UDC:621.396.96

High Performance Automotive Millimeter Wave Radar System

● Masatsugu Kamimura ● Kanako Honda ● Yasuhiro Fujita

Fujitsu TEN has developed a practical automotive millimeter-wave radar system with digital signal processing (FFT). The radar uses Fujitsu TEN's own FT8802 digital signal processor to find the frequency of radar beat signals in real time.

As more emphasis is placed on safety, a radar system that senses objects around a car will become a valuable feature.

Our system measures distance and speed accurately and with good stability, and can also distinguish two or more targets in the radar detection area.

A new signal processing algorithm achieves the following: highly accurate frequency identification using phase information, effective noise suppression, and predicting a target frequency using previous observation results.

This paper describes the measurement principle of millimeter-wave radar, outlines an experimental system, discusses the advantages of our new signal processing algorithm compared to a conventional system, and presents results of evaluating an experimental system.

1. Introduction

Intensive study of automotive microwave radars began in the U.S.A. around 1970. Although a practical automotive radar was expected to be developed quite quickly, more than 20 years have passed without success because of various problems. For example, millimeter wave devices needed to make radars smaller were restricted to military use and were not generally available, the oil crisis caused a business downturn, and radio wave authorities imposed restrictions on microwave use.

Low performance of early high-frequency devices and signal processing held back a practical automotive radar. Microwave devices have since made great progress. In particular, high-speed and highly accurate signal processing is now easy using a DSP because microprocessors are widely used and their performance has improved. Obstacles that prevented smaller-size and higher performance automotive radars are being removed one by one.

We have developed a very practical radar system that uses a technique of frequency analysis in FM-continuous-wave (CW) radar signal processing to solve conventional problems. This report describes our new radar system.

2. Overview of a millimeter wave radar

2.1 Features of a millimeter wave radar

An automotive radar must have excellent environment resistance and characteristics to operate in a moving vehicle. Millimeter waves have many desirable properties. For example, they are less affected by sunlight, fog, snow, and mud than light, and are not affected by the color or material of objects. Also, millimeter waves are less affected by air turbulence than supersonic waves.

The antenna unit of a millimeter wave radar can be made smaller and lighter than many conventional products that use radio waves in the microwave range. A millimeter wave radar system also has the advantage that it can measure relative speed very accurately because its Doppler shift is large.

Radars are classified into various types, including CW radars and pulse radars. We chose the FM-CW type because the high-frequency circuit unit is relatively easy to build, and distance information and relative-speed information can be obtained at the same time.

2.2 Principle of measurement

Figure 1 shows the principle of measurement by the FM-CW millimeter wave radar.

The high-frequency transmitted signal emitted from the sensor is modulated using a frequency f_0, modulation repetition frequency is f_m, and frequency deviation is ΔF. The radar signal is reflected by the target, and the radar sensor receives the reflected signal. Beat signals are obtained from the transmitted and received signals, and the beat frequency is proportional to the distance between the target and the radar sensor. The signals in the modulation frequency up and down intervals, f_{up} and f_{dn} (called up and down intervals from here on), are analyzed to produce a pair of frequencies. Expressions 1, 2, and 3 give the relative distance and speed of the target.

$$f_b = \frac{4 \cdot \Delta F \cdot f_m}{c} \cdot R \pm \frac{2 \cdot f_0}{c} \cdot V \quad (1)$$

$$R = \frac{c}{2 \cdot \Delta F \cdot f_m} (f_{dn} + f_{up}) \quad (2)$$

$$V = \frac{c}{f_0} (f_{dn} - f_{up}) \quad (3)$$

Relative speed and relative distance can be determined by measuring the beat frequencies.

3. Millimeter wave radar system using a DSP

3.1 Development aims

If there is more than one target within the detection area, as shown in Figure 2, the beat signal is composed of two or more sine waves. Conventional frequency identification by counting pulse-shaping waves cannot separate these multiple waves.

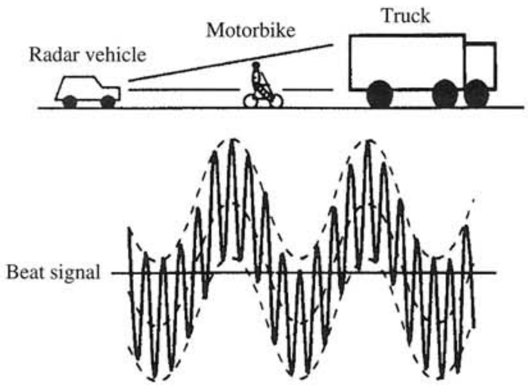

Figure 2. Multiple targets and beat signal

Our development aims were to recognize multiple targets and to measure distance and speed highly accurately. To do this, we use a DSP with floating-point capability to analyze the frequencies in the beat signal directly and in real time.

3.2 Specifications

Table 1 lists the specifications of the prototype millimeter wave radar system.

Table 1. Radar system specifications

Modulation method	FM-CW
Carrier center frequency	49.5 GHz
Modulated-frequency deviation	75 MHz
Beam angle	2°
Detecting distance	5 to 100 m
Distance error	5% Max.
Speed error	5 km/h Max.
Recognition of two or more targets	Possible
Distance of target resolution and recognition	5 m

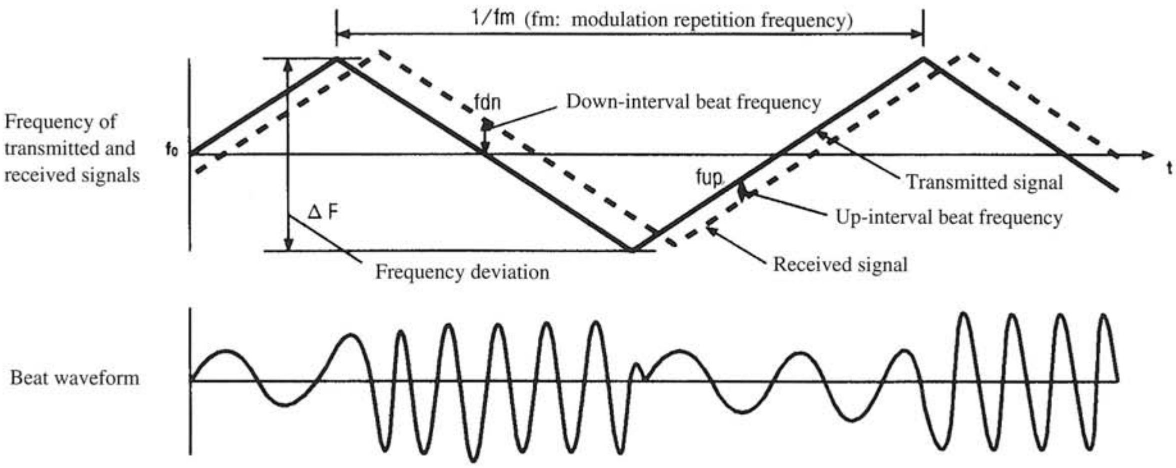

Figure 1. Principle of FM-CW

3.3 System configuration

3.3.1 Outline

Figure 3 shows the configuration of the millimeter wave radar system. The radar system consists of a sensor unit, a signal processing unit, and a control unit.

The sensor unit transmits and receives high-frequency signals, and outputs a beat signal generated by mixing the transmitted and received signals.

The signal processing unit converts the beat signal into discrete signals, and analyzes their frequencies. This unit then calculates the relative distance and speed of the target.

The control unit operates according to the radar application. For example, the radar may detect a collision danger and issue an alarm. Or, it may control the throttle to maintain a constant distance between two cars.

3.3.2 Sensor unit

The sensor consists of antennas and a high-frequency circuit unit.

Transmitting and receiving antenna for 2° by 6° beams are formed by combining a parabolic and a slot antenna. The antennas are arranged in a V shape to obtain a sharp beam angle of 2° by 2°. This beam angle gives a detecting width of one highway lane (3.5 m) for a distance of 100 m.

The high-frequency circuit unit sends the signal fed from the oscillator to the transmitting antenna via a directional coupler. This signal is emitted forwards from the front of the vehicle. The receiving antenna receives the signal reflected by the target. The received signal is fed to a mixer and mixed with the local signal branched from the directional coupler. This generates a beat signal.

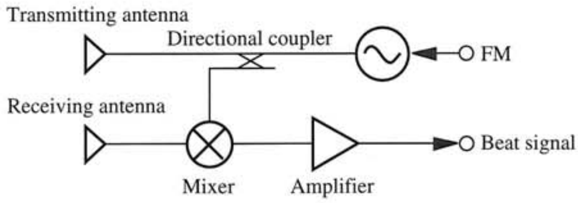

Figure 4. Radar sensor configuration

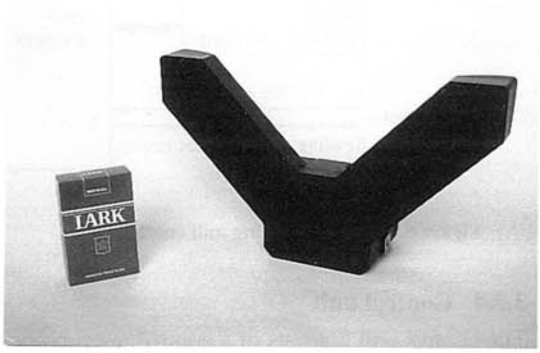

Figure 5. Radar sensor

3.3.3 Signal processing unit

We used Fujitsu TEN's own FT8802 DSP as the signal processing IC. Data was 24 bits (18-bits mantissa, 6-bit exponent). The DSP can perform both fixed-point arithmetic and floating-point operations. The basic instruction execution cycle is 75 nanoseconds. A fixed-point arithmetic instruction takes one cycle, and a floating-point instruction takes two cycles.

The RAM is 24 bits by 4 kilowords, 2 kilowords of which are used for FFT.

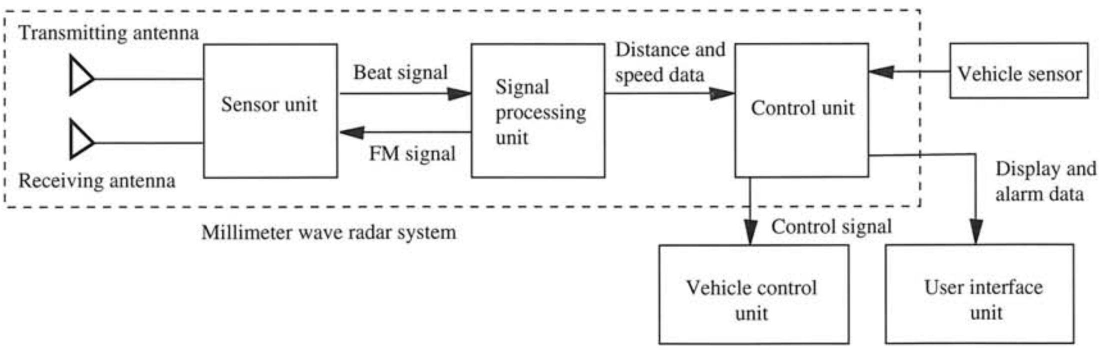

Figure 3. Radar system configuration

The analog-to-digital converter has a resolution of 12 bits, to handle the dynamic range of the beat signal. The converter samples signals at 200 kHz.

Figure 6 shows the configuration of the signal processing unit.

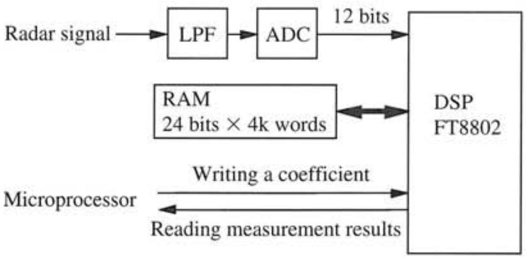

Figure 6. Signal processing unit configuration

3.3.4 Control unit

The control unit consists of a control microprocessor and an input-output section.

The control unit receives various sensor signals (e.g., the vehicle speed sensor signal, the steering sensor signal, and the brake signal), and the microprocessor calculates individual parameters. The signal processing unit sends information about the distance and the relative speed of the target to the control unit as serial signals. Based on this data and values calculated by the sensor, the control unit calculates the safe distance between two cars, issues an alarm, and controls the throttle.

The control unit provides the driver with information on a data display.

3.4 Signal processing

3.4.1 Frequency identification

For high accuracy, a radar system must exactly identify the peak frequency in the beat signal. If FFT is used for frequency analysis, frequency resolution must be carefully designed because the time for acquiring data is limited.

If the observation time is T, the frequency resolution Δf is given by expression 4.

$$\Delta f = \frac{1}{T} \tag{4}$$

The observation time T is calculated from expression 5, where fs is the sampling frequency and N is the number of FFT points. The frequency resolution Δf can, therefore, also be calculated from expression 6.

$$T = \frac{N}{f_s} \tag{5}$$

$$\Delta f = \frac{f_s}{N} \tag{6}$$

Simply increasing the number of FFT points N to obtain the required frequency resolution is not practical because the operation time increases. Instead, we used frequency identification from phase information (i.e., complex-frequency interpolation). Our method involves only simple vector operations and identifies frequencies highly accurately.

Figure 7 shows the phase of the frequency with peak energy and the principle of frequency identification.

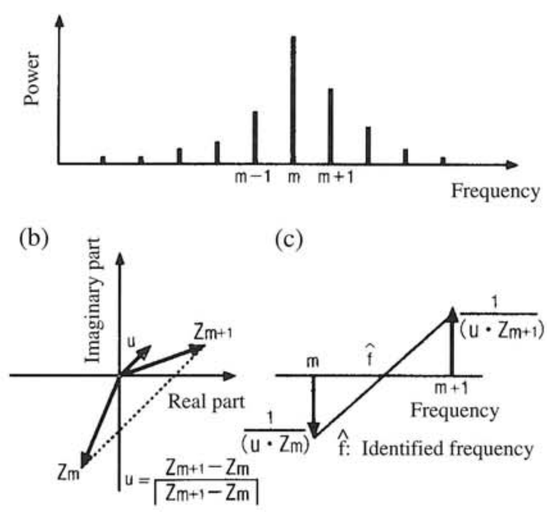

Figure 7. Phase of peak frequency and frequency identification

3.4.2 Suppressing noise

The peak frequency of the beat signal identified from individual FFT results varies because it is affected by reflection of radio waves, small movements of the target, and other factors. The peak frequency also varies if the beat signal contains noise. Therefore, some steps must be taken to eliminate noise in order to stabilize measurement.

In general, the results of FFT performed several times are summed for each spectrum component to eliminate random noise from the FFT results. This method greatly improves the signal-to-noise ratio because white noise averages out to zero.

The measuring time for one FFT operation is only 0.64 millisecond. This is short enough to eliminate changes in the peak frequency almost entirely. Summing several spectra therefore effectively suppresses noise.

This method has the problem that phase information needed for frequency identification is lost as a result of summing. To avoid this, we eliminated noise after frequency identification by applying the results of summing.

The processing procedure is as follows:

1) The peak frequency is identified on the basis of individual FFT results by complex-frequency interpolation. The result of identification is stored in memory.
2) The results of FFT, repeated several times, are summed, then the point with the peak value is selected as a possible actual peak frequency.
3) Each of the peak frequencies stored in memory is compared with the possible peak frequency. If the comparison finds matching frequencies, the actual peak frequency is determined. A frequency that is not associated with a frequency in memory is considered to be noise and is removed.

Figure 8 outlines noise suppression.

3.4.3 Measurement stabilization by prediction

If distance and speed are calculated from results obtained each time frequency is measured, calculation results will vary and, in some cases, calculation cannot be made. Possible causes of these problems are detection failure caused by a temporary drop in the signal level and the effect of noise that could not be eliminated.

Because targets do not suddenly appear or disappear, measurement can be made more stable if the relationship with previous measurement results is considered.

As shown in Fig. 9, the next peak frequency to be measured is estimated from previous measurement results. An attempt is made to associate the estimated peak frequency with the next measured value for each target. Associated peak frequencies are stored for each target. If a peak frequency cannot be associated, a new target is assumed and that peak frequency is stored.

Stored frequencies are processed, by complementing or filtering, to calculate the relative distance and relative speed of the target. The number of frequencies stored for a target in a fixed time might be less than the specified number because, for example, the level of the received signal was low. In such cases, the results for that target are not output to prevent noise from being mistaken for a signal.

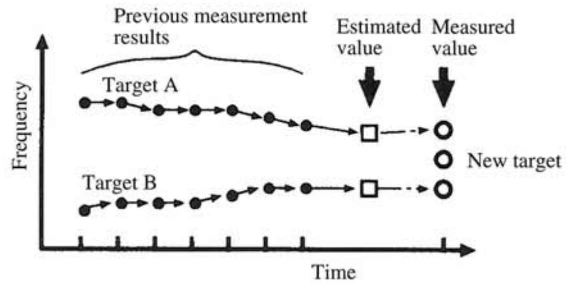

Figure 9. Target frequency prediction

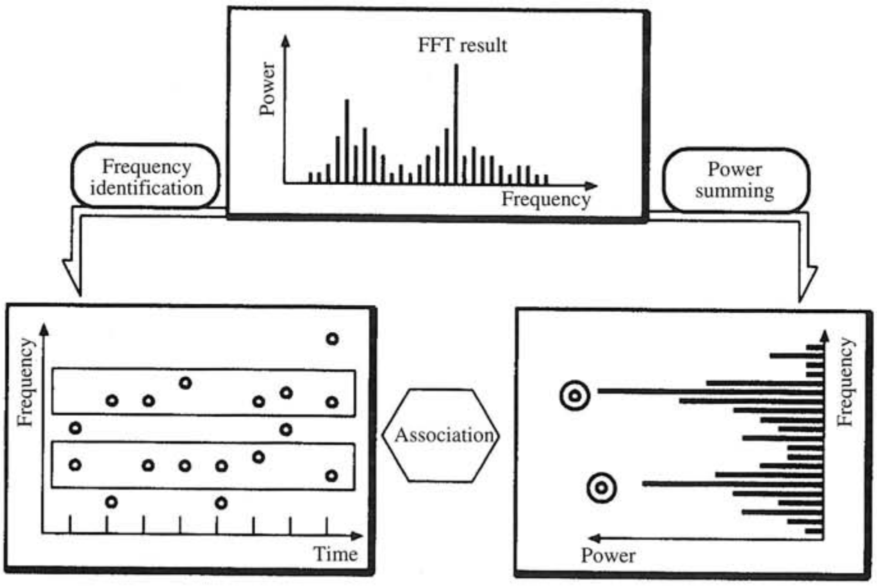

Figure 8. Noise suppression

4. Experimental results

4.1 Recognizing a stationary target

We moved and stopped a car in front of a radar sensor in steps of 5 m, from 5 m away from the radar sensor to 100 m away from it, to evaluate radar performance when measuring a single stationary target. Figure 10 shows the results.

The largest measurement error of the radar was less than 1 m, so performance is satisfactory.

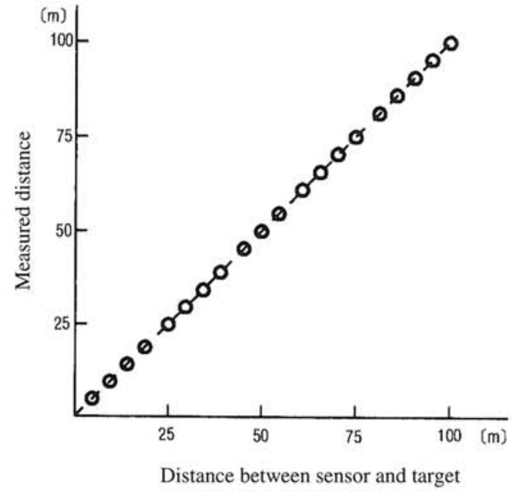

Figure 10. Stationary-target measurement

4.2 Recognizing multiple targets

We placed a van 60 m in front of a radar sensor, and moved and stopped a 125-cc motorbike in steps of 5 m, from 5 m away from the radar sensor to 55 m away from it, to check multiple-target distinction and detection performance. Figure 11 shows the results.

The radar sensor correctly measured distances, although the measured distance to the van, which was a long way from the radar, was about 1 m less than the actual distance in some cases. The radar sensor was able to distinguish the two targets.

When the distance between the sensor and the motorbike was less than or equal to 20 m, the van was not recognized. This problem occurred because the wave reflected from the van was masked by the motorbike, which was directly in front of the receiving antenna of the sensor. While traveling on the road, a motorbike often moves to the right and left. In such a case, the sensor correctly recognizes both targets.

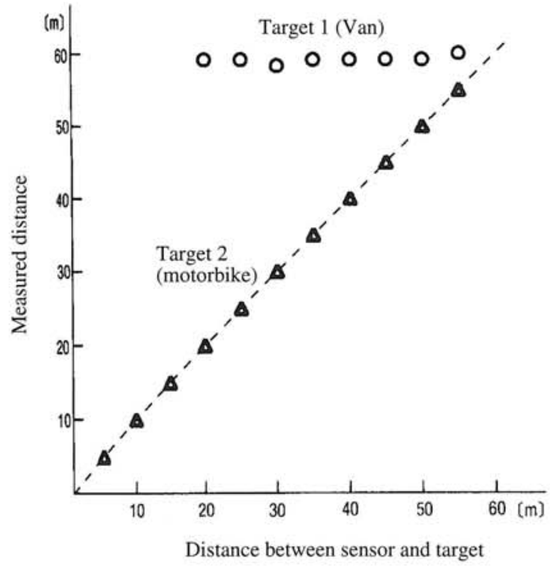

Figure 11. Results of two-target measurement

4.3 Evaluation for a moving vehicle

Figure 12 shows measured data when the radar vehicle was running on a test course, with a varying distance to the car ahead.

The measured distance, speed accuracy, and response characteristics are satisfactory. The radar also recognizes the target correctly when the vehicle is running.

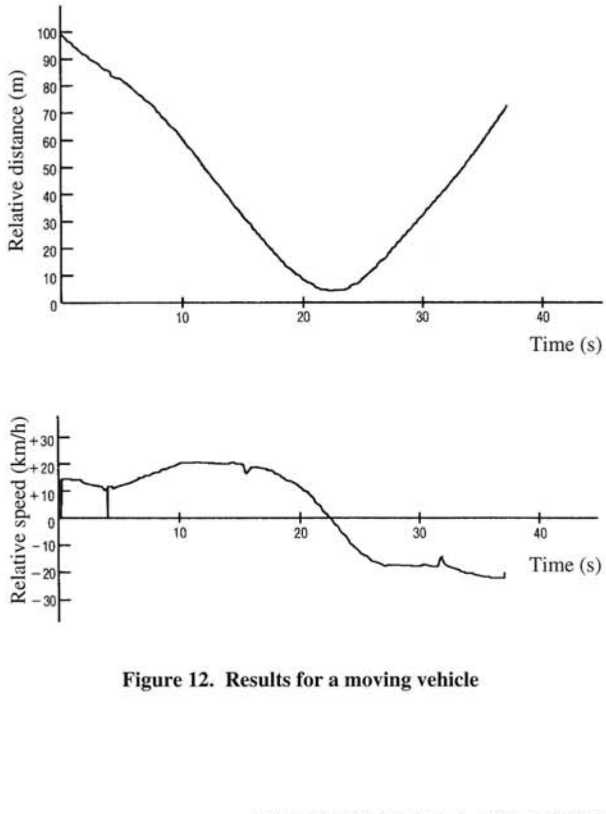

Figure 12. Results for a moving vehicle

5. Summary

We used a DSP to process radar signals. We developed a reliable radar system that accurately measures distance and speed. Evaluation of a prototype system confirmed the effectiveness of frequency analysis using FFT, noise suppression, and a signal processing algorithm to estimate target frequency.

The error in measured distance is 5 percent and the speed error for a moving vehicle is +3 km/h. This performance suggests that the developed millimeter wave radar system will soon find practical applications.

Several issues remain to be solved in the future to produce a more reliable system. One is to reduce the frequency at which the multipath propagation and interference of radar waves make the target invisible. Another is to prevent an object beside a curve in the road from being recognized as a target. Others are to develop an alarm system for distance between cars and to develop a radar system linked with another system such as adaptive cruise control system.

We will make antennas smaller by using ICs in sensors, and will simplify the signal processing circuit. These improvements will give us an inexpensive system with high performance.

Finally, we thank Mr. Shigematsu at Toyota's Higashi Fuji Research Center for his useful advice while we were developing this system. We also thank the staff of Electronics Engineering Division 3, who helped us to evaluate our system.

Fujitsu TEN has developed a practical automotive millimeter-wave radar system with digital signal processing (FFT). The radar uses Fujitsu TEN's own FT8802 digital signal processor to find the frequency of radar beat signals in real time.

As more emphasis is placed on safety, a radar system that senses objects around a car will become a valuable feature.

Our system measures distance and speed accurately and with good stability, and can also distinguish two or more targets in the radar detection area.

A new signal processing algorithm achieves the following: highly accurate frequency identification using phase information, effective noise suppression, and predicting a target frequency using previous observation results.

This paper describes the measurement principle of millimeter-wave radar, outlines an experimental system, discusses the advantages of our new signal processing algorithm compared to a conventional system, and presents results of evaluating an experimental system.

Masatsugu Kamimura

Employed by Fujitsu TEN since 1986. Engaged in developing digital audio and radar signal processing systems. Currently in the Communication Engineering Department, AVC Division.

Yasuhiro Fujita

Employed by Fujitsu TEN since 1970. Engaged in developing electronic equipment for automobiles. Currently in the Engineering Department II, Vehicle Electronics Devision.

Kanako Honda

Employed by Fujitsu TEN since 1988. Engaged in developing millimeter-wave radar systems. Currently in the System Research & Development Department, Vehicle Electronics Division.