60-GHz Millimeter-Wave Automotive Radar

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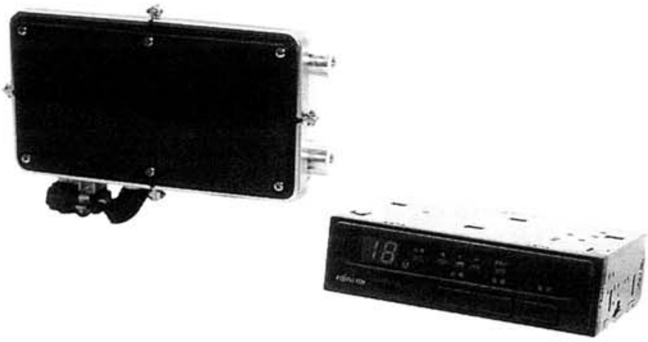


Millimeter-wave automotive radar can recognize targets more accurately and is more resistant to fog, rain, snow, and other natural conditions than current types of laser radar. They will therefore be indispensable in future systems for safe automobile driving. Automobile manufacturers plan to equip their automobiles with millimeter-wave radar, which always observes what is ahead of the car to provide an intelligent means of collision warning and cruise control.

Our millimeter-wave radar was the first in Japan to be given a technical standard conformity certificate. The Radio Equipment Inspection and Certification Institute granted this in March 1996. In March 1997, we began to market this certified radar for installation on construction machines.

This paper discusses our recently developed millimeter-wave radar focusing on a planar antenna, the radar performance as achieved in the field, and the millimeter-wave IC unit, which uses high electron mobility transistors (HEMTs).

1. Introduction

Simple millimeter-wave radio equipment for wide-band transmission is already in use. Since millimeter waves have very short wavelengths, efforts are being made to develop radar for this band to take advantage of small antennas and high resistance to meteorological conditions. The Japanese government has allocated the 60-GHz band for use by automobiles in Japan and plans to do the same with the 76-GHz band. In the U.S. and Europe, certain frequency bands are also being allocated for automobiles.

Millimeter-wave radar has evolved from simple indicators or alarms, such as collision or obstacle warning devices, to indispensable sensors in driving support systems, which are responsible for intelligent cruise control (ICC), the throttle, braking, and other controls.

2. Characteristics of millimeter-wave radar

In general, millimeter waves reside in the frequency band from 30 to 300 GHz, which corresponds to 10 to 1 mm in terms of wavelength, which is very short. This chapter discusses the concepts of antenna beam width, antenna size, propagation loss, and meteorological influences and how they apply to millimeter-wave radar.

2.1 Antenna beam width and size

The size of equipment greatly depends on the size of the antenna that serves it. Let $G(\theta)$ be the antenna gain. The antenna's beam width is represented by the angle $\Delta\theta$, which gives one half of the maximum of $G(\theta)$ as follows:

$$\Delta\theta \fallingdotseq 70 \times \lambda / D \qquad (1)$$

λ: Wavelength

D: Antenna aperture

Figure 1 shows the relationship between the frequency and the antenna size, as calculated by Equation (1).

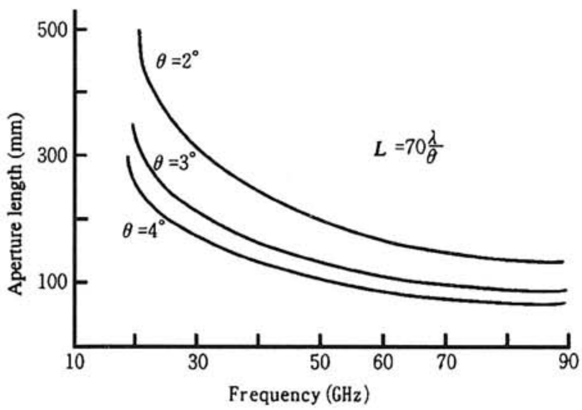


Figure 1. Antenna beam width (frequency) vs. aperture (antenna size)

The maximum gain G_{max} of an antenna is given by the following equation:

$$G_{max} \fallingdotseq 27000 / (\Delta\theta_H \times \Delta\theta_V) \qquad (2)$$

$\Delta\theta_H$, $\Delta\theta_V$: Horizontal and vertical beam widths

Equations (1) and (2) indicate that, given the beam width and gain, the antenna size required to obtain the desired performance of millimeter-wave radar is smaller when the wavelength is shorter.

2.2 Propagation loss

The main cause of propagation loss is by attenuation through the air. Figure 2 shows how this attenuation relates to frequency. Resonance absorption due to steam occurs at 22, 183, and 323 GHz and absorption due to oxygen molecules occurs at 60 and 119 GHz.

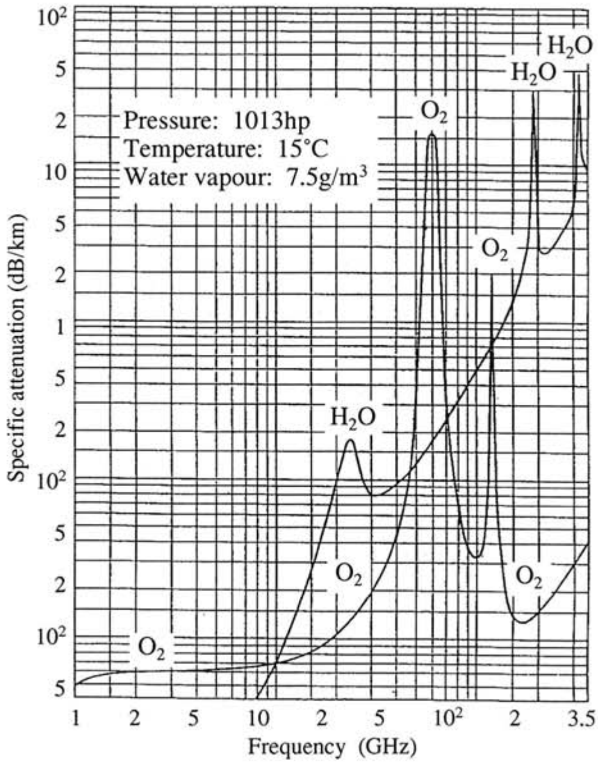


Figure 2. Attenuation due to atmospheric gases

2.3 Influence of meteorological conditions

The influence of rain often raises problems when millimeter waves are used for communication.

This problem is twofold: spatial propagation involves attenuation due to raindrops, and target recognition performance deteriorates because reflections from raindrops are mistaken as target echoes. The resulting reduction in the received power is insignificant because it only amounts to about 3 to 4 dB along a length of 100 meters. In contrast, unwanted reflections from raindrops are uniform over the entire search area of FM-CW radar[2].

3. Overview of the radar

This chapter discusses the global trends in frequency allocation and the millimeter-wave radar.

3.1 Global frequency allocation

Table 1 indicates the frequencies allocated for automobiles in Japan, Europe, and the U.S. The allocation of the 60-GHz band has already been legislated in Japan. Efforts are being made to put this band into practical use for automobiles.

Table 1. Frequencies allocated for automobiles in Japan, Europe, and the U.S

Area \ Frequency	47GHz	60GHz	76GHz	94GHz	139GHz
Japan		○ 60 to 61	△ 76 to 77		
United States	○ 46.7 to 46.9		○ 76 to 77	△ 94.7 to 95.7	△ 139 to 140
Europe			○ 76 to 77		

○ Already decided
△ Being studied

In May 1997, the Ministry of Posts and Telecommunications received part of the report entitled "Technical Requirements for Low-Power Millimeter-Wave Radar Using Frequencies in the 76-GHz Band" from the Electric Communication Technology Council. The allocation of the 76-GHz band will also be legislated in 1998. When developing and manufacturing millimeter-wave radar, it is important to be aware of the direction in which respective governments will be steering their policies on radio communication.

The regulations regarding the 60-GHz band are as follows:

Radio frequency band: 60 GHz
Antenna power: 10 mW or less
Antenna gain: 40 dB or less
Frequency bandwidth: within 1 GHz

3.2 FM-CW radar

A number of radar types are available for automobiles including FM-CW, pulse, 2-frequency CW, and SS radar. Before we began development, we decided to use the frequency-modulated continuous-wave (FM-CW) method.

The principle of an FM-CW radar is as follows.

FM-CW radar has a simple structure and can measure the distance to a target and the relative velocity of the target simultaneously. It is therefore suitable in areas where cost is a primary concern, as in the case of car radar.

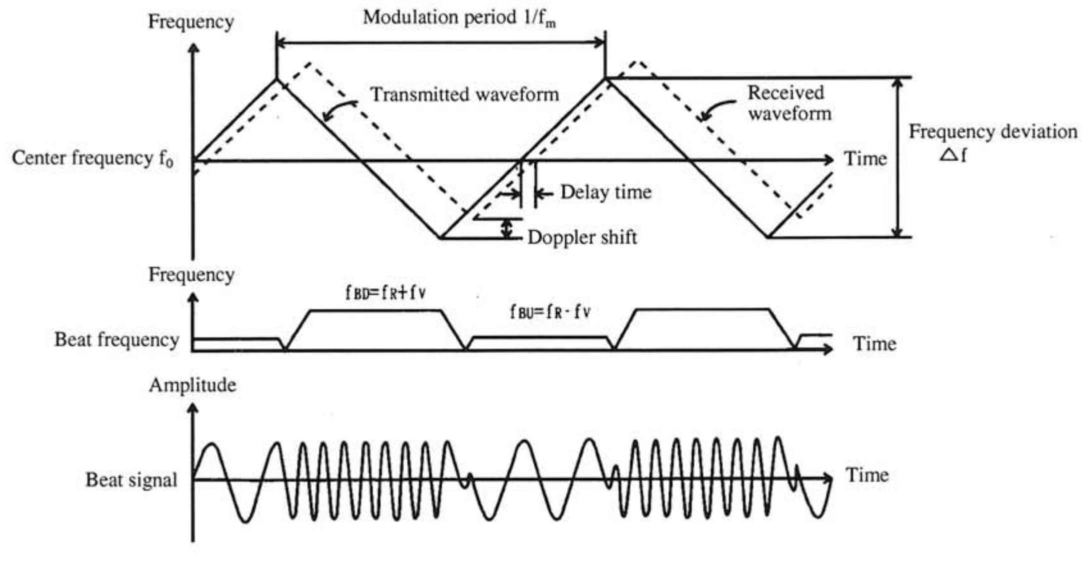


Figure 3. Principle of FM-CW radar

Figure 3 shows how an FM-CW radar works[3]. A wave FM-modulated on a triangular wave is transmitted from an antenna. A target, such as another car, reflects the wave and bounces it back to the antenna. It is then mixed with the sent wave to obtain the beat frequency. The beat frequency f_B is given by Equation (3):

$$f_B = f_R \pm f_V \quad (3)$$

where f_R is the range-dependent frequency (proportional to the range of the target from the radar) and f_V is the velocity-dependent frequency (proportional to the target's velocity relative to the radar).

The plus and minus signs in equation (3) are used in sections where the sent wave's frequency is lowered and increased, respectively. The beat frequency is called a down-beat frequency f_{BD} when the plus sign is used and an up-beat frequency f_{BU} when the minus sign is used.

Frequencies f_{BD} and f_{BU} are given by

$$f_{BD} = f_R + f_V \quad (4)$$

$$f_{BU} = f_R - f_V \quad (5)$$

Then, we have f_R and f_V as

$$f_R = 4 \cdot \Delta f \cdot R \cdot f_m / C \quad (6)$$

$$fv = 2 \cdot fo \cdot V/C \quad (7)$$

where C is the wave propagation speed (equal to the velocity of light), f_m is the modulation frequency on the triangular wave, f_0 is the center frequency, and Δf is the triangular wave modulation width.

From Equations (3) to (7), we obtain range R and velocity V as

$$R = (f_{BD} + f_{BU})\, C/8\Delta f \cdot f_m \quad (8)$$

$$V = (f_{BD} - f_{BU})\, C/4fo \quad (9)$$

The range and relative velocity can be obtained by measuring the beat frequencies f_{BU} and f_{BD}, where the frequency is lowered or increased, and by calculating the sum and difference of the frequencies.

The power of the wave reflected by the target is obtained from the following radar equation:

$$Pr = \lambda^2 PtGrGt\ \sigma/(4\pi)^3 R^4 LaLr \quad (10)$$

The variables in equation (10) are as follows.

P_t and P_r: power of the wave transmitted and power of the wave received

G_t and G_r: gain of the transmitting antenna and gain of the receiving antenna

R: range from the radar to the target

L_a: attenuation in air

L_r: attenuation due to rain

λ: wavelength

σ: reflection cross-section

In general, automotive radar is required to have a measurement range of from several to 100 meters. Compared to microwaves and shorter wavelengths, millimeter waves attenuate considerably due to rain; in the 60-GHz band, they are attenuated by as much as 16 dB/km by oxygen molecules when propagated in free space. For example, consider the maximum search range of 100 meters. If rain is falling at 100 mm/hour, the attenuation of 9.6 dB is considerably higher than in the case of free-space propagation. These attenuation values must be considered when the antenna gain, transmission power, and other required parameters are designed[4].

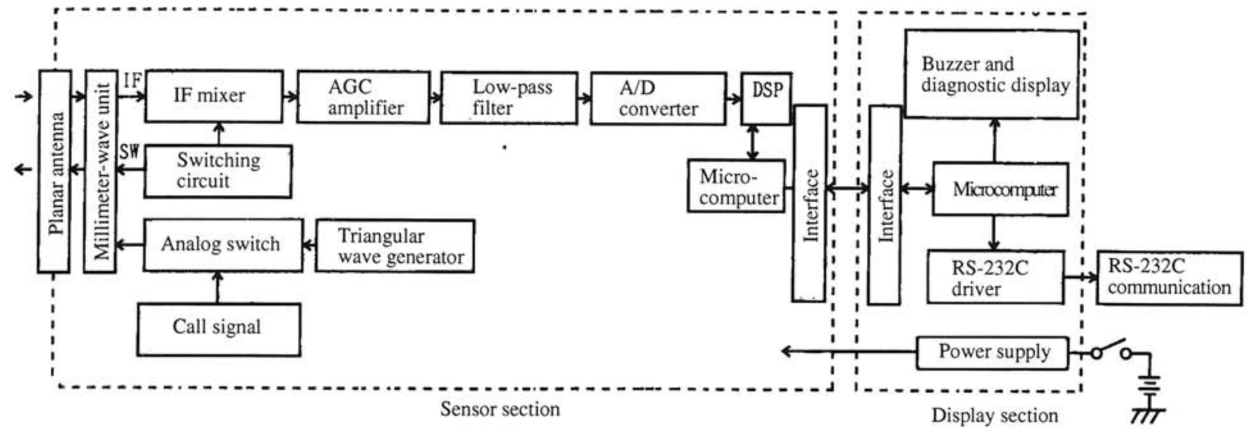


Figure 4. Block diagram of 60-GHz FM-CW radar

3.3 60-GHz millimeter-wave radar

Figure 4 is a block diagram of the 60-GHz millimeter-wave radar. This radar is comprised of a sensor section and a display section. The sensor section consists of an antenna, a millimeter-wave unit, and a signal-processing unit. The display section has the functions needed for outside communication.

Figure 5 shows the exterior of the radar, and Table 2 lists its specifications.

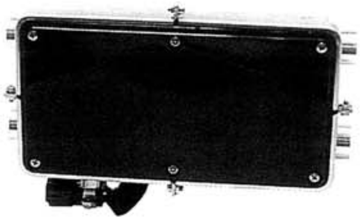


Figure 5. 60-GHz radar sensor

Table 2. Millimeter-wave radar specifications

Parameter	Specification
Radar system	FM•CW
Center frequency	60.5GHz
Transmission power	3 mW or less
Antenna polarization characteristic	45° linear polarization
Beam width	2.8° in azimuth angle 2.8° in elevation angle
Maximum detection distance	Approximately 100 meters
Speed detection range	±100km/h
Processing speed	40msec
Weight	2 kg or less
Dimensions	228 (W) × 123 (H) × 62 (D) mm

This millimeter-wave radar was first delivered in March 1997 to Komatsu Ltd. Komatsu uses it as a sensor for supporting the unattended operation of dump trucks working in mines or stone crushing yards. It is the world's first 60-GHz millimeter-wave radar to be put into practical use. Figure 6 is a photograph of a dump truck equipped with the millimeter-wave radar.

3.4 Antenna

When developing an automotive millimeter-wave radar, it is necessary to consider restrictions on where the radar is installed on the vehicle. This leads to the necessity to reduce the overall size and the thickness of the radar sensor. It should be noted then that the antenna is a component requiring much structure consideration when designing the shape of the sensor.

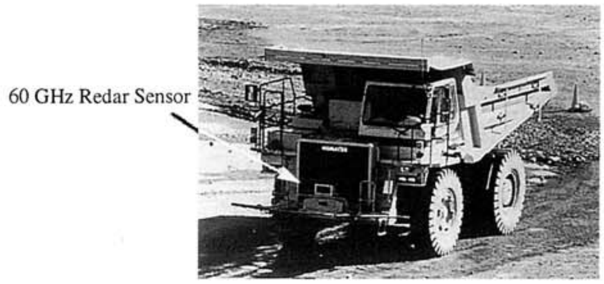
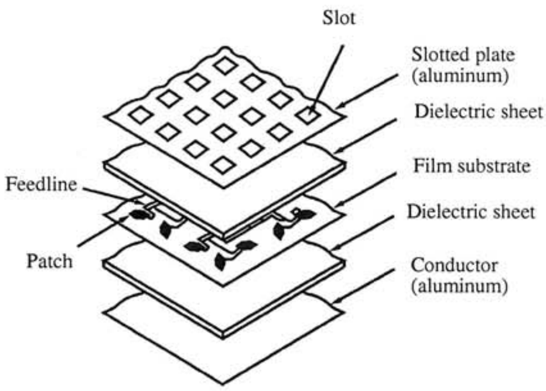


Figure 6. Dump truck equipped with radar sensor

Our sensor uses a 400-element planar antenna with a triplate transmission line structure, because this type of antenna is advantageous for reducing the overall size and thickness of the equipment (Figure 7)[5]. The antenna has a gain of 31 dB, a beam width of 2.8°, and a relative side lobe level of -10 dB or less.



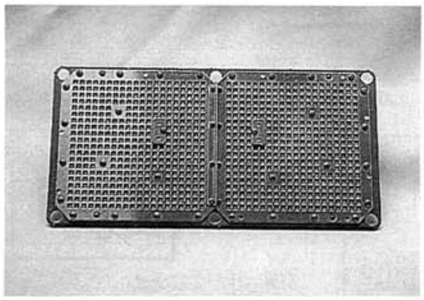


Figure 7. Planar antenna structure

With the increasingly widespread use of automotive radar, radio interference from on-coming automobiles is more likely than ever. To avoid this, our antenna is designed to use linear polarization with the polarization plane inclined 45° to the left when seen from the front of the radar. With this arrangement, the radio interference involved in two approaching automobiles equipped with radar will be reduced by 30 dB or more.

3.5 Millimeter-wave unit

The millimeter-wave unit is the heart of the millimeter-wave radar. It is adjustment-free because a monolithic microwave IC (MMIC) design based on high electron mobility transistors (HEMTs) is used in the transmission/reception section.

Figure 8 depicts the exterior of the millimeter-wave unit and Figure 9 is a block diagram of the unit.

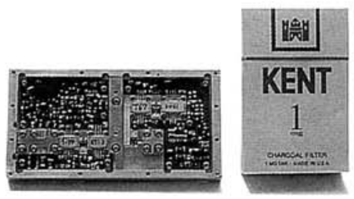


Figure 8. Millimeter-wave unit

The millimeter-wave circuit consists of four modules: a 30-GHz VCO module sealed in an airtight package, a transmission module, and two reception modules. The airtight package was specially developed for use with millimeter-wave bands.

The 30-GHz VCO module is a voltage-controlled oscillator that employs a microwave IC (MIC) that uses GaAs MESFETs and a varactor diode. It receives a triangular modulation wave and produces an FM-modulated 30-GHz signal.

The transmission module doubles the frequency of the 30-GHz high-frequency signal from the VCO module to obtain a 60-GHz signal, then amplifies this signal to a level necessary for transmission. It is based on MMIC design with a doubler and a four-stage amplifier. The MMIC includes AlGaAs HEMTs having a gate length of 0.25 μm and implemented on a GaAs substrate.

Reception module 1 amplifies the weak reflection signal from the target, which is captured at the receiving end of the module. Reception module 2 receives part of the output signal from the sending end via a directional coupler and through frequency conversion produces an intermediate-frequency (IF) signal using the received signal as a local signal. For simple heterodyne reception, the drain voltage of the amplifier is turned on and off to produce the effect of a switch. Like the transmission module, both reception modules 1 and 2 are of the HEMT-based MMIC design to integrate a four-stage amplifier and a frequency converter.

3.6 Signal processing and microcomputer processing

The signal-processing unit consists of a modulation signal generator and a signal processing circuit of a digital signal processor (DSP) design.

In addition to generating a triangular modulation signal, the modulation signal generator also has a circuit that generates a binary FSK signal, which results from converting the call sign specified by the Ministry of Posts and Telecommunications in accordance with the Radio Law.

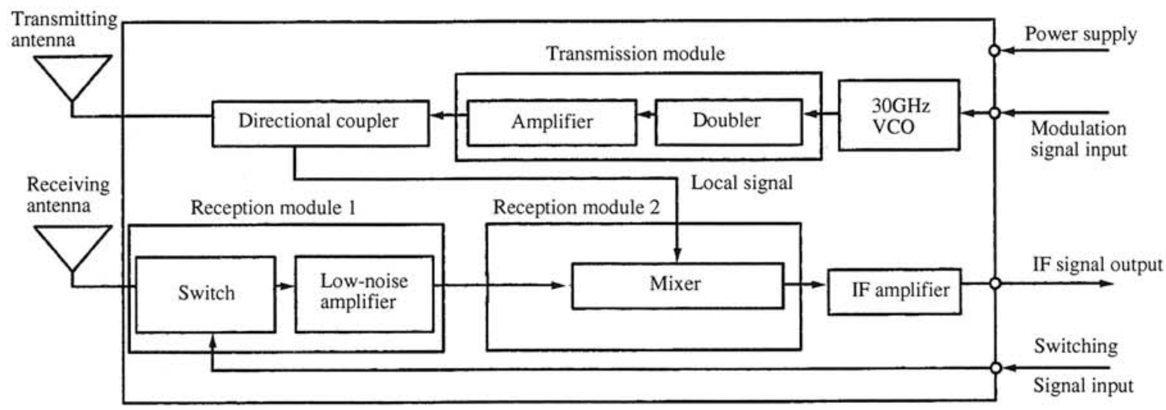


Figure 9. Block diagram of millimeter-wave unit

The beat signal is band-limited through an antialiasing filter (low-pass filter) and then converted to a digital signal.

At the time of the A/D conversion, the signal is sampled to synchronize the frequency with subsequent sampling. After the A/D conversion, the signal obtained during each interval is subjected to a fast Fourier transform (FFT) in the DSP. The range and relative velocity can be determined by substituting the result into Equations (8) and (9).

The microcomputer observes the difference between the relative velocity obtained through range changes and the measured relative velocity. When it exceeds a certain threshold, the microcomputer considers the target to be an unwanted reflection and erases the data. It also observes the continuity of the range and velocity. When it recognizes continuity for one target several times, it assumes that the radar has caught a true target and keeps the data. The continuity of this target is judged by comparing it to that of a previous target. The range and relative velocity obtained are delivered to the display unit as target data.

4. Important design aspects

This chapter discusses the performance and specifications of the radar as important aspects of design.

4.1 Millimeter-wave unit

A simple heterodyne technique operating ideally would assume that the IF carrier does not exist in the IF spectrum. In the millimeter-wave region, however, early models encountered a problem due to incomplete circuit coupling and spatial coupling. This problem caused the IF carrier leak higher than the signal to appear in the IF band spectrum (Figure 10) thus affecting the operation of the circuit dealing with the IF signal. This led to a malfunction

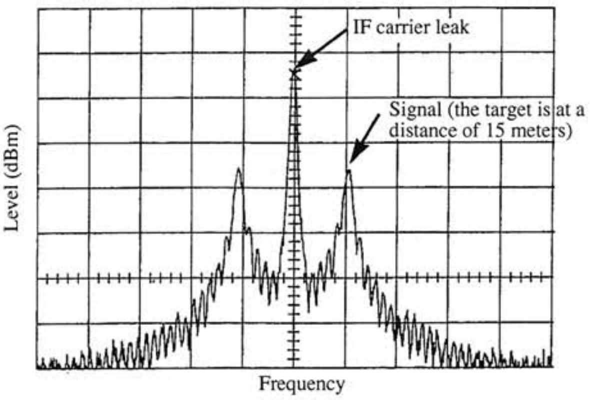


Figure 10. IF output (before the employment of corrective measures)

in the signal-processing unit. The rest of this section describes the cause of this IF carrier leak and its solution.

4.1.1 Cause of IF carrier leak

Early models of millimeter-wave units contained a reception module (shown in Figure 9) that was enclosed in an airtight package.

One of the causes of the IF carrier appearing in the IF signal might be because part of the local signal was fed back to the input of the low-noise amplifier (hereafter referred to as the amplifier). This can be confirmed by a spectral analysis conducted during a non-modulation period.

The cause of this local signal feedback might be ① a local signal leak due to a mismatched impedance at the output end of the amplifier or ② a spatial coupling inside the airtight package that feeds back the local signal to the amplifier input. To verify cause ①, we inserted an attenuator between the amplifier and the mixer and confirmed a reduction of the local signal leak. This reduction was due to the attenuator, which helps eliminate the mismatched impedance problem at the amplifier output end and, as a consequence, reduces the local signal leak. To verify cause ②, we observed the results of removing the cover of the air-tight package.

4.1.2 Solution to the IF carrier leak problem

To solve the problem of the IF carrier leaking to the IF output, we inserted an isolator between the mixer and the amplifier (①). This achieved impedance matching at the amplifier output end and alleviated the problem of the local signal leak. The isolator, which is made of ferrite, a magnetic material, is a two-port passive non-reciprocal device, which produces an output only when the input is from a specific direction.

We also enclosed the mixer and the amplifier in separate packages (②). This helped prevent spatial coupling of the local signal[6].

Figure 11 shows the resulting IF output waveform. This figure indicates that the IF carrier leak was improved by about 30 dBm compared to the early model.

4.2 Filter characteristics

Suppose for example, that the baseband width is 100 kHz. If a peak caused by a target appears at 110 kHz, a sympathetic peak occurs at 90 kHz (100 - 10 kHz) and is interpreted as representing a false target. An antialiasing filter (low-pass filter) is used to prevent the occurrence of sympathetic versions of beat frequencies above 100 kHz.

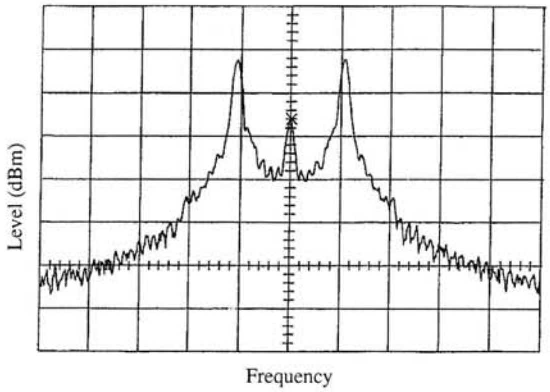
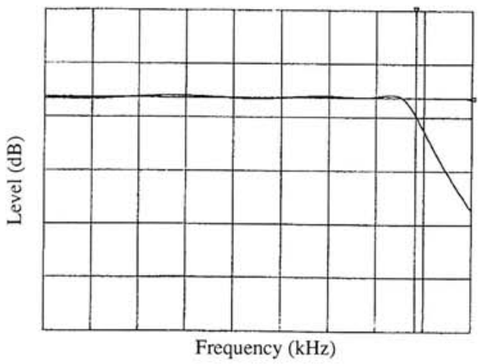


Figure 11. IF output (after the employment of corrective measures)

Figure 12 shows baseband filter characteristics.

Figure 12. Characteristics of antialiasing filter



4.3 Time-series processing

To assure stable radar performance, display data subjected to time-series processing is delivered to the system's computer.

When designing the time-series processing sequence, we determined the number of data required to judge the presence of a target and to assure the best performance in terms of the following processing speed and stability.

Figure 13 shows the measurement results with a sensor fixed at a height of 1.5 meters from the ground and a passenger car passing by in front of the sensor. The data denoted by the dotted line represents measurements taken without time-series processing and suggests that the radar loses the vehicle sometimes at long distances. In contrast, the data denoted by the solid line represents measurements taken with time-series processing and indicates that interpolation was conducted to fill data blanks that occurred when losing the vehicle, resulting in a stable sensor output.

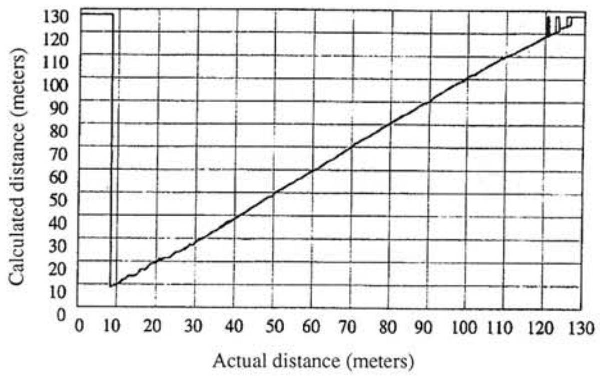


Figure 13. Vehicle running data

4.4 Diagnostic and fail-safe features

A diagnostic feature for detecting radar faults is essential for automotive radar. The principal causes of radar faults are improper connections between the sensor and signal processing unit and damage to the millimeter-wave unit.

The fail-safe feature of our millimeter-wave radar works as follows. The radar monitors data communication errors, faults in the transmitter of the millimeter-wave unit, IF output abnormalities, high temperatures, and other abnormal conditions by constantly measuring communication times and voltages. Upon detecting a fault, it sends out a certain diagnostic code to notify the remote computer.

4.5 Breathing structure

The sensor section of this millimeter-wave radar must be completely watertight for practical use because the radar is installed on the front of an automobile. Watertight structures include sealed, potting, and breathing structures. Considering the advantages, disadvantages, and feasibility of each, we decided to use a breathing structure.

In selecting a breathing structure, we considered that the radar should be able to withstand immersion into water at a temperature differing by 70°C from the atmospheric temperature. We adopted the following design concepts:

(1) The structure should include a component-free space so that air cannot enter or exit the sensor section directly.
(2) The component-free space should contain air passages arranged in a grid so that the sensor does not admit the entry of water or mud.

With this in mind, we succeeded in fabricating a sensor that contains a component-free space whose volume is 30% of the total interior volume of the sensor and which satisfies the required water-tightness. To verify the water-tightness, we conducted a water immersion test and confirmed that the structure encountered no problems. The water immersion test consisted of repeatedly heating the sensor in a high-temperature oven at 85°C and immersing it in water at 15°C. Water did not enter the component-loaded space.

In addition to providing this component-free space, we also tried to reduce the thickness of the millimeter-wave unit. To achieve this, we reduced the thickness of the component-loaded space.

5. Radar performance

This chapter concentrates on the results of evaluation tests conducted in the field.

5.1 Characteristics of target reflections

The reflection cross-section (RCS) from a target depends on the target shape, radio wavelength, and incident angle. An object exhibits a sharp directivity if it is regarded as a plane when seen in the direction of the wavelength. A complex surface, such as the rear of an automobile, however, causes the reflected wave to diverge.

A general method for determining radar performance is to emit radio waves in a wide-open space and then measure the reception level of the reflected waves. However, different targets give different results. The measured reception level may vary with the same target according to the angle at which the radio wave hits the target. Considering these restrictions, we used a standard reflector (corner reflector) for radar performance measurement.

Figure 14 shows the structure of the corner reflector. Its shape is obtained by cutting one corner of a cube obliquely. Each side is made of smooth sheet metal so that it reflects incident waves completely.

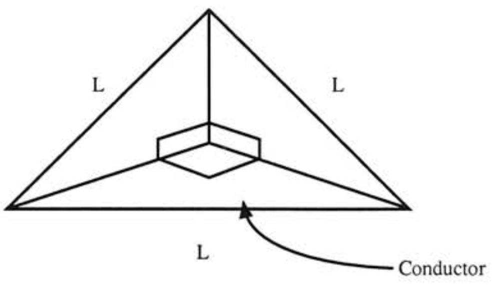


Figure 14. Corner reflector

The RCS is given by the following equation.

$$RCS = \pi L^4 / 3\lambda^2 \quad (11)$$

For example, assuming 60 GHz and RCS = 10 dB, Equation (11) gives L = 0.12 meters. The RCS of the corner reflector used in our tests was 12.2 dB (at 60 GHz), which is nearly equal to that of a passenger car.

5.2 Distribution of received wave intensities reflected by the standard reflector

Figure 15 displays the results of the measured intensities of received waves reflected by corner reflectors placed at 10-meter intervals. The sensor and corner reflectors were 1.5 meters above the surface of an asphalt-paved road. The test was conducted under clear conditions. Multipath reception caused the waves to either increase or reduce the intensity of other waves. This is observed as peaks and valleys in the figure.

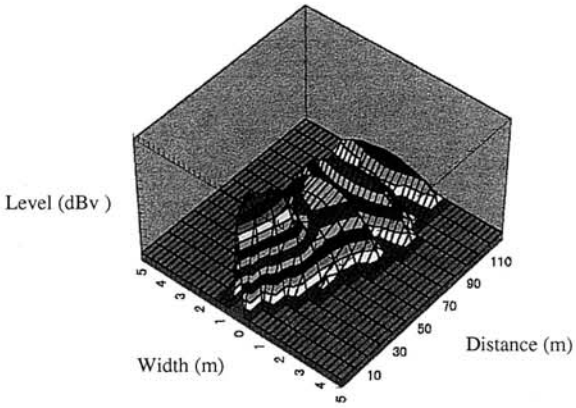


Figure 15. Distribution of wave intensities received on an asphalt-paved road

Figure 16 shows the simulation results of multipath reception under the same conditions. These results well agree with the results of actual measurement.

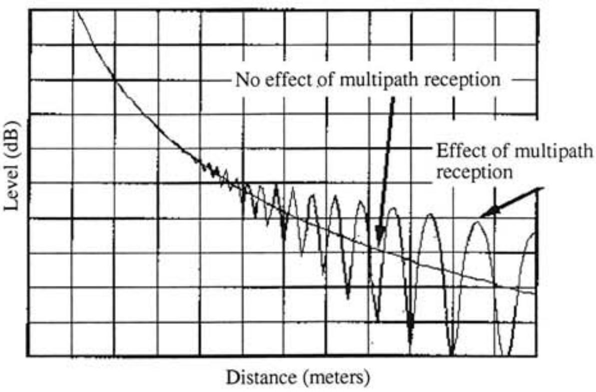


Figure 16. Simulation of multipath reception

To evaluate radar performance in bad weather conditions, we measured the distribution of wave intensities reflected by corner reflectors when snowing. Measurements were conducted when the target vehicle and when the sensor's front were covered with snow. The results are discussed below.

5.3.1 Distribution of received wave intensities measured on a snow-covered road

Figure 17 shows the distribution of received wave intensities measured on a snow-covered road. Although the test conditions were the same as in Figure 15, this figure indicates that the distribution varies when the road conditions change, particularly at long distances. The reason is that the index of reflection varies between locations on the road, and therefore the behavior of multipath reception changes accordingly.

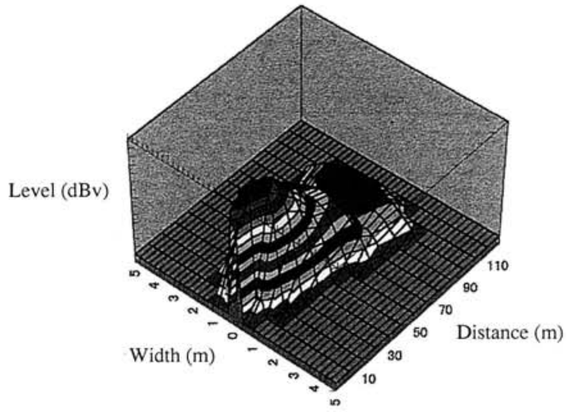


Figure 17. Distribution of received wave intensities measured on a snow-covered road

5.3.2 Snow-covered target vehicle

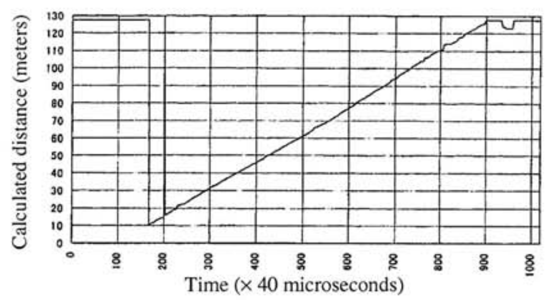
We evaluated if the recognition performance of the radar depends on whether or not the target vehicle is covered with snow. Figure 18 shows two photographs depicting a vehicle not covered with snow (a) and a vehicle covered with snow (b). In photograph (b), the rear of the vehicle is entirely covered with snow. These vehicles were driven on a snow-covered road.

The results are given in Figure 19. A target vehicle being covered with snow does not lead to a significant difference in the recognition performance. In either case, the target was recognized at about 125 meters. It has thus been confirmed that snow on targets is not so influential on radar performance.

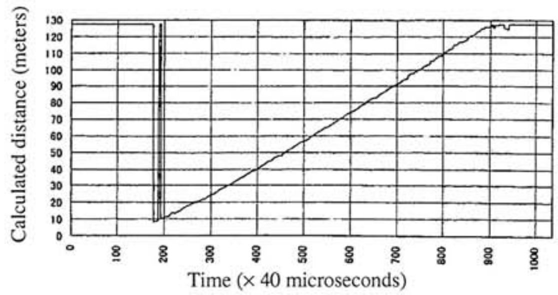
(a) Vehicle not covered with snow

(b) Vehicle covered with snow

Figure 18. Vehicles for testing the influence of snow on radar performance



(a) without covered snow



(b) with covered snow

Figure 19. Results of tests conducted to evaluate the influence of snow on vehicles

5.3.3 Sensor front covered with snow

Table 3 gives the results of evaluating the maximum recognition ranges observed when the sensor front was covered with snow. In actuality, an expanded polystyrene box (10-mm thick) was packed with snow and placed in front of the sensor. We had already confirmed that expanded polystyrene does not influence the performance. The results demonstrated that the recognition performance is influenced by the amount of snow in front of the sensor. When the snow was 2-cm thick, it did not affect the recognition performance of the radar. At 4 cm, the maximum recognition range was reduced by about 30%. It is therefore necessary to check the amount of snow on the vehicle when actually using the radar for target recognition while considering where the sensor is installed on the vehicle. This evaluation conducted has also proven that the thickness of the snow is influential, whereas the density of the snow is not.

Table 3. Effect of snow covering the sesor front

Amount of snow on sensor	Maximum detection distance
None	125 m
4 cm of fresh snow	96 m
8 cm of fresh snow	94 m
4 cm of fresh snow compacted down to 2 cm	125 m
8 cm of fresh snow compacted down to 4 cm	98 m

5.4 Product reliability

We conducted various tests on the millimeter-wave radar and confirmed its high reliability.

We established the test conditions for these reliability tests by considering the various environments in which the sensor may be used. For temperature, humidity, vibration, and water-tightness tests in particular, we set up test accelerations and combined various tests to subject the product to complex conditions. The radar has been proven to be reliable in harsh environments.

We also tested the individual components in the same manner as the radar as a whole and found no problems with them.

6. Conclusion

Extensive efforts are being made in Japan, Europe, and the U.S. for national projects to put millimeter-wave radar into practical use. Millimeter-wave radar is expected to be used in automobiles for maintaining safe inter-vehicle distances and to provide danger warnings as integral components of Intelligent Transport Systems (ITSs) and Automated Highway Systems (AHSs). They are expected to be key components of the infrastructures needed for implementing such systems. There is strong demand for their practical use.

We plan to make further efforts to develop millimeter-wave radar of smaller sizes, lighter weights, and lower costs in order to satisfy what users really want.

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