Raised Profile Line Marking Detection by MMW Radar System

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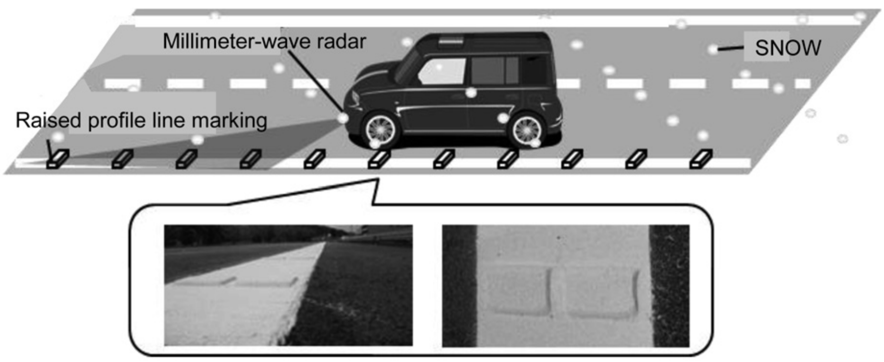


Abstract

With recent development of vehicle autonomous driving technology, traffic congestion and accidents are expected to be reduced. A location of a travelling host vehicle is estimated in an autonomous driving mode, using vehicle-mounted sensors. However, the performance of the optical sensors, such as a camera, is decreased in snow, rain, fog and other bad weather conditions. If the location of the host vehicle cannot be estimated, it is difficult to keep travelling in an autonomous driving mode. In such a case, control of the vehicle has to be given to the driver, or the vehicle needs to evacuate to a safe place. It takes some time to execute those functions. Thus, a system needs to be robust to the natural environment.

Therefore, we propose a method that uses a millimeter-wave radar system robust to the natural environment and raised profile line markings to estimate the location of the host vehicle. We found that the millimeter-wave radar could detect convex portions on the raised profile line markings, from test results. Moreover, the test demonstrated that attenuation of the radar system was not large even in the case of snow on roads, and that the system could detect the raised profile line markings up to some centimeters of snow on roads from beginning of snow. Thus, we believe that we can contribute to realization of the automobile society having no accidents, employing this technology to the development of the autonomous driving technology robust to the natural environment.

1 Introduction

Autonomous driving technology has been recently advanced. A location of a host vehicle is estimated in an autonomous driving mode, using external sensing information and GPS information. A currently-studied[1) 2)] system detects white lines on roads to estimate the host vehicle's location, using a vehicle-mounted camera or a Light Detection and Ranging (LiDAR) method for the external sensing, and the system is used for lane keeping control[3)]. However, when it rains or roads are covered with snow, signals are reflected by the water or snow on white lines of the roads. Thus, detection performance of the vehicle-mounted camera or the LiDAR method decreases. Especially, in the case of snow on the roads, as shown in **Fig. 1**, since the white lines are covered with snow, it is difficult for the vehicle-mounted camera or the LiDAR method to detect them. In the case where an autonomous driving system cannot continue to operate due to the snow on the roads, it needs to automatically evacuate to a safe place or to give control of the vehicle to the driver. For safe transition from the autonomous driving mode to driver control, it takes about five to ten seconds[4)]. Therefore, it is necessary that the autonomous driving mode should be continued in the beginning of snow. Thus, the system needs to be robust to the natural environment and weather.

Table 1 shows comparison among major vehicle-mounted sensors[5)]. According to **Table 1**, attenuation of millimeter-wave radar systems by fog, rain and snow is smaller than that of vehicle-mounted cameras and LiDAR, and the systems are sensors robust to the natural environment. In other words, the millimeter-wave radar systems can detect white lines through snow on the roads. However, generally, the white lines are so flat that signals transmitted from the millimeter-wave radar systems are reflected rearward, as shown in **Fig. 2 (a)**. Thus, the radar systems cannot detect the white lines.

On the other hand, white lines of some highways and main roads have bumps or ribs (hereinafter raised profile line marking) in Japan, like the one shown in **Fig. 3**. As for the raised profile line markings, convexities called "rib" are provided on the white line at equal intervals. Since those ribs do not submerge, even if it rains, visibility of the raised profile line markings can be secured. The raised profile line markings include concavities and convexities. Therefore, it is considered that the millimeter-wave radar systems can detect the white lines because the signals transmitted from them are reflected, as shown in **Fig. 2 (b)**.

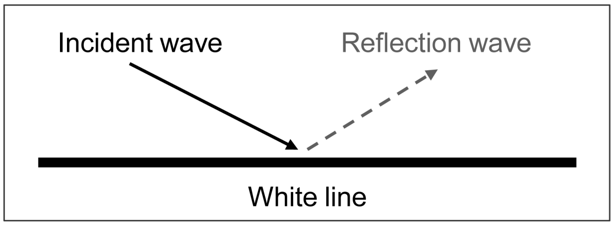
This paper evaluates performance of a millimeter-wave radar system with regard to detecting the raised profile line marking, and verifies feasibility of raised profile line marking detection by the millimeter-wave radar system. Moreover, it evaluates performance of the system regarding detecting the raised profile line marking with snow, and verifies the feasibility of the raised profile line marking detection in a bad weather so as to demonstrate whether an autonomous driving mode can continuously take control in such weather.

Table 1 Comparison among Major Vehicle-mounted Sensors

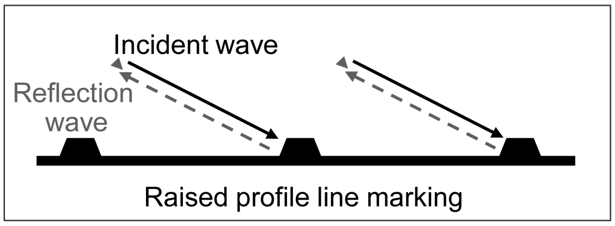
Sensor	Wave-length	Robust (Fog/rain/snow)	Azimuth resolution	Distance resolution
Camera	Short	×	○	△
LiDAR	Short	△	○	○
MMW radar	Long	○	△	○

(a) No snow on road (b) Snow on road

Fig. 1 White Line Detection Conditions with/without Snow



(a) Signal reflection by normal white line



(b) Signal reflection by raised profile line

Fig. 2 Signal Reflection by Each Type of White Lines

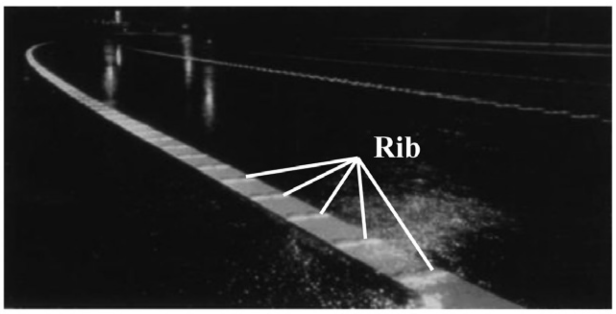


Fig. 3 Raised Profile Line Markings

2 Reflective Property Evaluation on Raised Profile Line Marking

2.1 Reflective Property Evaluation on Single Rib

This section will examine whether signals from the millimeter-wave radar system can be reflected by small targets, such as ribs of the raised profile line marking. We evaluated the reflective property of ribs, using evaluation ribs (hereinafter "single ribs"). Having a depth of 20 mm, a width of 200 mm and a height of 10 mm, those evaluation ribs were placed on asphalt as the imitations of the convex portions of the raised profile line marking.

2.1.1 Evaluation Method for Reflective Property Evaluation on Single Ribs

Fig. 4 illustrates a test environment for the reflective property evaluation on the single ribs. As illustrated in **Fig. 4**, we transmitted signals to the ribs placed at equal intervals to evaluate their reflection intensities. Then, we measured the reflection intensities in the case where there were the ribs and in the case where there were no ribs. In other words, we measured the reflection intensities of the ribs and an asphalt surface (hereinafter "ground clutter"). Moreover, in the test, the signals were transmitted toward the ribs located 3 m away. The distance means that an incident angle of the signal to a target rib is from 0° to 40° when the signal is transmitted to the ribs from a radar system mounted on a 1.6 m-width car travelling in a lane having the width of 3.5 m as shown in **Fig. 5**.

Standard frequency of 79 GHz and bandwidth of 2 GHz were set as test conditions to detect reflection from each of the ribs placed at 300 mm intervals. Moreover, in order to improve gain of the signals reflected by the ribs, integral process was performed. The integral process here means a process of averaging data obtained several times in time-series order. In this test, we evaluated the result of the test without the integral process and the average of data obtained 10 times.

Moreover, in this test, we compared reflection from a corner reflector with reflection from the ribs to calculate the RCS (radar cross-section). Here, RCS indicates reflection intensity per unit area. As its value is greater, it means that the rib has a higher capability of reflecting signals.

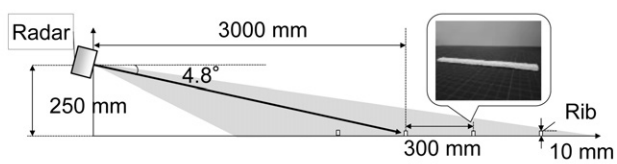


Fig. 4 Test Environment for Reflective Property Evaluation on Single Rib

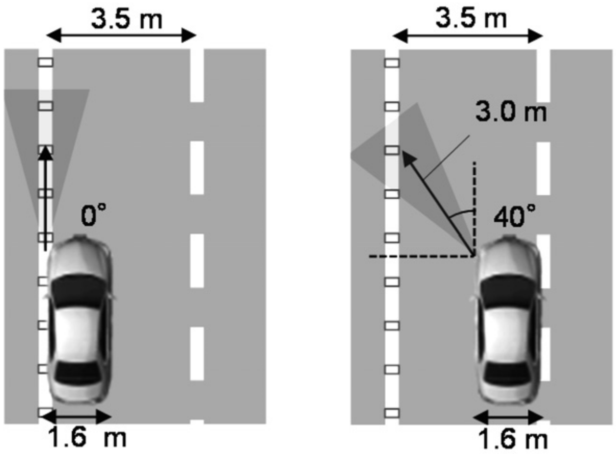


Fig. 5 Use Case of Raised Profile Line Marking Detection

2.1.2 Reflective Property Evaluation Results of Single Ribs

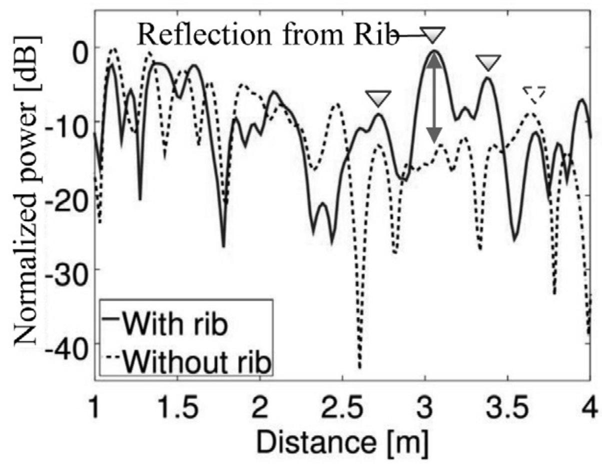
Reflective property evaluation results of single ribs are shown in **Fig. 6**. Here, **Fig. 6 (a)** illustrates reflection intensity of the ribs and the ground clutter in the case where the integral process was not performed. The horizontal axis represents distance from the radar, and the vertical axis represents reflection intensity normalized by taking the maximum value of the ground clutter as 0 dB in order to relatively compare the gain difference between reflection from the ribs and the ground clutter.

Fig. 6 (a) shows that a difference in reflection intensity between the rib and the ground clutter existing about 3.0 m away is approx. 15 dB, and that the millimeter-wave radar system could detect the convex portions with a height of 10 mm. The reflection intensity of the rib toward which the signal was directly transmitted was high. However, other ribs could not be detected stably, resulting in the differences in reflection intensities between the ribs and the ground clutter were approx. 4 dB, 11 dB and -2 dB.

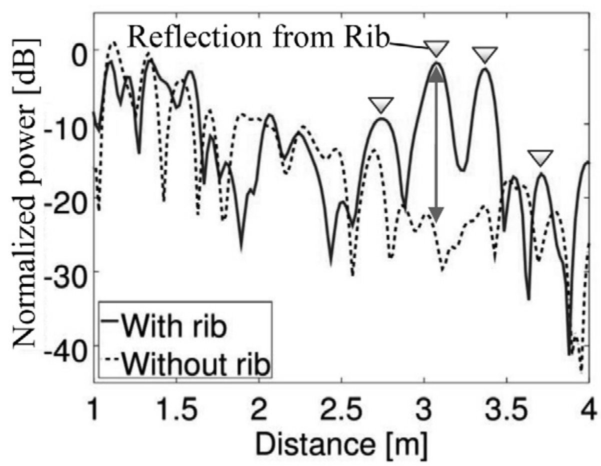
On the other hand, **Fig. 6 (b)** shows reflection intensities of the rib and the ground clutter in the case where the integral process was performed. The vertical axis in **Fig. 6 (b)** represents reflection intensity calculated based on the maximum value of the ground clutter without the integral process is set as 0 dB. **Fig. 6 (b)** indicates that a difference in reflection intensity between each rib and the ground clutter was improved by approx. 8 dB on average by performing the integral process. Thus, the evaluation demonstrated that the raised profile line marking could be stably detected by employing the process of improving gain.

Moreover, the RCS of the single rib calculated by comparing reflection from the corner reflector and the single ribs was -15 dBsm. It demonstrated that the reflection rate was low but the signal surely returned.

This evaluation confirmed that the millimeter-wave radar system could detect minute convex portions existing on the asphalt, and thus that the radar system could detect the raised profile line marking.



(a) Reflection intensity without integral process



(b) Reflection intensity with integral process

Fig. 6 Reflection Intensity of Ribs and Road Clutter

2.2 Reflective Property Evaluation on Twin Ribs

This section will explain the evaluation that we performed on the raised profile line marking currently used for part of highways and main roads in Japan. **Fig. 7** illustrates the raised profile line markings that were used for the evaluation. Two pieces of convex portions are placed side by side, and each of them is 50 mm in depth, 80 mm in width and 6 mm in height. In this paper, the rib having two convex portions is referred to as "twin rib." This section will evaluates the reflective property of the raised profile line marking having the twin ribs to verify whether the millimeter-wave radar system can detect the markings that are generally in place in Japan.

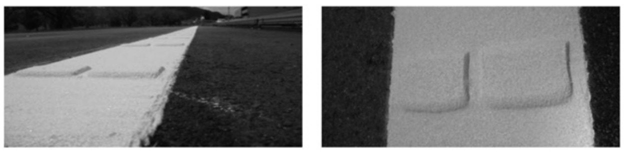


Fig. 7 Raised Profile Line Markings (Twin Rib)

2.2.1 Method for Reflective Property Evaluation on Twin Rib

Fig. 8 illustrates the test environment for the reflective property evaluation on the twin raised profile line marking. As shown in **Fig. 8**, we moved the radar system by 5° in a range from 0° to 180° around the raised profile line marking and measured reflection intensity of the rib existing 3.0 m ahead of the radar system.

We used the test conditions same as the one explained in the previous section, which were the center frequency of 79 GHz and the frequency bandwidth was 2 GHz. In the test, we calculated the RCS by comparing reflection from a corner reflector with reflection from the rib.

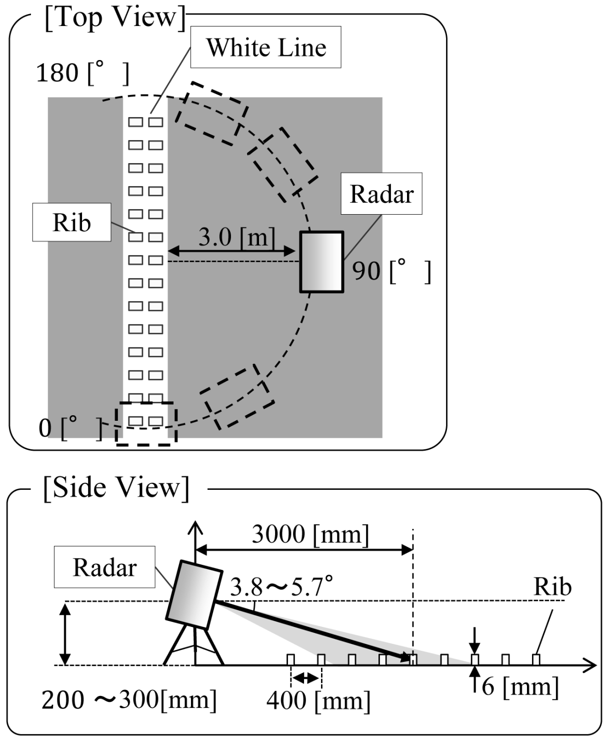


Fig. 8 Test Environment for Twin Rib Reflective Property Evaluation

2.2.2 Reflective Property Evaluation Results of Twin Ribs

Reflective property of twin raised profile line marking is shown in **Fig. 9**. The horizontal axis represents angle, and the vertical axis represents RCS in **Fig. 9**. Moreover, a solid line, a dashed line and a dashed-dotted line in **Fig. 9** represent the RCS of the twin ribs when the height of the radar is 200 mm, 250 mm and 300 mm, respectively. According to **Fig. 9**, the RCS of the twin rib at 0° is approx. -20 dBsm. Thus, it demonstrated that the reflection from the twin ribs could be detected.

Moreover, the RCS of the twin rib in the range from 0° to 40° is greater than the RCS in the range from 50° to 130°. This is considered as follows: Since the depth of the twin ribs is 50 mm, even if the angle was changed, a size of a radiated area did not decrease sharply so that reflection returned back even when the angle was changed. Having smaller depth than the twin ribs do, the single ribs can be detected in the range approx. from 0° to 5°. Thus, it is considered that the RCS of the twin ribs is less than the one of the single ribs, but the twin ribs have a wider area to reflect the signal.

This evaluation on the reflective property demonstrated that reflection from the twin raised profile line markings that are generally placed can be detected by the radar system.

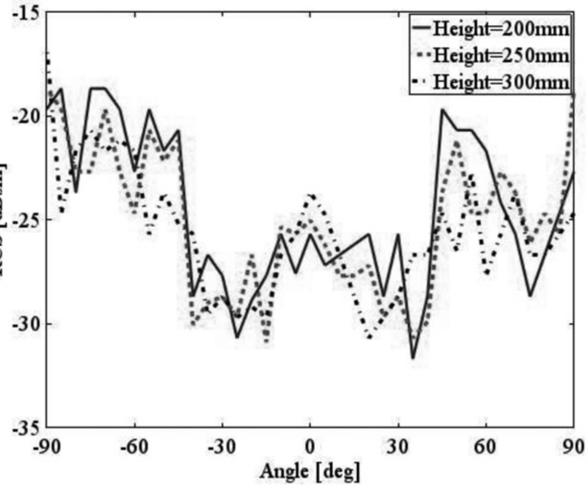


Fig. 9 RCS Pattern of Raised Profile Line Marking (Twin Rib)

3 Evaluation on Attenuation Amount of Millimeter-wave Radar System Due to Snow

This section will study a case in which there is snow on the raised profile line markings in a bad weather. Moreover, this section will demonstrate an attenuation amount of the millimeter-wave radar system due to snow by changing snow depth and obtaining reflection intensity of a rib for each depth. However, as cited in the previous section, the RCS of the ribs is not so high that there is a possibility that the reflection signal may not be measured due to attenuation caused by the snow. Therefore, in this section, the attenuation amount due to snow is measured, using a metal rib having higher reflection rate, as an evaluation rib.

3.1 Test Conditions for Evaluation on Attenuation Amount of Millimeter-wave Radar System Due to Snow

Fig. 10 illustrates the test environment for the evaluation on attenuation amount due to snow in the actual environment. As shown in **Fig. 10**, a height of the radar system was set at 500 mm. In order to raise the upper limit of measurable snow depth, the radar system was placed at a higher position, as compared to the test conditions in the previous sections. Moreover, the radar system transmitted signals to the metal rib located 3000 mm ahead at the angle of depression of 9.6°. Further, **Fig. 11** shows the metal rib that was used for the evaluation. The metal rib with 20 mm in depth, 200 mm in width and 6 mm in height was used.

Being same as the ones described in the previous sections, the center frequency of 79 GHz and bandwidth of 2 GHz were set as the test conditions. In the test, a depth of the snow on the metal rib was changed in a range from 0 cm to 10 cm. The density of the snow used for the test was 0.08 g/cm^3. We artificially scattered the snow to change the depth of the snow on the rib.

Moreover, we calculated[6) 7)] attenuation amount in the millimeter wave bandwidth of the radar system for each snow depth to compare the attenuation amounts.

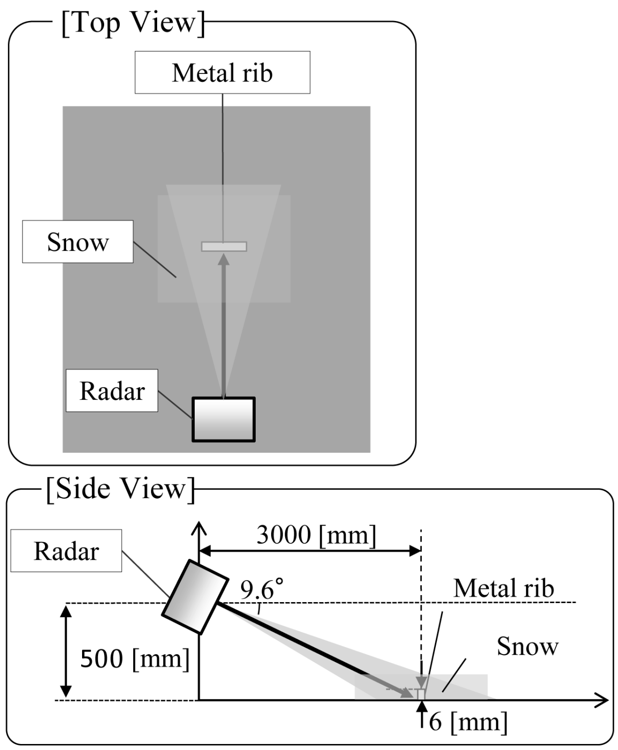


Fig. 10 Test Environment for Evaluation on Attenuation Amount Due to Snow

Fig. 11 Metal Rib

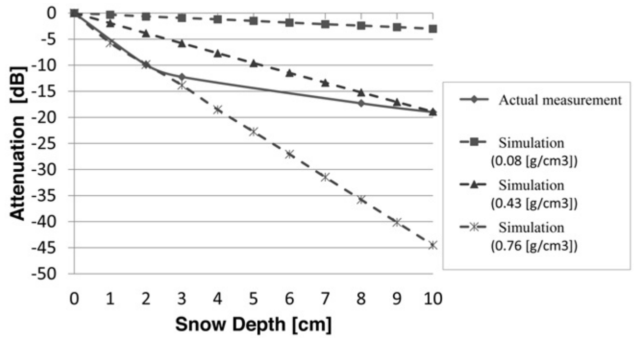


Fig. 12 Actual Evaluation Results and Simulation Results of Attenuation Amount Due to Snow

3.2 Test Results of Evaluation on Attenuation Amount of Millimeter-wave Radar System Due to Snow

Fig. 12 illustrates results of the evaluation on attenuation amount of the millimeter-wave radar system due to snow. The solid line in **Fig. 12** shows the evaluation result measured in the actual environment. Each of the broken lines shows the simulation result per snow density. The horizontal axis and the vertical axis in **Fig. 12** represent snow depth and attenuation amount, respectively.

According to the evaluation results in **Fig. 12**, as the snow depth increases, the attenuation amount decreases. However, the results evaluated in the actual environment did not linearly decrease, being different from the simulation results. It seemed because snow was frozen when being artificially scattered, and thus its density was uneven. Therefore, it is considered that the snow density was approx. 0.76 g/cm^3 in the case where snow depth is up to 3 cm and approx. 0.08 g/cm^3 in the case where snow depth is from 3 cm to 10 cm.

Depending on humidity and other elements, the density of fresh snow near the top surface is generally approx. 0.10 g/cm^3. Therefore, it is considered that the attenuation of the radar system is small in the bandwidth of the millimeter wave until the depth of the snow becomes some centimeters from the beginning of snow. Thus, the radar system can detect the raised profile line marking even in the bad weather.

4 Verification of Performance in Detecting Raised Profile Line Marking with Snow

This section will evaluate the reflection intensity of the raised profile line marking with snow to clearly understand the reflection intensity and the attenuation amount when snow is on roads in the actual environment.

4.1 Test Conditions for Evaluation on Raised Profile Line Marking with Snow

Fig. 13 illustrates the test environment of the evaluation on the raised profile line marking with snow. As shown in **Fig. 13**, the millimeter-wave radar was placed at a height of 300 mm above the raised profile line marking. The height was determined under the assumption that the radar was mounted near a bumper of a vehicle. Moreover, the angle of depression of the radar was 5.7° and the signal was transmitted toward the rib 3000 mm ahead of the radar.

Among the test conditions, the center frequency was set at 79 GHz and the bandwidth was 2 GHz to detect reflection from each rib. Moreover, in the measurement, the depth of the snow was 7.5 cm. As a result of measurement of the density of the snow located near the surface and the bottom close to the road, the density was in the range of 0.10 g/cm^3 to 0.25 g/cm^3. Integration was performed 20 times for each measurement, and then an average value was calculated based on results of the measurement that was performed 50 times.

In the test, reflection intensities of the white line with snow and without snow were measured.

Fig. 14 (a) and **(b)** illustrate the test environments with snow and without snow, respectively.

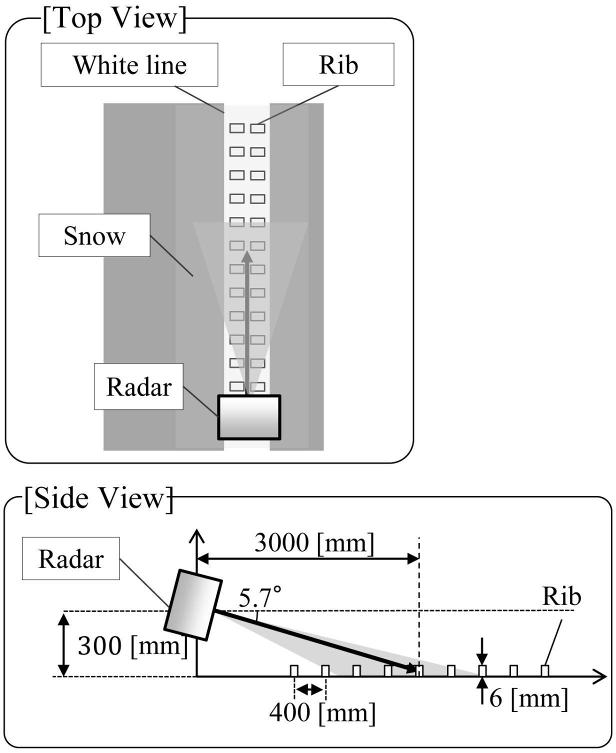
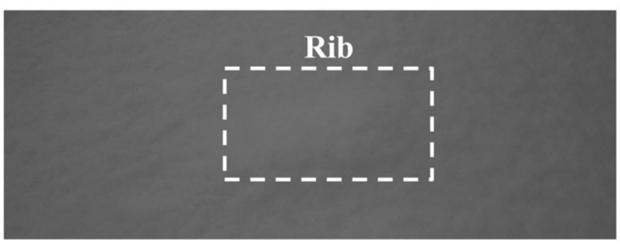
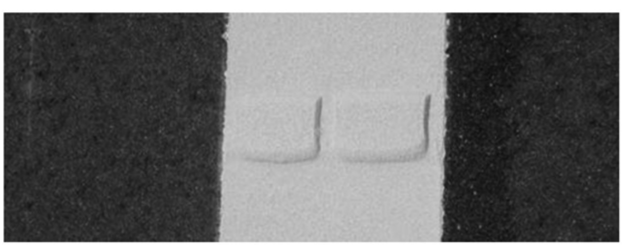


Fig. 13 Test Environment for Snow Evaluation on Raised Profile Line Markings



(a) Raised profile line marking with snow



(b) Raised profile line marking without snow

Fig. 14 Pictures of Test Environment with/without Snow

4.2 Test Result of Evaluation on Raised Profile Line Marking with Snow

Fig. 15 illustrates the reflection intensities of a rib approx. 3 m away from the radar. Here, the vertical axis of **Fig. 15** represents an averaged power and the horizontal axis represents results of the evaluations with snow and without snow. As shown in **Fig. 15**, an attenuation of approx. 10 dB occurred due to snow in the case of the rib near 3 m away. The Section 2 indicated that the RCS of a single rib was approx. -15 dBsm, and gain difference between the rib and the ground clutter was approx. 15 dB. The RCS of the twin rib is approx. -20 dBsm so that the difference in gain between the twin rib and the ground clutter is approx. 10 dB. Thus, in the case where the gain decreases 10 dB due to snow, it is estimated that the reflection from the ribs cannot be detected because it is hidden among the ground clutter. Therefore, it is necessary to improve the gain to compensate the attenuation amount, depending on the snow depth.

Moreover, **Fig. 16** illustrates attenuation amounts due to snow measured in simulation and an actual measurement. We calculated the attenuation amounts in the simulations in the case of snow densities of 0.10 g/cm^3 and 0.25 g/cm^3. Moreover, the result shown in **Fig. 15** is used as the attenuation amount due to snow in the actual measurement in **Fig. 16**.

As shown in **Fig. 16**, the result of the actual measurement measured when the snow with a density from 0.10 to 0.25 g/cm^3 is located between the simulation results of the snow densities of 0.10 g/cm^3 and 0.25 g/cm^3, which means that an attenuation amount due to snow calculated in the simulation is equivalent to the one that is measured in the actual environment. Thus, if a density of snow is 0.10 g/cm^3 that is the normal density of fresh snow, the attenuation amount will be some dB in the case of some centimeter snow on the roads. Therefore, the radar system can detect the raised profile line markings in the case of some centimeter-snow from the beginning of snow.

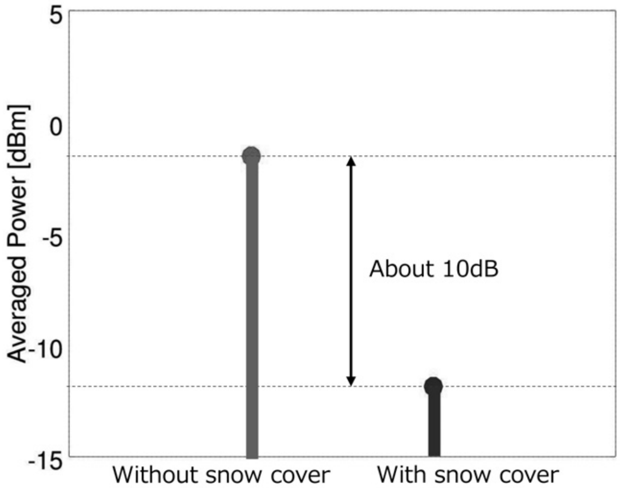


Fig. 15 Reflection Intensity of Rib Approx. 3 m Away

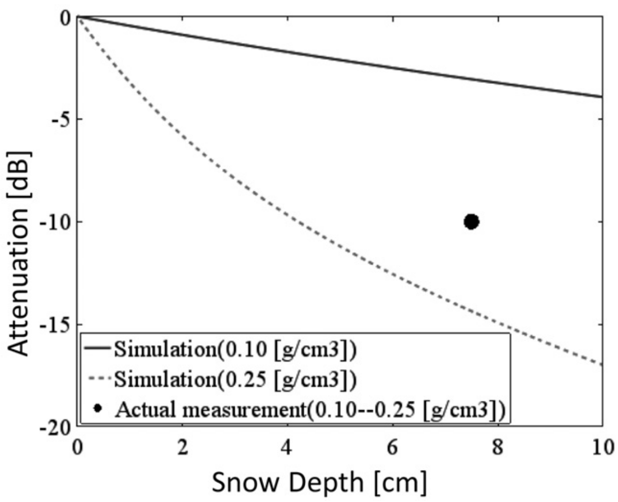


Fig. 16 Attenuation Amounts Due to Snow Measured in Simulation and Actual Measurement

5 Conclusion

This paper examined the performance of the millimeter-wave radar system in terms of detecting the raised profile line markings. The actual test results demonstrated that the 79GHz-band millimeter-wave radar system can detect ribs of raised profile line markings that have been already placed.

Further, we evaluated the reflective property of the raised profile line markings when snow was on roads to verify the performance of the millimeter-wave radar system in detecting the white lines in a bad weather. According to the test results, in the case of high density or large amount of snow, it is necessary to improve the gain to compensate the attenuation amount by the snow. However, when it starts snowing, vehicles can gain time to change modes from autonomous driving to manual driving or to autonomously evacuate.

In the future, we would like to contribute to realization of the automobile society with no traffic accident, employing this technology for development of autonomous driving technology robust to the natural environment.

The details described in this paper are part of results gained from the study on "Development and Verification of Lane Marker Detection System in All-weather Condition," entrusted by Ministry of Economy, Trade and Industry as a Cross-ministerial Strategic Innovation Promotion Program lead by Cabinet Office.

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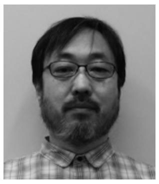

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