Applications of Millimeter-Wave Sensors in ITS

by Shigeaki Nishikawa and Hiroshi Endo**

ABSTRACT There is considerable public and private support for intelligent transport systems (ITS), which promise spectacular improvements in road traffic safety and transportation efficiency. This paper deals with research efforts relating to radar sensors using millimeter-wave technology, which is fundamental to enabling the all-weather operation of ITS. One of these is for an automotive radar and is used for forward looking and to detect the distance and relative velocity of vehicles ahead. The other is a radar for infrastructure (right-of-way installation) and is used to detect obstructions and vehicles. Both use spread-spectrum (SS) technology, which offers outstanding performance in separation and detection of multiple vehicles. The automotive radar has multiple receiving antennas to determine the direction in which the target lies, using a method whereby the angle is calculated by comparing the power of the signals.

1. INTRODUCTION

Intelligent transport systems (ITS) are under active development worldwide as a means of reducing loss of life and limiting economic and environmental costs. In Japan, the Ministry of Construction and other government agencies have been carrying out a variety of projects since the 1970s, but in July 1996 these were unified into a national project. This was jointly announced as a "Basic Guidelines on the Promotion of ITS" by five government agencies--The National Police Agency, The Ministry of International Trade and Industry, The Ministry of Transport, The Ministry of Posts and Telecommunications and The Ministry of Construction. The scheme proposed 20 user services, and serves as a blueprint for efficient and systematic R & D and commercial introduction.

This paper reports on applications of millimeter-wave sensors in ITS, specifically an automotive millimeter-wave radar using spread-spectrum (SS) technology, and an obstacle and vehicle detection radar for installation on the road right-of-way.

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2. Automotive Millimeter-Wave Radar Using SS Technology

2.1 Automotive Radar and Its Applications

Of the wide range of technologies used in ITS, millimeter-wave technology is an important element applicable to the sensors (radar) and communications. Because its performance is particularly unaffected by weather, it has attracted attention as a replacement for infrared laser radar systems currently in use, and is itself nearly ready for commercial launch.

Automotive millimeter-wave radars are used in such applications as forward looking to warn drivers of dangers, and studies are under way on using it to measure the distance to vehicles ahead and to maintain constant intervals between vehicles. It is hoped that the wider use of automotive millimeter-wave radar will reduce serious traffic accidents that so frequently occur on limited-access highways in foggy or snowy conditions.

In addition, automotive millimeter-wave radars could be used to monitor the driver's "dead zone", and serve as a peripheral monitoring sensor in the automated cruising systems of the future. Studies are also under way in ITS areas besides vehicles, such as detection of obstacles on the road, detection of moving vehicles, etc.

Systems applying automotive millimeter-wave radar include collision avoidance and cruise control featuring interval control, and development is under way toward commercially viable products.[1)] Table 1 shows typical performance requirements for a radar for autonomous intelligent cruise control (AICC). The main issue is the provision of wide-range angle measuring capability.

Table 1 Typical AICC Radar Performance Requirements

Maximum range	100 ~ 120 (m)
Relative velocity	± 200 (km/h)
Range accuracy	± 3 % (min ± 1 m)
Relative velocity accuracy	± 3 % (min ± 1 km/h)
Field of view	14 ~ 20 (˚)

2.2 Features of SS Method, and Prototype Configuration and Specifications

Considered for automotive radars, the SS method has a number of features that make it easy to achieve the following characteristics: [2)~7)]

- Accurate distance measurement;
- Separation and detection of multiple vehicles located in the range direction;
- Accurate measurement of reception power; and
- Interference eliminating capability.

It is reported that, in the FMCW method, ranging is governed by the linearity of the local millimeter-wave transmitter, whereas in the SS method, even when the phase noise characteristics of the transmitter are poor, compensation is provided by the mixer, making it more advantageous in the development of millimeter-wave transmitters.[4)]

For the reasons mentioned above, the SS method was considered more suitable for automotive radar, and it was used in the development of the millimeter-wave radar.

Table 2 shows the specifications of the prototype radar.

Table 2 Specifications of Prototype Radar

Item	Specifications
Modulation method	Direct-sequence SS
Frequency	76.5 GHz
Bandwidth	480 MHz
Output power	–2 dBm
PN sequence	M-sequence, 127 chips Chip rate: 24 Mchip/s
Antennas	Tx: 1 (11˚ (AZ)) Rx: 3 (4˚ (AZ))
Range	100 m
Relative velocity	±200 km/h

With respect to angle measurement, a method was adopted whereby the signals were received by three antennas of different directionality. The power information received by each is detected at the stage of SS signal demodulation, and angle information is taken from their amplitude intensity ratios.

Figure 1 shows the hardware configuration of the prototype radar. A 1-GHz intermediate frequency band signal is modulated by a PN sequence in the IF circuit. The spread signal is up-converted to 76.5 GHz in the RF circuit, and is then transmitted from the transmitter antenna.

This transmitted signal is then reflected from an object in front of the radar, and received by the three receiver

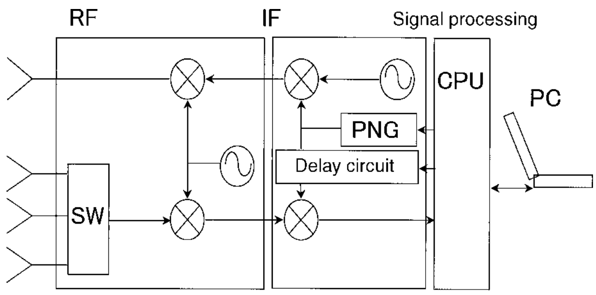

Figure 1 Hardware configuration

antennas. After each of the received signals is selected sequentially at the switch provided in the RF circuit, it is down-converted to the IF signal by the local signal of the millimeter-wave used in the up-converter and sent to the signal processor, which comprises, in addition to the control circuitry, the following algorithms:

- object detection algorithm,
- object tracking algorithm, and
- angle measurement algorithm

The radar detects the distance, the relative velocity and the reflected power of multiple objects using object detection algorithm. In the object tracking algorithm, multiple objects are tracked based on the features of values instantaneously measured, which are then time-stream processed and assigned to the objects. In the angle measurement algorithm, the output data of the object tracking algorithm for the identical object received by each receiving antenna are selected, and amplitude information based on received power is compared, analyzed and processed to estimate the angle of the object.

2.3 Performance Evaluation

Figure 2 shows the evaluation system for field test. The RF unit of the prototype radar was mounted near the front grille, and the IF and signal processing units were positioned inside the cabin. The situation evaluated was recorded on video tape.

The first items of performance evaluated were for distance and relative velocity on a limited-access highway straight-away, using a passenger vehicle as the target. Figure 3 shows the results, which confirmed that the prototype radar could provide stable measurements of the distance and relative velocity of a vehicle in front at ranges of up to 100 m. A separate static test confirmed that distance measurements were accurate to within approximately ±1 m. Evaluations were also conducted using a number of passenger vehicles as the targets, and similar

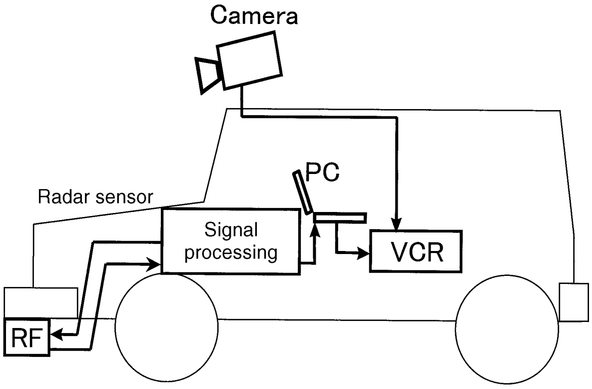

Figure 2 Evaluation system

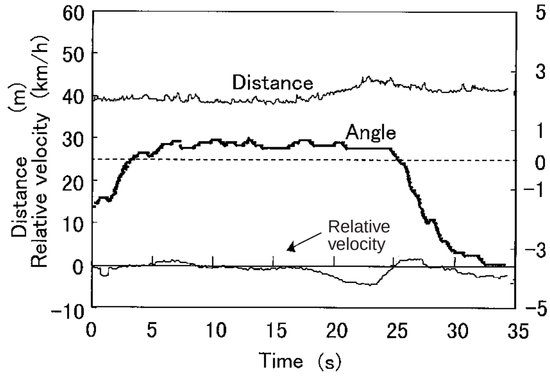

Figure 4 Example of angle, distance and relative velocity measurements

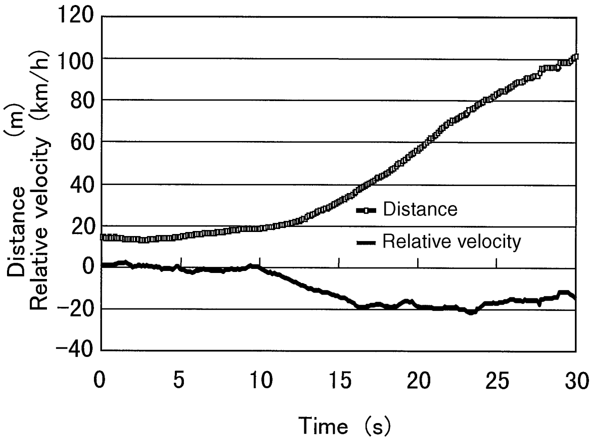

Figure 3 Example of distance and relative velocity measurements

performance was confirmed for each of them.

Next the performance of the angle measurement method was evaluated on a curved section of limited-access highway having a radius of approximately 300 m. Figure 4 shows the results, which confirmed that the prototype radar was capable of stable measurement of the angle of a passenger vehicle running approximately 40 m ahead within a range of ±4°.

2.4 Accuracy and Range of Angle Measurements

The accuracy of the angle measurement method was evaluated by a test conducted under four sets of static conditions: with a vehicle placed at orientation θ of 3 and 4°, and distance L of 30 and 40m. Figure 5 shows the results. The white squares on the plots represent measured values, while the vertical lines show the width of the vehicle at each distance. In all cases, it was confirmed that the measured value was within the vehicle width range.

The tests demonstrate that stable angle measurements were possible up to a range of approximately 40 m. Since with the method adopted here it is essential that stable detection of a single object be provided almost simultaneously by a plurality of antennas, reception sensitivity must be such that, in an automotive radar for which small size is essential, reception is possible even in the region of low antenna gain. With respect to achieving the required

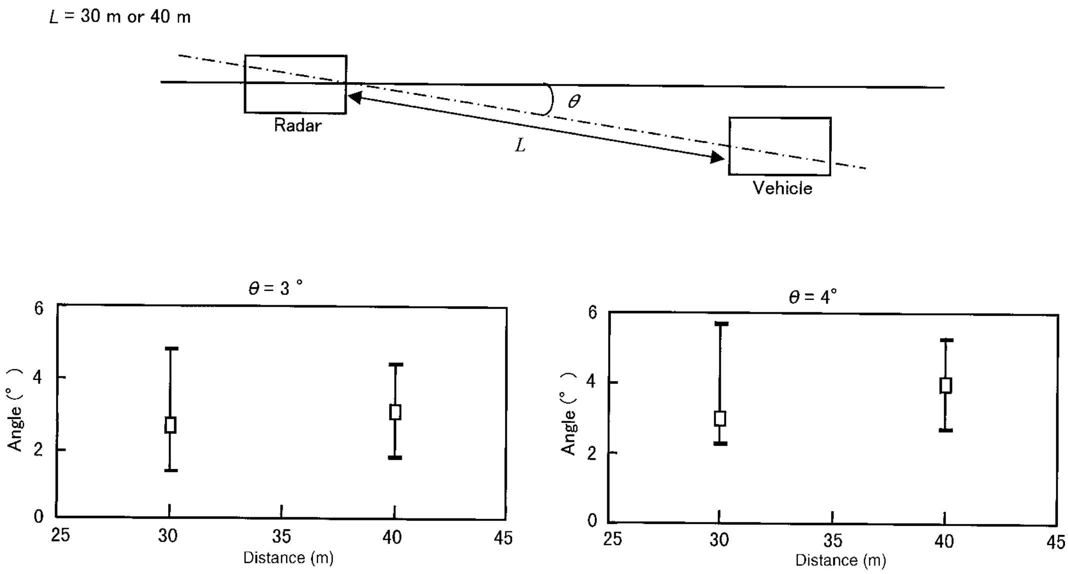

Figure 5 Results of static observations

angle measurement performance, further consideration, extending to the method adopted here, is an issue remaining for the future.

3. MILLIMETER-WAVE SENSORS FOR ITS INFRASTRUCTURE

3.1 ITS and AHS

Table 3 shows the 20 user services that are incorporated within the overall concept of ITS. Of these, VICS (vehicle information and communication system) and ETC (electronic toll collection) are already largely practicable, and will be followed by AHS (advanced cruise-assist highway system).

AHS is the most technologically sophisticated system within ITS, and is intended, by means of equipment installed on the road right-of-way, to improve safety by reducing accidents and promote economic efficiency and environmental protection by increasing transportation efficiency. In the United States, AHS tends to be understood in the sense of automated cruising, but in Japan it is understood to comprise three levels of support: "i" for provision of information, "c" for control support, and "a" for automated cruising, so that these may, so to speak "progress" as actual services are made practicable. Automated cruising, in particular, places the onus for traffic accidents on the infrastructure (installations on the right-of-way), and thus requires that major legal and societal hurdles be surmounted, to say nothing of technical problems, but prior to that, at the "i" and "c" levels, fully practicable systems can be configured. Furthermore studies in Japan are proceeding with reference not only to limited-access toll roads, but also to the ordinary highway network.

September 1996 saw the establishment of the Advanced Cruise-Assist Highway System Research Association, of which Furukawa Electric, together with 20 other major manufacturers, is a member. Under contact with the Public Works Research Institute of the Ministry of Construction, this organization is working on a wide range of AHS R & D activities, including establishing the AHS concept, system design, and major factor technologies. The developmental effort concentrates on right-of-way infrastructure, but allocation and coordination between infrastructure-based functions and vehicle-based functions is a major issue and is an object of study.

Table 3 ITS Development Areas and User Services

Development Areas	User Services Provided
1 Upgrading navigation systems	(1) Provision of route guidance traffic information
	(2) Provision of destination-related information
2 Electronic toll collection systems	(3) Electronic toll collection
3 Assistance for safe driving	(4) Provision of driving and road conditions information
	(5) Danger warnings
	(6) Assistance for driving
	(7) Automated highway systems
4 Optimization of traffic management	(8) Optimization of traffic flow
	(9) Provision of traffic restriction information on accident management
5 Support for road management	(10) Improvement of maintenance operations
	(11) Management of special permitted commercial vehicles
	(12) Provision of roadway hazard information
6 Support for public transportation	(13) Provision of public transport information
	(14) Assistance for public transport operations and operations management
7 Improving operating efficiency of commercial vehicles	(15) Assistance for commercial vehicle operations management
	(16) Automated platooning of commercial vehicles
8 Support for pedestrians	(17) Pedestrian route guidance
	(18) Vehicle-pedestrian accident avoidance
9 Support for emergency vehicle operation	(19) Automatic emergency notification
	(20) Route guidance for emergency vehicles and support for relief activities

3.2 Detection of Obstacles on the Road

Implementation of AHS requires the following broad categories of equipment and functions:

- Collection and recognition of information by sensors installed on the right-of-way
- Information processing and control by local sensors
- Transmission of information by road-to-vehicle com munication equipment
- Management of traffic information by wide-area and local centers.

Among right-of-way sensors, which form a major part of equipment for the implementation of AHS, sensors for determining road conditions are fundamental. That is to say they tie in the detection of obstructions--fallen objects on the road, stopped vehicles, bicycles, pedestrians and the like--with danger warnings and control assistance, and by keeping informed of all moving vehicles, serve to ascertain traffic conditions, warn of danger and assist in control. They are required to function in all types of weather, including heavy fog and heavy rain. Various types of sensors--using visible light, infrared rays, laser light and radio waves--have all been considered, but object detection sensors using radio waves have a number of distinct advantages over those using light in the visible or infrared range, including:

- Very little absorption by fog, snow, rain, etc., making all-weather systems possible;
- Excellent environment resistance with respect to dust and mud.

Within the radio spectrum, the use of millimeter waves (30-300 GHz) was found to offer a number of advantages over microwaves (3-30 GHz), including:

- Higher directionality, reducing spurious operation and interference;
- More compact and lightweight equipment, particularly antennas;
- Greater Doppler shift, improving the accuracy of velocity measurement;
- Wider band for higher range resolution;
- Comparatively high attenuation in air, reducing inter ference when two systems are installed close together, and thereby allowing a number of systems to coexist.

The detection area required for infrastructure-based sensors depends on the service provided, but may be taken, typically, to be approximately 12 m (or 3 traffic lanes) in the transverse direction and about 100 m in the length direction. For such an area to be covered by a single radar, the millimeter-wave beam must scan. Scanning may be effected either mechanically or electronically, but given the budgetary constraints, mechanical scanning is the most practical method at the current state of the art.

The installation position was also considered--whether to mount the radar equipment high (on gantries or overpasses about 5 m or more above the road surface), or lower (on roadside poles or atop guard rails at a height of about 1 m). At the higher position it was found that to achieve a 12-m-wide detection area from near to far distances required 2-dimensional scanning of the millimeter-wave. This greatly increased the measurement time with mechanical scanning and was therefore impractical. Mounting at the lower height, as shown in Figure 6, however, it was possible to cover the detection area with a horizontal 1-dimensional scan, so that the system was feasible in terms of measurement time.

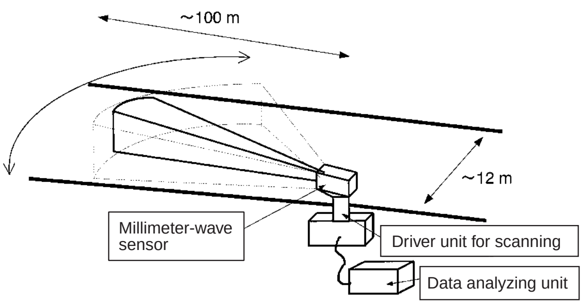

Figure 6 Millimeter-wave sensor installed on road right-of-way

It is necessary to bear in mind, however, that if there happens to be a large vehicle in the foreground of the object to be detected, the possibility that the waves will be blocked and detection impossible is greater for the lower position that the higher. Based on the above factors, the most practicable method is to install the radar at the lower position, on the roadside at a height of about 1 m above the road surface, and to provide 1-dimensional left-right mechanical scanning. In future it may well be possible to adopt high-speed 1- or 2-dimensional electronic scanning, or to install a larger number of low-cost millimeter-wave radars.

The ability to detect multiple objects is an important function of obstruction and vehicle detection sensors used in AHS. As noted in Section 2 above, the spread-spectrum radar now under development by Furukawa Electric features comparatively simple separation and detection of multiple vehicles in the range direction, and is therefore well suited to AHS applications.

4. CONCLUSION

The authors are working on millimeter-wave radar for the ITS market, which is expected to enjoy considerable growth. Measurement of distance and relative velocity is described as related to spread-spectrum (SS) millimeter-wave radar for automotive applications. Activities relating to obstruction and vehicle detection radar for right-of-way installation are also described.

ACKNOWLEDGMENT

We would like to express our sincere thanks to Prof. Ryuji Kohno of Yokohama National University for his continued guidance.

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Manuscript received on July 17, 1998.