# Automotive Anticollision Radar

*The authors present experimental results of millimeter wave automotive sensing system tests conducted by member companies of the study committee commissioned for this purpose by the Ministry of Posts and Telecommunications in Japan.*

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Over 50 million automobiles on the roads complicate the traffic condition and impact driving safety in Japan. It is, therefore, essential that drivers quickly notice changes in traffic conditions and react to them. In order to alleviate the driver's load and increase safety, several sensing systems for automobiles are being studied and developed [1].

*Outer sensors, in which vehicular radar provides forward and backward looking collision warning, were studied.*

Automotive sensors generally include engine control, stability or suspension control, and outer situation monitoring. Among these, outer situation monitoring is being developed as an automotive radar to aid the driver's sight and hearing, both as a forward looking collision warning sensor and a backward looking warning sensor.

The collision warning sensor must be able to detect longer range situations in contrast to the short range backward sensor useful for parking. To provide longer range detecting capability, infrared and millimeter wave are considered suitable radar media, but millimeter wave is preferable from the standpoint of bad weather conditions such as fog, rain or snow as well as penetration of adhered dust on the antenna and reduced risk of radiation hazards to human and animal eyes.

*Millimeter is preferable to infrared not only for weather and dust penetration but also because it presents a more benign radiation hazard to eyesight.*

As shown in Figure 1, the history of development of automotive radar began in the 1970s in the R&D activities of National Highway Transportation Safety Association (NHTSA), but studies were dormant thereafter for about a decade. In the past few years, however, automotive radar study has been stimulated by the development of millimeter wave devices which seem to promise the realization of high electronic performance, very small size components, and low cost fabrication. The main technologies promising those benefits are compound semiconductor advances in microwave monolithic integrated circuits (MMIC), and flat or active millimeter wave antennas.

| | 1970s | 1980s | 1990s |
|---|---|---|---|
| Microwave Technology | - 10GHz | 20 - 30GHz - 50GHz | - 90GHz |
| NHTSA Study | ⟶ | | |
| MPT of Japan | | '84 MPT Study and Research for Millimeter Wave System | MPT Experiment & Study of Automotive MMW Sensor |
| Infrared, Ultrasonic | | Infrared / Ultrasonic Automotive Sensor | |

**Figure 1. Millimeter Wave Radar Development in Japan.**

In 1984, the Ministry of Posts and Telecommunications in Japan commissioned the Millimeter Wave Sensing System Study and Research Committee to study application systems utilizing millimeter wave technology. In the late 1980s the Committee began to collect basic data for developing new automotive millimeter wave radars through various experiments.

This paper outlines some of the experimental results described in the Committee's reports [2] and helps to clarify what must be done to put millimeter wave automotive radar into practice.

*Experimental Systems*

The basic experimentation was carried out by means of three radar systems, using different combinations of two modulation systems, three types of antennas, and three well spaced frequencies. These systems are listed in Table 1.

*The study employed radars with two modulations, fixed and scanned antennas and frequencies of 50, 60 and 70 GHz.*

| | | |
|---|---|---|
| SYSTEM A | FREQUENCY | 50GHz |
| | MODULATION | FM-CW |
| | ANTENNA | FIXED, SINGLE (Mill's cross) |
| | ALARM LOGIC | CAR SPEED, RELATIVE SPEED/DISTANCE |
| | EXPERIMENTS | SCATTERING PATTERN, ROAD TEST |
| SYSTEM B | FREQUENCY | 60GHz |
| | MODULATION | PULSE DOPPLER |
| | ANTENNA | 2D-SCANNING(Mechanical), SINGLE |
| | ALARM LOGIC | IMAGE PROCESSING/RECOGNITION |
| | EXPERIMENTS | SCATTERING PATTERN, TARGET IMAGING |
| SYSTEM C | FREQUENCY | 70GHz |
| | MODULATION | FM-CW |
| | ANTENNA | 1D-SCANNING, MULTI-HORN/BEAM |
| | ALARM LOGIC | DIRECTION, SPEED, DISTANCE |
| | ANALYSIS | DIRECTION from 2-BEAMS, CURVED ROAD |

**Table 1. Experimental Systems.**

The modulation systems examined were FM-CW and pulse-doppler. The antenna experimentation used a Mill's cross single fixed beam, a scanning beam, and multi-beam antennas. Finally the radars operated at 50, 60 and 70 GHz.

In addition, the logistic of alarm usage was studied on a theoretical basis regarding when and how to activate alarms depending on the measured and analyzed signals. The alarm criteria were applied to the measured radar results obtained from the experiments and the impact of sounding or not sounding alarms under various conditions noted in the studies.

The 50 GHz radar system employed FM-CW modulation, and the Mill's cross antenna. The FM-CW modulation can detect relative distance and relative speed between vehicles. The Mill's cross antenna (Figure 2) consists of transmit and receive antennas at right angles to each other, each utilizing a slot array waveguide antenna and a cylindrical reflector. The cross section of the reflector is para-

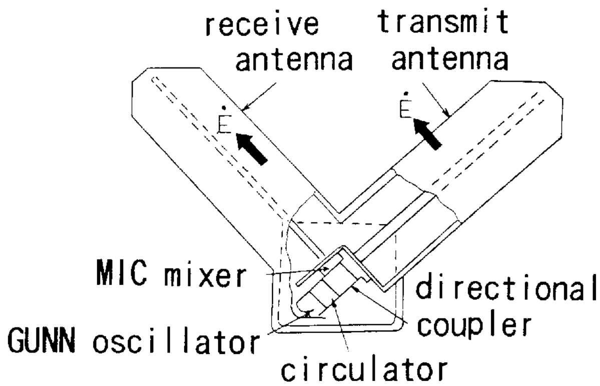



**Figure 2a. Antenna Structure of 50 GHz Automotive Radar.**

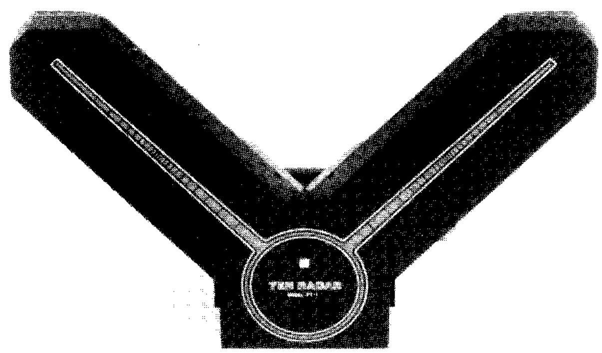


**Figure 2b. 50 GHz Automotive Radar Antenna (courtesy of Fujitsu-Ten).**

bolic, so the beam of each antenna is 2 x 6 degrees, but the resultant transmit/receive beamwidth is only 2 x 2 degrees, sufficiently narrow to distinguish targets of interest.

In the base of the antenna system, the millimeter wave electronic circuit was integrated and installed. The 50 GHz, 50 milliwatt signal is generated by a direct Gunn oscillator with varactor diode used to give 75 MHz peak to peak frequency modulation. For reception a homodyne receiver (the transmitter serves as the local oscillator as well) with a Schottky barrier diode mixer is used, also located in the same base of the antenna.

A newly designed 60 GHz circuit has been presented recently [3], which utilizes a 30 GHz GaAs FET voltage-controlled oscillator, a GaAs frequency doubler, a balanced mixer with GaAs Schottky barrier diodes and a HEMT switch to improve receiving sensitivity.

The 60 GHz radar (experimental system B in Table 1.) has been studied to measure the essential image data using scanning antennas. Its configuration is shown in Figure 3. Transmitting and receiving antennas are attached to the mechanical scanner which moves along X and Z axes in order to image the two dimensional reflected 60 GHz signal.

In the measurement of the cross sectional scattering patterns of various targets, narrow beam parabolic antennas are used, and pyramidal horn antennas are used in the measurement of the imaging data. The 60 GHz signal generated by the Gunn diode oscillator is transmitted to the object and reflected. Then the received signal is fed to the spectrum analyzer and the various pixel data processed to form an image by means of the personal computer and CRT display.

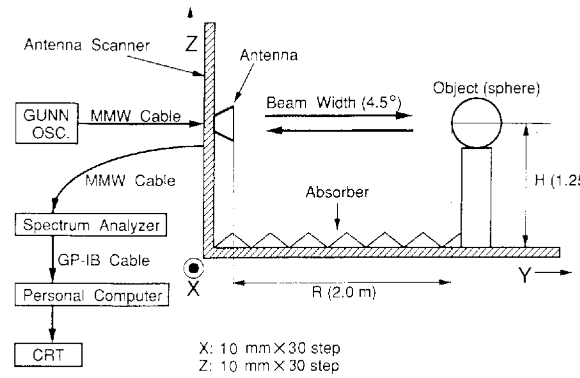



**Figure 3. 60 GHz Scanning Radar Experiment.**

The 70 GHz radar (System C in Table 1.) employs the FM-CW modulation and multi-beam antenna system in order to extract the target direction as well as its relative range and speed from the received signals. The experiments used a multi-beam antenna consisting of a primary multi-horn radiator and a parabolic reflector. However, it will be realized by an electrically switched, flat, active antenna in the future.

*Studies included electronics of the radar as well as target characteristics and imaging, radio interference, road testing, and driver's reaction.*

## *Experimental Results*

Each system shown in Table 1 was used to collect the basic data necessary to develop an automotive radar. Through those experiments, the basic electronic and radio wave characteristics of each system, measurement and evaluation of the scattering patterns, radio interference, road test, driving test, and imaging data processing were evaluated.

The 50 GHz radar system employs a Mill's cross antenna which effects a narrow beam resulting from crossing transmitting and receiving fan beams at right angles to each other, as shown in Figure 2.

The transmitting array antenna has slots in the longitudinal direction on the wall of the waveguide, and the receiving array antenna has slots on the wave-guide edge. Each waveguide is set where the slots are facing the cylindrical reflector, the radiated E plane of each antenna is as shown in Figure 2a. In Figures 4a and 4b are the measured patterns of the transmit antenna. Figure 4c shows the relationship of the composite beam and antennas, and Figures 4d and 4e are the composite patterns which are calculated from the patterns Figures 4a and 4b respectively. The desired objective values are compared to those measured in Table 2.

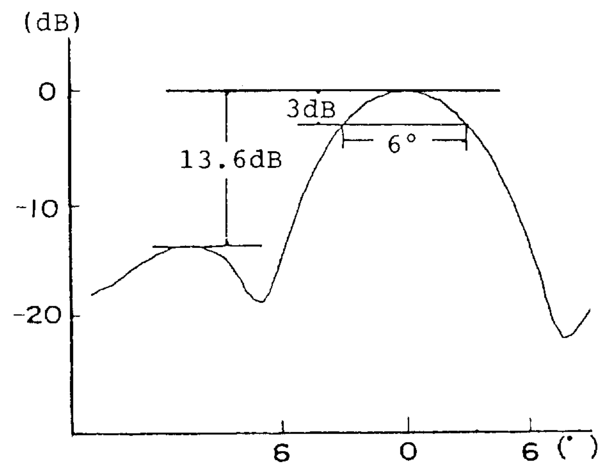



**Figure 4a. Mill's Cross measured wide beam pattern.**

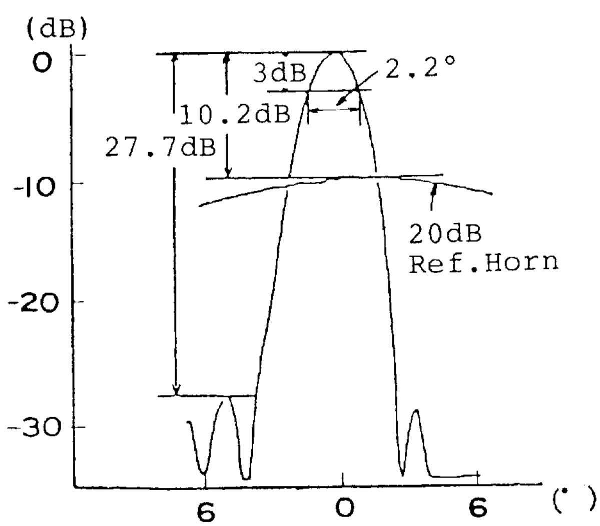



**Figure 4b. Mill's Cross measured narrow beam pattern.**

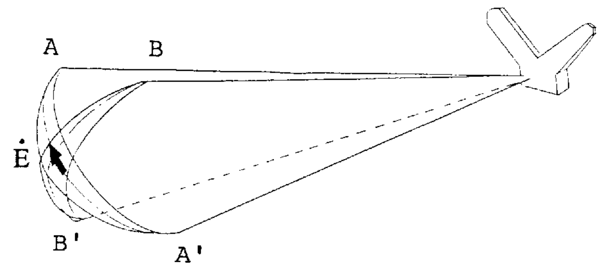



**Figure 4c. Mill's Cross composite beam schematic.**

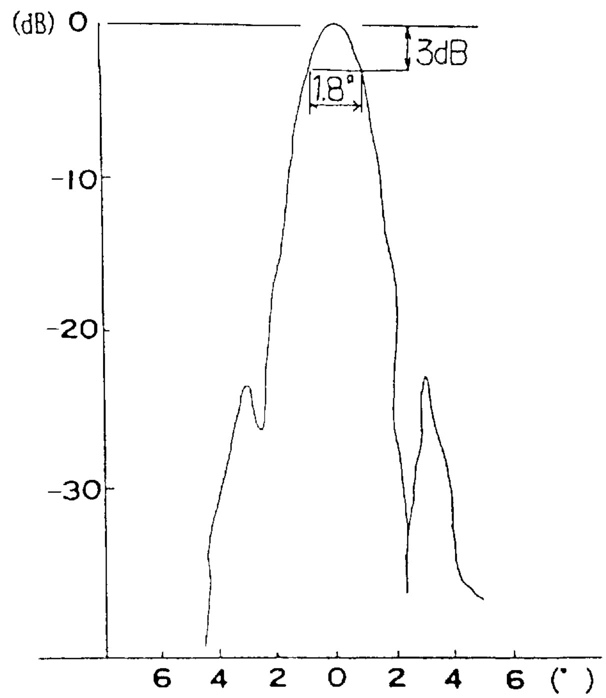



**Figure 4d. Mill's Cross calculated composite E-plane beam (A-A').**

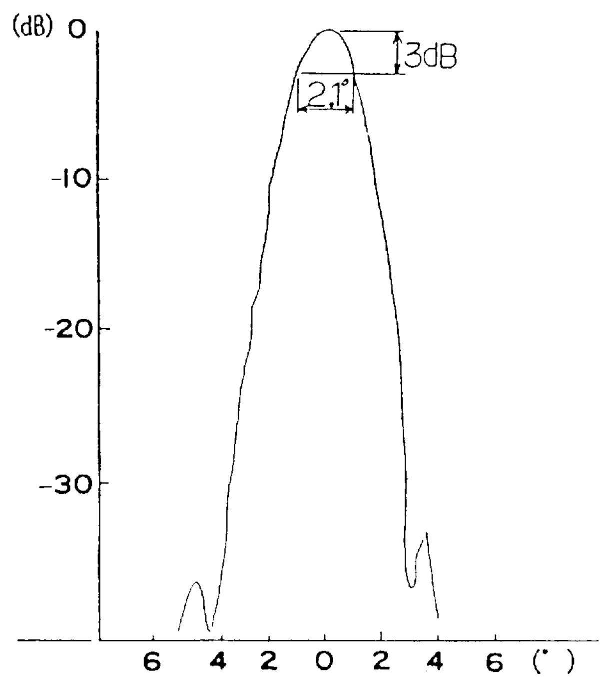



**Figure 4e. Mill's Cross calculated composite H-Plane beam (B-B').**

| BEAM PATTERN | | OBJECTIVE | MEASURED | |
|---|---|---|---|---|
| | | | TX ANT | RX ANT |
| BEAM WIDTH (deg.) | WIDE BEAM | 2° ± 10 % | 2.2° | 2.0° |
| | NARROW BEAM | 6° ± 10 % | 6.0° | 5.9° |
| SIDE LOBE (dB) | WIDE BEAM | > 17 dB | 22.7 | 22.2 |
| | NARROW BEAM | > 12 dB | 13.6 | 12.9 |
| COMPOSITE BEAM | E PLANE | | 1.8° | |
| | H PLANE | | 2.1° | |

**Table 2. Mill's Cross antenna objective specifications and actual performance.**

*Cross Sectional Scattering Patterns*

Automotive radar must be able to detect vehicles, motorcycles, and other obstacles on the motor road. Because such targets have many different individual features in their shapes and forms, their radar signatures (relative received signals for a particular set of radar illuminations) vary widely. Figure 5 shows the cross sectional scattering patterns measured for sample targets.

Passenger vehicles have almost the same patterns independent of the car size, with a large reflection being received from the front or rear directions but a very small reflection when the vehicle is viewed by radar on a diagonal. A cargo truck has a more uniform reflection level for every direction of observation. A motorcycle has smaller level when viewed from front and rear than at the side. A bicyclist or a walking person has much smaller returns than other vehicles no matter what the direction of observation.

*Targets include small and large cars, trucks, motorcycles, bicyclists and pedestrians. Their radar return signal strengths vary widely from target to target as well as in viewing angle of a given target.*

The angle at which a flat target object, such as guard rails and traffic control signs, can be detected is narrow. Therefore only small signal reflection is to be expected from these objects for most of the driving time. However, cylindrical objects such as metal poles are nondirectional in their radar returns. Consequently they have relatively high reflections at all times, and would be expected to be detected frequently with attendant activation of alarm circuitry.

*Radio Interference*

As radar systems are introduced on a large scale into numerous vehicles in the future, their individual performance can be expected to degrade due to their mutual radio interference. One way to minimize this interference is to choose an operating band for which there is high atmospheric attenuation, such as near 60 GHz for which the transmission loss caused by oxygen molecules is about 15dB/km. Then radar signals do not propagate much farther than the sensing domain of the vehicle from which they are transmitted, attenuating before they encroach very much into the sensing domains of other vehicles' radars.

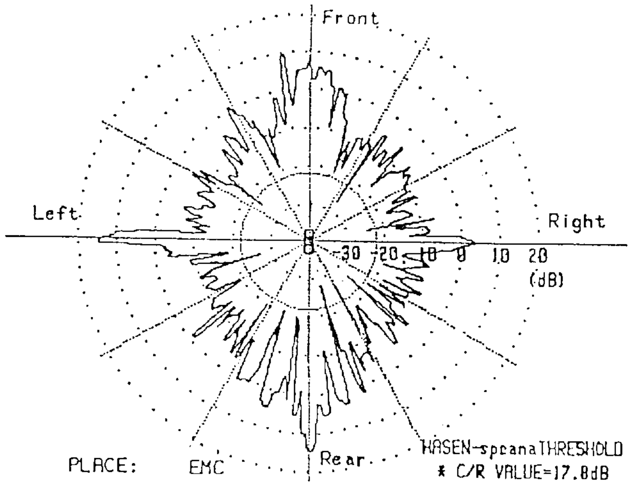
*Future systems will not be isolated, radio interference among automotive radars will be an important system consideration. Two methods for minimizing it were considered.*

Another approach to minimize interference is for the radar beams of different vehicles to have polarization diversity. The 50 GHz radar system was evaluated in this respect. It experiences a low interference signal from a similarly equipped vehicle approaching from the opposite direction. This is because the transmitting polarization of the two vehicles are plus and minus 45 degrees to the ground respectively, as shown in Figure 2a, with a total difference in polarization of 90 degrees. Ideally, this completely isolates approaching vehicles from each other, a desirable characteristic since it is between two mutually approaching vehicles that the greatest interference would be expected.

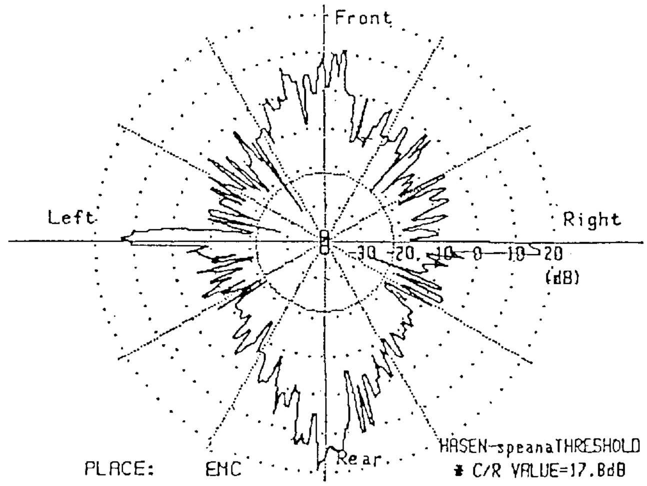
For the same system, it was also found that the interference level between adjacent vehicles travelling in the same direction but in parallel lanes was also very low, owing to two factors. First, there is a low side-lobe level for the composite beam of the Mill's Cross antenna system and, second, because of their narrow beamwidths, neither illuminates targets in the other's lane very strongly.

*Road Test*

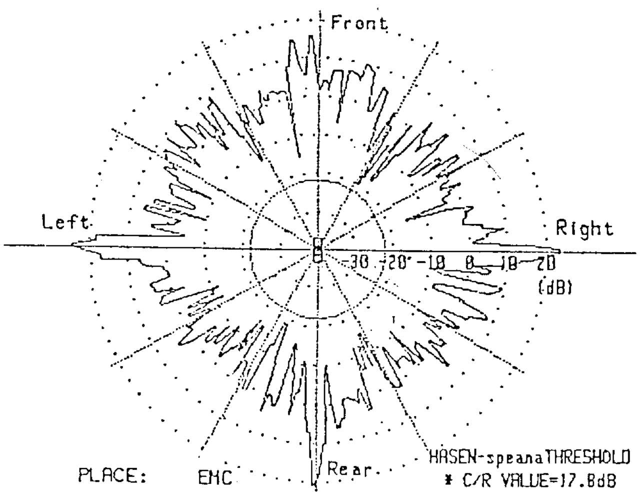
To evaluate the 50 GHz radar system under actual road conditions, several road tests were performed. In Figure 6, road test conditions are shown. The radar activated no alarm in cases shown in



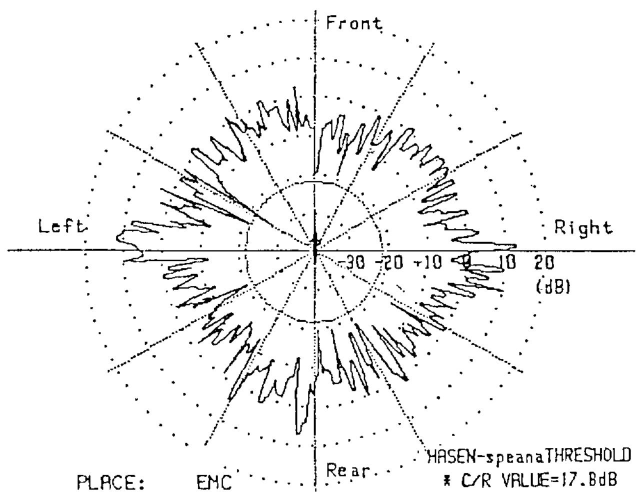

(a) 3,000cc 4 Door Sedan



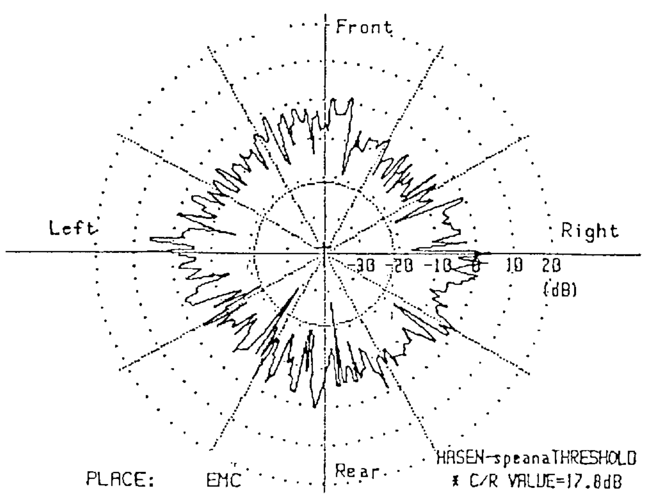

(b) 1,300cc Compact Car



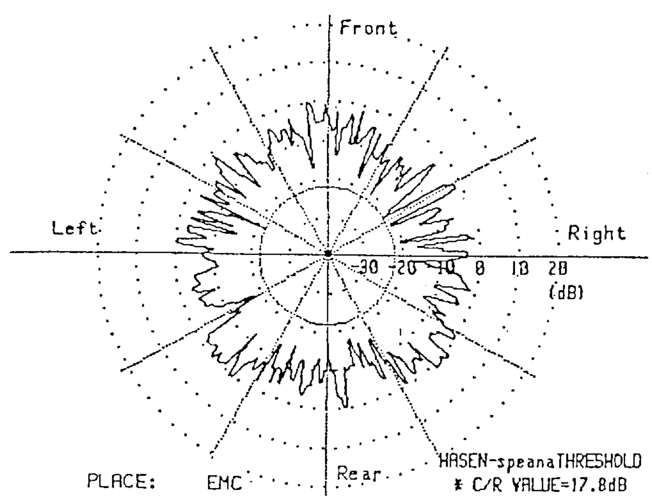

(c) Cargo Truck




(d) Motorcycle




(e) Bicycle




(f) Personnel

**Figure 5. Cross sectional scattering patterns.**

Figures 6a and 6d, but activated alarms in the situations described in Figures 6b, 6c and 6c. This suggests that the alarm logic should be improved for curved roads by utilizing steering information. In road conditions such as those depicted in Figure 6d, some reflecting targets intentionally might be placed in front of trees for radar signal return enhancement.

On upgrades and downgrades, Figures 6f and 6g, the system activated alarms when there was an obstacle like iron in front, but did not alarm for radar returns from the road surface only (Figure 6f). In cases such as those in Figures 6h and 6i, the radar system may lose track of the vehicle ahead when that vehicle leaves the sensor vehicle's radar beam due to the road's slope.

Those results demonstrate that even though the system functions in an electrically correct manner, there remains a need for improving the man-machine interface between the sensor system and the driver.

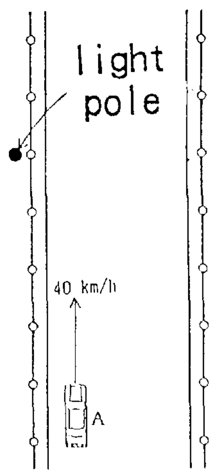



**Figure 6a. A road test consisting of a guard rail along a straight road.**

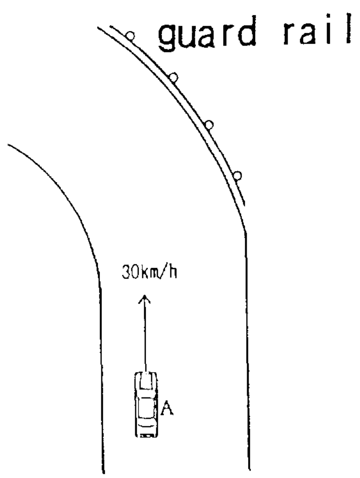



**Figure 6b. A guard rail along a curved road.**

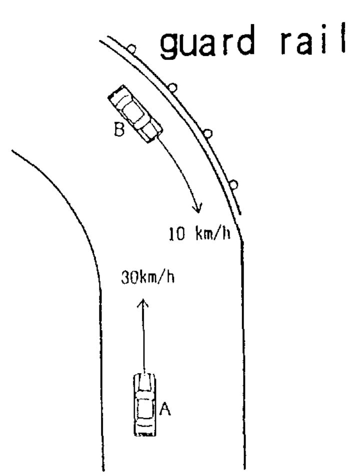



**Figure 6c. An on-coming car on a curve.**

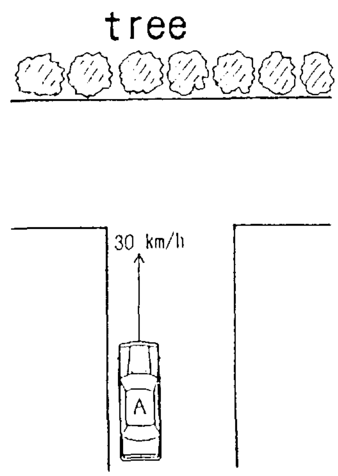



**Figure 6d. Approaching woods or plants.**

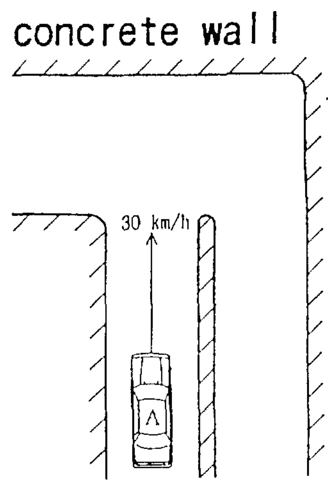



**Figure 6e. A concrete wall.**

*Even though the experimental radars operated in an electrically satisfactory manner, there remains work to be done in the driver-sensor interface.*

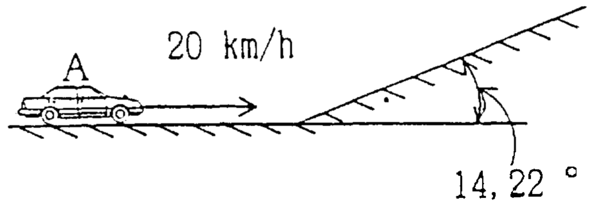



**Figure 6f. Road reflection for an upward slope.**

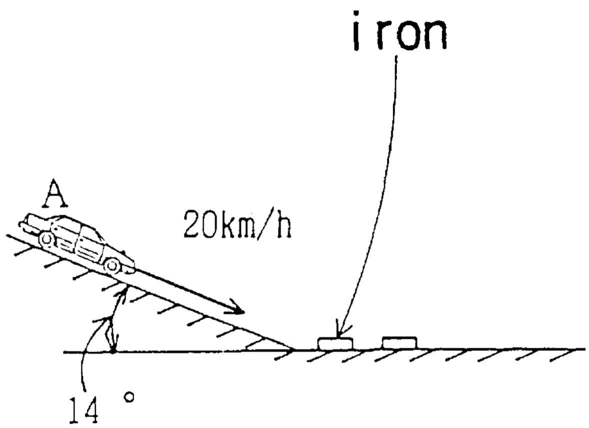



**Figure 6g. Iron reflection at the end of a downgrade.**

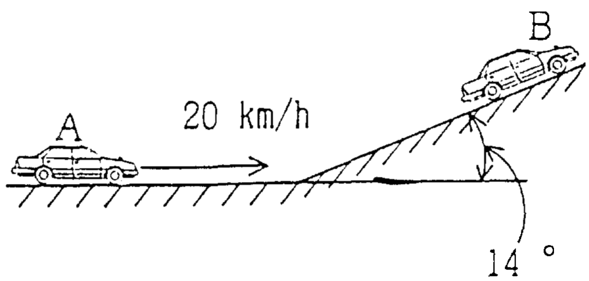



**Figure 6h. Beginning of an upward slope.**

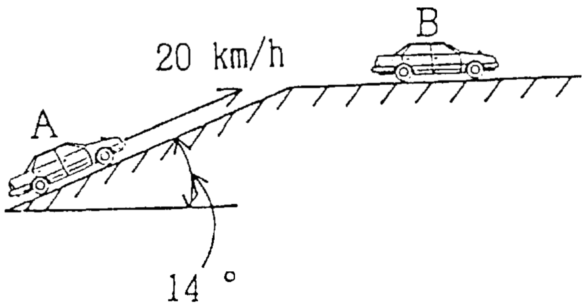



**Figure 6i. End of an upward slope.**

## *Driving Test*

The 50 GHz radar system was tested over 1,000 kilometers on actual roads to evaluate sensing functions, alarm times and false alarm rates. Figure 7 shows a condition for which an alarm is desired when a trailer truck in front of the test car slows

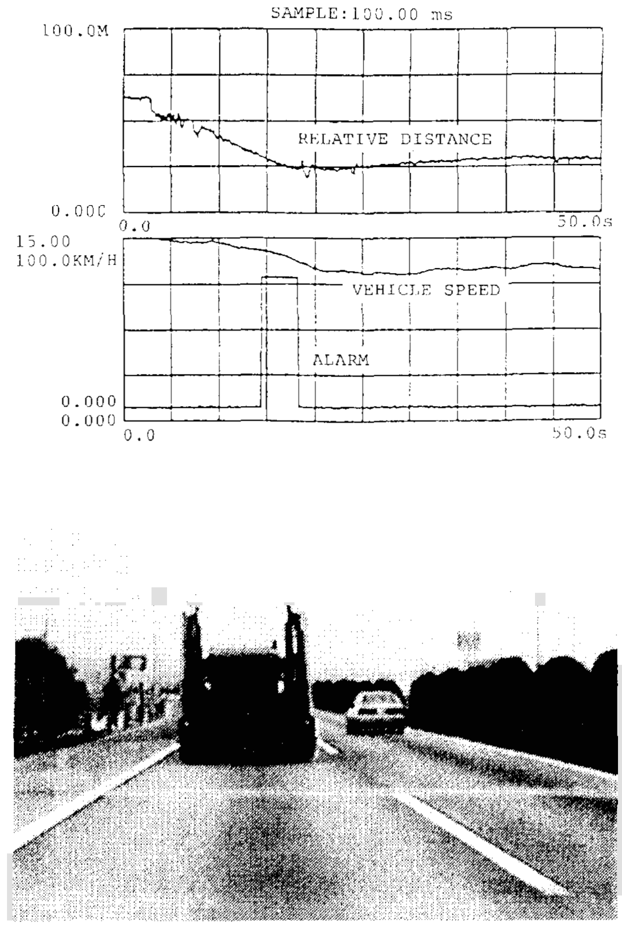



**Figure 7. Demonstration of an alarm condition when the truck 30 meters ahead suddenly drops speed below the 95 km/hr of the following car with radar sensor. Alarm ceases when vehicles are 25 meters apart but traveling at nearly equal speeds.**

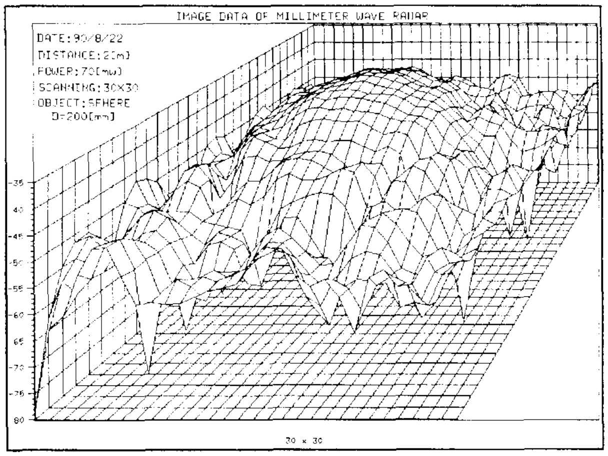
down within 14 seconds until it is only 30 meters ahead, while the speed of test car was about 95 kilometers per hour(kmph). In the test an alarm occurred as shown in the Figure, and continued until the test car slowed down to 90 kmph. The alarm ceased with the vehicles' separation at 25 meters but their speeds nearly matched.

*The false alarm rate was judged by drivers to be only 1.5% on the freeway, but much higher in rural and city areas.*

The test results over 1,000 kilometers are listed in Table 3. In this test, false alarms were judged subjectively by the drivers to be reasonable or not, based only on the driver's sense of the driving situation. The false alarm rate was judged to be satisfactorily low enough (1.5%) for practical use on freeways but the system must be improved for

| ROAD | DRIVING DISTANCE (km) | ALARM (times) | FALSE ALARM (times) | FALSE ALARM RATE (%) |
|---|---|---|---|---|
| DOWNTOWN | 215.0 | 310 | 22 | 7.1 |
| RURAL | 482.5 | 314 | 32 | 10.2 |
| FREEWAY | 378.0 | 135 | 2 | 1.5 |
| TOTAL | 1075.5 | 759 | 56 | 7.4 |

**Table 3. Alarm Data of the Road Test.**




(b) Sphere (200 ϕ)

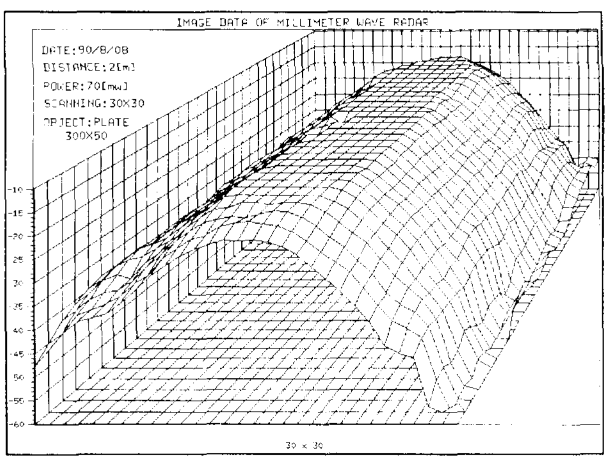
**Figure 8b. Imaging data for a sphere (30 x 30 samples).**

downtown and rural roads. Perhaps utilizing more extensive techniques to adapt the system to conditions, such as incorporation of vehicle steering and antenna beam steering into as well as refinement of the signal processing and alarm logic.

## *Reconstruction of Image Data*

This experiment was conducted using the two dimensional 60 GHz CW radar shown in Figure 3, aiming it at a spherical object and a rectangular plate as targets. As shown in Figure 8, even though the edges are blurred due to the wide beam (4.5 degrees) the shapes of targets are quite well imaged.

In the case of a rectangular plate (Figure 8a) the distribution of the reflection intensity is unimodal, the maximum intensity is almost at the central position, and monotonously decreasing outward in all directions. In the case of the sphere's reflection (Figure 8b) the maximum intensity is also almost at the center, but there is no monotonous decrease; decreasing and increasing occur alternately. This experiment reveals how comparatively good image data possibly can be obtained from a simple intensity measurement used in conjunction with an electronic scanning or mechanically steered beam.




(a) Rectangular Plate (300x50)

**Figure 8a. Imaging data for a rectangular plate using 900 radar returns (30 x 30 samples).**

## *Climatic Factors*

Although the greatest difficulty of using millimeter wave is thought to be the susceptibility to precipitation, this experimental test shows the radar is very effective even in rain as heavy as 10mm/hr (0.4 inches/hour). This is because the sensor range need only cover about 100 meters ahead of the vehicle, and in this range the estimated extra attenuation due to rain is only a few decibels. However, the experiment did reveal that the real problem was raindrops on the antenna surface which formed a non-uniform water layer, distorting the radar's antenna beam.

*The experiments revealed that while rain itself did not reduce the radar's capability very much, droplets of water on the antenna did.*

Finally, in snow and fog conditions, experiments revealed that the radar retains sufficient performance in detecting targets, even when both the sensor and target are covered with thick snow (Figure 9).

**Figure 9. The radar retained sufficient performance even with the target and sensor vehicle covered with thick snow. (Photo courtesy of Toyota).**

## *The Future*

The rapid increase of vehicles in most countries suggests the necessity for a driver's aid to ensure safety and comfort under heavy traffic conditions, and an automotive radar system may be the most practical and desirable. A millimeter wave radar is among the most capable technologies from the standpoint of detection range, beam width, target reflectance, weather conditions, and the most benign as a radiation hazard to eyesight.

However, as a result of these studies and experiments, it is evident that several points need further attention before implementing millimeter wave automotive radars for practical use.

A standard frequency band selection is necessary, at 50 GHz or higher, both to permit a sufficiently narrow beam and small sized antenna as well as to take account of the oxygen-absorption peaks at 60 or 120 GHz to minimize mutual radio interference.

Cost reduction and reliability engineering also are necessary for practical use. Metallized plastic molded waveguide, dielectric flat antenna or active integrated antennas, and monolithic millimeter wave integrated circuit are likely to be important techniques.

The radar system is sure to become increasingly important as an accident prevention and driving safety system in the near future.

## *Acknowledgment*

The authors acknowledge the members of the Millimeter Wave Sensing System Study and Research Committee for their cooperation during these studies and experiments, especially Messrs E. Akutsu, Y. Fujita, H. Fukuhara, T. Takahashi for their helpful discussions and suggestions.

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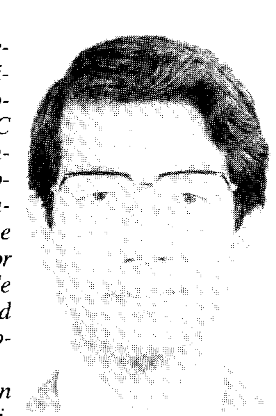

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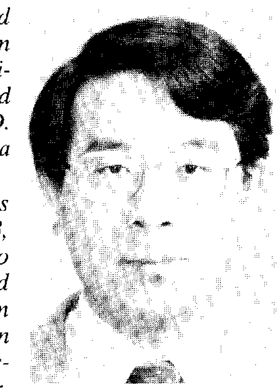

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*Dr. Kotaki joined Communications Research Laboratory of MPT in 1973, where he was engaged in the radio noise observation by satellites and made global maps of thunderstorm distribution. He was also engaged in development of HF Ocean Radar systems and was the committee chairman of the studies of millimeter wave application systems in Japan.*

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