warning application.

TABLE 3. Conceptual Radar System Parameters.

Parameter	Value
Horizontal field of view	+/- 10 deg.
Horizontal angular resolution	1.2 deg.
Vertical field of view	3 to 4 deg.
Acquisition range	75 m
Range error	Largest of 0.07% or 0.7 m
False alarm rate	less than 1 in 10^{-5} per second
System delay time	< 300 msec
Data sampling rate	>10 times minimum bandwidth
Vehicle speed	0 to +/- 10 km/hr
Radar frequency	76.5 GHz +/- 0.05 GHz
Transmitted power	10 mW
Minimum target radar cross section	0.1 m^2
Prime power input	9 to 16 volt dc, 12 volt nominal
Operating temperature	-40 deg. C to +85 deg. C
Humidity	must operate in rainfall of 10mm/hr
Altitude	-100 m to + 4000 m

Test Radar System

A simple radar system was assembled for the purposes of testing the Spinning GratingTM antenna in the railroad grade crossing environment. A standard Gunn diode oscillator operating at 76.5 GHz was used as the MMW source. It produced about 20 mW of RF power and was modulated at 1 kHz. Detection was accomplished by a Schottky diode in conjunction with a lock-in amplifier. The radar was connected to the bistatic antenna and was tested by illuminating targets in a parking lot and alley. One-dimensional images were generated for evaluation purposes. Figure 19 shows an example of the images generated by the radar. The primary goal of the test was to detect vehicles as they might appear at a grade crossing; the data shown in Figure 19 shows good correlation with the photograph in Figure 20. The radar distance from the cars was about 80 feet, a reasonable distance for the application. At that distance the simple system could resolve two cars with a separation of 3 feet or less. The purple and yellow lines in Figure 19 represent the radar image of the background with no vehicles present. Although the radar image was generated by scanning motionless objects (cars), detection of moving objects does not represent a problem. Motion is easily detected through the measurement of the Doppler shift or range rate.

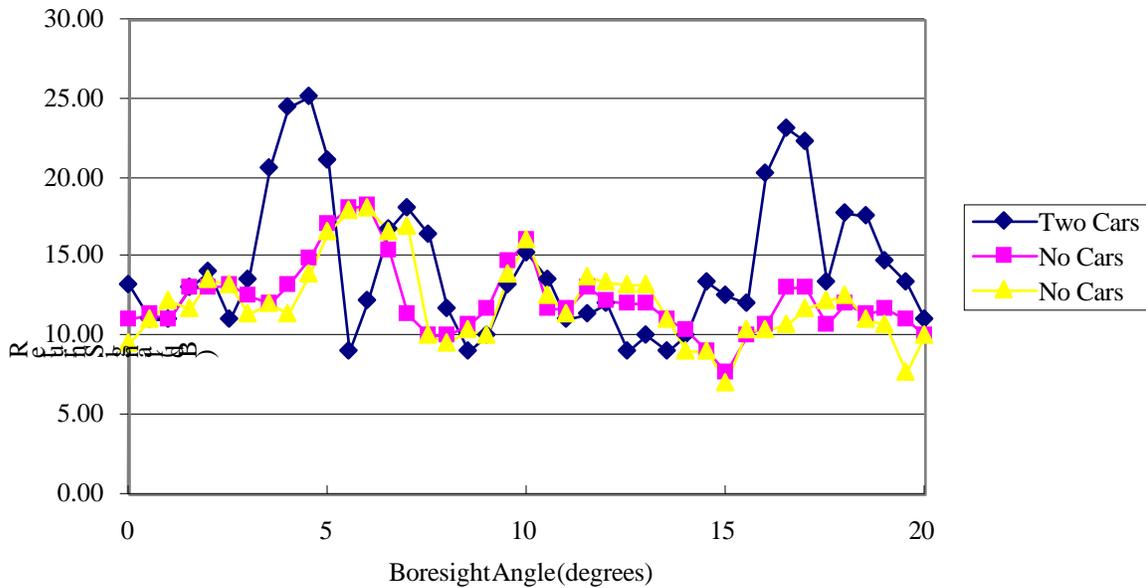


FIGURE 19. Radar image of vehicles in a parking lot.

FIGURE 20. Photograph of the scene corresponding to Figure 19.

Passive Sensors

Typical MMW passive sensors are radiometric receivers. These devices are very wideband receivers that are able to detect energy that is naturally emitted or reflected from all bodies above zero degrees Kelvin (blackbody radiation). At MMW frequencies, enough energy is available for reliable detection if the receiver is low noise, has a broad bandwidth and stable gain characteristics. From the world of radio astronomy and satellite remote sensing of the Earth, radiometers have developed to the point that they are mature devices. Application of such sensors to the railroad grade crossing obstacle detection problem will provide suitable discrimination between obstacles and the background in principle. A MMW radiometer detects objects by their apparent differences in temperature and vehicles have a very large temperature difference when compared to the typical background.

TRW has made available to WaveBand a MMW radiometer that operates at 94 GHz. While this frequency is higher than that which we initially intended to work with it is a well known radiometric band. Our intentions were to collect data under real conditions at a grade crossing that is part of the Burlington Northern Santa Fe system and then process the data in the laboratory. (Real time processing is beyond the scope of this project.) The antenna that would be used is one developed for autonomous landing guidance systems operating at 94 GHz (see Figure 21). Table 4 depicts the sensor characteristics including those of the 94 GHz antenna. Interface problems and lack of funds have put this option on hold.

TABLE 4. 94 GHz Radiometer Characteristics.

Parameter	Specification
Center Frequency	94.3 GHz
Bandwidth	1 GHz
Sensitivity	0.4° K
Integration Time	10 ms
Field of View	+/- 15°
Antenna Gain	39 dB
Azimuth Beamwidth	0.5°
Elevation Beamwidth	5.0°
Scan Rate	10 Hz
Sidelobes (first)	-15 dB
Sidelobes (remainder)	-30 dB

FIGURE 21. 94 GHz Scanning Antenna.

ESTIMATED PRODUCTION COSTS OF THE SPINNING GRATING™ ANTENNA

The California Manufacturing Technology Center was commissioned to develop a low-cost manufacturing approach for the 76.5 GHz antenna. The results of the study are quite encouraging. The manufacturing concept makes use of existing robotics technology and minimal hand labor. Materials are molded plastic and metals (where required). Very few pieces make up the antenna and those are easily assembled by a multi-axis industrial robot.

We expect additional cost reductions can be gained by further design optimizations and by competitive bids and cost negotiations with suppliers.

PLANS FOR IMPLEMENTATION

WaveBand has a two-pronged plan for introducing this technology into the two markets. For the railroad market, we will work with Burlington Northern Santa Fe (BNSF) to find additional funding for the development of prototype sensors that will be installed at selected grade crossings for test and demonstration. Working with BNSF we will provide the data and information necessary to determine how to best use the sensor as an obstacle detector at crossings. This is expected to be a two year effort with funding needs of approximately \$300,000.

For the automotive market, we plan to continue work with the U.S. automotive radar sensor manufacturers such as Delco, TRW, and Eaton VORAD. We will be seeking funding to develop 40 to 50 units in the production configuration and provide them to the sensor manufacturers for test and evaluation.

CONCLUSIONS

The Spinning GratingTM antenna developed as a result of this project will provide the ability to apply radar sensor systems to the automotive and railroad industries. The high performance coupled with low cost make the antenna an ideal solution to the collision warning / obstacle detection sensor system.

INVESTIGATOR PROFILE

The Principal Investigator is **Dr. Lev Sadovnik**. He received his M.S. degree in Physical Optics from the University of Chernovtsy (Ukraine), and his Ph.D. from the University of Southern California Signal and Image Processing Institute. His expertise is in diffraction optics, holography and optical image processing. Among his professional achievements, Dr. Sadovnik is the co-inventor of the Micro-Patterning System for micro lithography. He is also a co-inventor of the Spinning GratingTM Scanning MMW Antenna, and a co-inventor of a scanning MMW antenna controlled by light. He proposed and experimentally verified a new principle of phase coding for an all-optical processor. Among his other inventions is an innovative algorithm and optical design for a distortion-invariant processor. His work experience has involved the management of system projects from conceptual design through full-scale development. He is the author or co-author of 38 publications and three patents.

Selected Directly Related Publications by the Principal Investigator:

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