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Automotive Radar Technology for Detecting Road Conditions. Backscattering Properties of Dry, Wet, and Icy Asphalt

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***Abstract*— This paper proposes that automotive radar technology could be used to detect low friction spots due to water or ice on asphalt. The backscattering properties of dry, wet and icy asphalt are experimentally studied in laboratory conditions at two automotive radar bands at 24 GHz and at 77 GHz. Both water and ice are found to change the backscattering properties of asphalt. The experimental results suggest that water could be detected using dual-polarised 24 GHz radar. Both water and ice could be detected using dual-polarised 24 GHz radar and 77 GHz radar.**

I. INTRODUCTION

After extensive research and development work of several decades [1], automotive radars are pushing into consumer market. The radars are expected to increase safety and convenience by improving driver's ability to perceive objects in low-visibility conditions or objects hidden in blind spots. Commercially available radars are used either for automatic cruise control (ACC) or blind spot detection (BSD). Forward looking ACC systems slow down the vehicle speed when approaching another vehicle and automatically accelerate the speed to the preset limit when the traffic allows. The ACC systems operate at 76 – 77 GHz and they are offered in several high-end passenger cars. Blind spot detection radars generally operate at 22 – 26 GHz band and they have been commercially available since 2006.

Automotive radars are also proposed for road condition recognition. Bistatic scattering measurements in laboratory from different road surfaces are reported in [2] at 24 GHz and in [3] at 76 GHz. It is stated that 76 GHz radar has potential for detecting moisture and ice on road. Results at 24 GHz show that the scattering properties of the road changes with the road condition.

References [4] and [5] report bistatic radar systems for road condition recognition, operating at 61 GHz and 76 GHz, respectively. These systems are attached under the car chassis, and they utilize the polarisation properties of the specularly reflected signal for detecting low-friction spots. Experimental tests verify that the system at 76 GHz is able to detect ice on road. Measurement results with prototype radar operating at 61 GHz showed that asphalt and cobblestone road pavements can be distinguished from each other.

Hetzner has measured different road conditions using an active bistatic radar and a passive radiometer at 35 GHz and 90 GHz [6]. He found radiometer more suitable for road condition recognition.

In this paper, we present how monostatic radar technology can be used for detecting road conditions i.e. water or ice on the asphalt. Currently water and ice is detected with infrared optical sensors which are not cost effective for ordinary passenger cars. The advantage of radar sensors over optical would be that forward looking radars could detect low friction spots from a long range whereas optical sensors' detection range is a few meters only. In addition, when using multipurpose radar sensors the total number of sensors is not increased giving also cost benefits.

This paper is organised as follows: Section II describes the experimental setup for measuring backscattering coefficient of asphalt, measurement procedure is described in Section III, results are presented in Section IV, and discussions and conclusions in Section V and VI, respectively.

II. MEASUREMENT SETUP

Monostatic backscattering of asphalt sample is measured with a network analyser (HP 8510) and a horn antenna. The measurement antenna is mounted on a rotating arm such that the incidence angle could be changed from 0 to 80 degree with 5 degree increments. A schematic layout of the measurement setup is shown in Figure 1.

Asphalt sample is taken from a road and the bitumen is therefore eroded from the surface exposing the rock filling. The size of the sample is 295 by 800 mm. When measuring backscattering from wet asphalt, the asphalt surface is watered only slightly, no ponds are formed. For icying the asphalt sample, it was first cooled down with liquid nitrogen (-196 °C), such that its surface temperature remained between -15…-5 °C during the measurements in a room-temperature laboratory. The cooled asphalt sample was watered to achieve 1-2 mm thick ice layer.

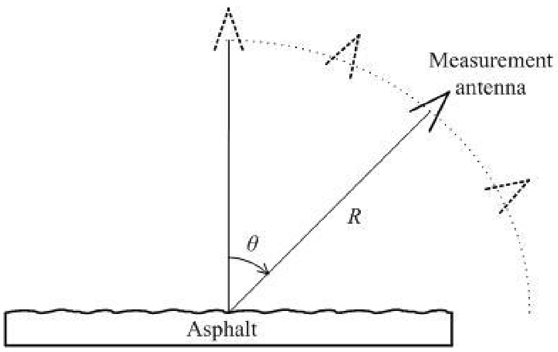

Fig. 1 A schematic layout of measurement setup. θ is the incidence angle and R denotes the distance to the antenna.

The backscattering is measured at two frequency bands: the lower band being from 18 to 26.5 GHz and upper from 50 to 79 GHz. Different horns are used for both bands. The measurement distances with both antennas were selected such, that the far-field criterion, $R \geq 2D^2/\lambda$, was fulfilled.

III. Measurement Procedure

A. Backscattering Coefficient

The strength of the backscattered signal from rough surface, such as asphalt, is difficult to predict deterministically. Therefore, we take a statistical approach and consider statistical average of the radar cross section of a rough surface, denoted as $\langle\sigma\rangle$.

A road is an area extensive target: its effective target size, and thus also radar cross section depends on the illuminated area. Such targets are characterised in terms of scattering coefficient, which defines the average radar cross section $\langle\sigma\rangle$ over illuminated surface area A_0 [7]:

$$\sigma_0 = \frac{\langle\sigma\rangle}{A_0}. \tag{1}$$

B. Power Calibration

The radar cross section can be calculated from

$$\sigma = \frac{(4\pi)^3 R^4 P_r}{P_t G^2 \lambda^2}, \tag{2}$$

where R is the distance of the target, P_t is the transmitted power, P_r is the received power, G is the antenna gain, and λ is the wavelength. In these measurements, the backscattered power is calibrated by measuring the normal reflection from a metal plate. In such a case, the received power is the transmitted power attenuated with the free space loss. The ratio of the received and transmitted power is given by

$$\frac{P_r}{P_t} = G^2\left(\frac{\lambda}{4\pi r}\right)^2, \tag{3}$$

where $r = 2R$ due to two-way signal path. Substituting (3) into (2) gives the effective radar cross section of the metal plate:

$$\sigma = \pi R^2. \tag{4}$$

The illuminated area A_0 at the distance of R can be approximated by

$$A_0 = 4R^2 \tan(\theta_{E,3dB}/2)\tan(\theta_{H,3dB}/2), \tag{5}$$

where $\theta_{E,3dB}$ is the 3-dB beam width in the *E*-plane and $\theta_{H,3dB}$ in the *H*-plane. The 3-dB beam widths for pyramidal horn antennas are approximately

$$\theta_{E,3dB} \approx 0.89\frac{\lambda}{D_E}, \tag{6}$$

$$\theta_{H,3dB} \approx 1.19\frac{\lambda}{D_H}, \tag{7}$$

where D_E and D_H are the aperture sizes of the horn antenna in *E*- and *H*-direction, respectively. Finally, by combining (4), (5), (6) and (7), we get the normalised backscattering coefficient

$$\sigma_{0,norm} = \left(\frac{S_{11,asphalt}}{S_{11,metal}}\right)^2 \cdot \frac{\pi}{4\tan(0.445\lambda/D_E)\tan(0.595\lambda/D_H)} \tag{8}$$

where $S_{11,asphalt}$ is the measured reflection coefficient from the asphalt and $S_{11,metal}$ is the measured reflection coefficient from the metal.

C. Time Gating for Reflection Reduction

The unwanted reflections due to impedance mismatch of the antenna and reflections in the laboratory are reduced with the time gating procedure. In the time gating, the measured frequency response is transformed into the time domain via Fourier transform. The time response is filtered with a gate function and then transformed back into the frequency domain to obtain the gated frequency response.

D. Statistical Average of Backscattered Signal

As backscattering coefficient is a statistical quantity, several measurements should be performed to obtain its average reliably. However, repeating the measurement several times with different asphalt samples is very laborious and time consuming. Therefore, the backscattered signal is averaged in this experiment over a frequency band under assumptions that the average backscattering remains constant in the band while backscattering at different frequencies are uncorrelated.

IV. MEASURED BACKSCATTERING COEFFICIENTS

The backscattering coefficients measured at different incidence angles for dry, wet, and icy asphalt at 24 GHz are shown in Figure 3 (TM-polarisation) and in Figure 4 (TE-polarisation). Backscattering coefficients at 77 GHz are shown in Figure 5 (TM-polarisation) and Figure 6 (TE-polarisation).

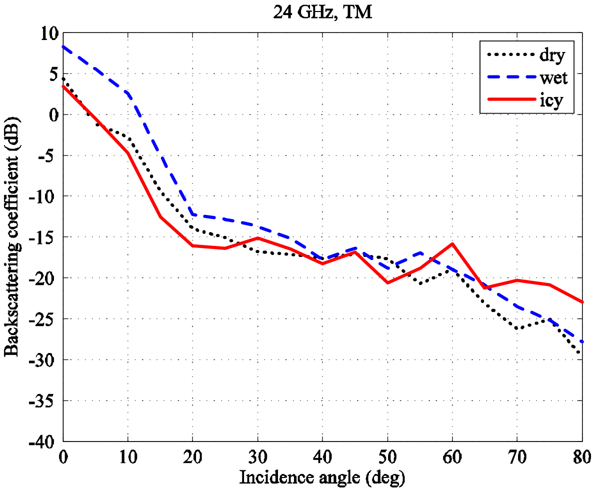

Fig. 3 Measured backscattering coefficient for dry (dotted line), wet (dashed line) and icy (solid line) asphalt at TM-polarisation at 24 GHz.

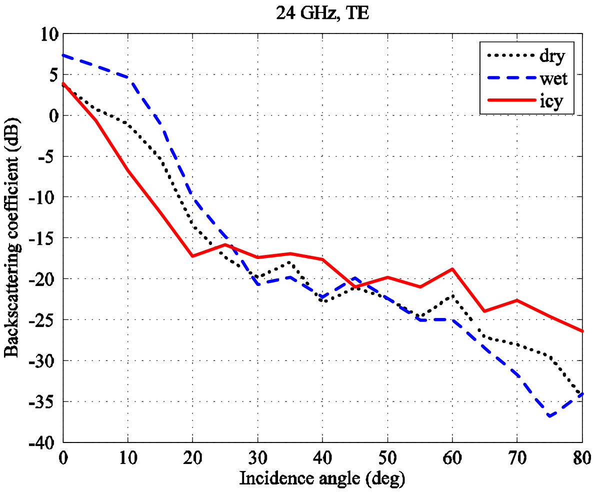

Fig. 4 Measured backscattering coefficient for dry (dotted line), wet (dashed line) and icy (solid line) asphalt at TE-polarisation at 24 GHz.

At 24 GHz, water on asphalt seems to increase the backscattering coefficient close to normal incident. At large incident angles water increases the backscattering at TE-polarisation whereas it decreases it at TM-polarisation. Ice does not change the backscattering coefficient at normal incidence. However, ice increases the backscattering coefficient at both polarisations at large incidence angles at 24 GHz.

At 77 GHz, both water and ice seem to increase the backscattering coefficient at normal incidence, as shown in Figures 5 and 6. At larger incidence angles, water decreases and ice increases the backscattering.

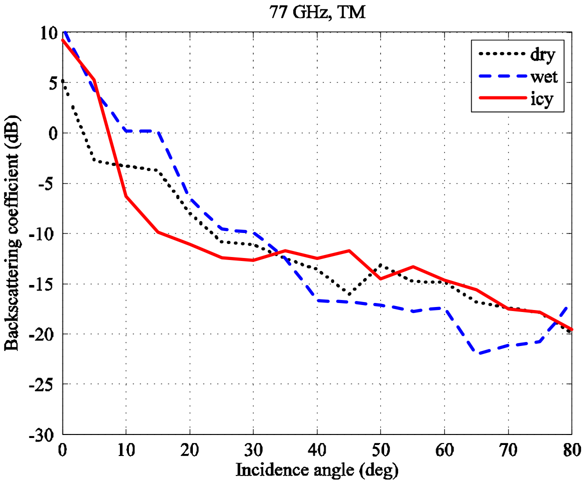

Fig. 5 Measured backscattering coefficient for dry (dotted line), wet (dashed line) and icy (solid line) asphalt at TM-polarisation at 77 GHz.

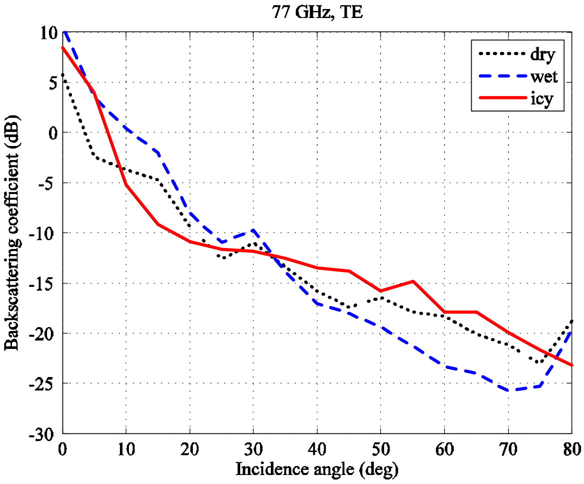

Fig. 6 Measured backscattering coefficient for dry (dotted line), wet (dashed line) and icy (solid line) asphalt at TE-polarisation at 77 GHz.

Absolute value of backscattering coefficient is not a feasible quantity for identifying water or ice on asphalt. First of all, absolute backscattering coefficient measurements are challenging with automotive radar since the target distance and weather conditions affect the backscattered signal strength. In addition, incidence angle and asphalt type, which are usually unknown parameters, affect the backscattered signal strength. Due to the above reasons, it is preferable to use ratios between backscattering at different polarisations or frequencies.

The ratio between backscattering coefficients at TM- and TE-polarisations at 24 GHz is shown in Figure 7. Figure 8 shows the ratio between backscattering coefficients at TM-polarisation at 24 GHz and 77 GHz.

According to these results, water could be detected at large incidence angles by comparing the backscattered signals at TM- and TE-polarisations at 24 GHz (Figure 7). As compared to dry or icy asphalt, water increases the ratio between the backscattering coefficients at these polarisations approximately 4 dB.

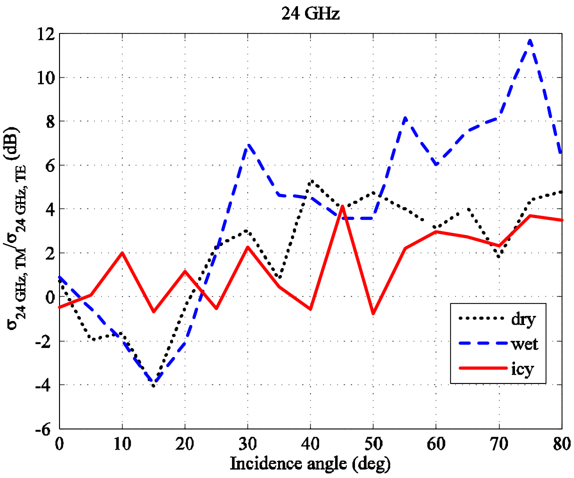

Fig. 7.The ratio between the backscattering coefficients at TM- and TE-polarisations at 24 GHz.

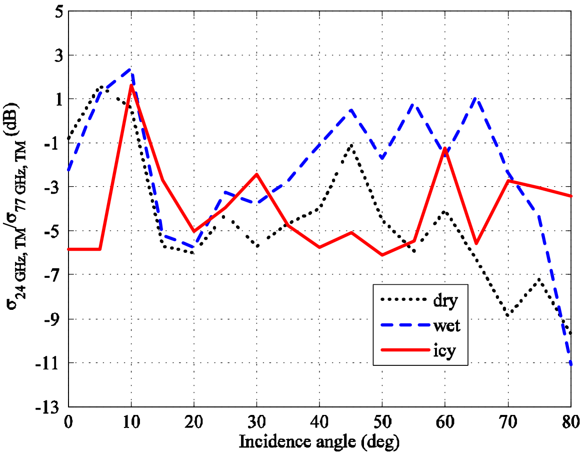

Figure 8. The ratio between the backscattering coefficients at TM-polarisation at 24 GHz and at TM-polarisation at 77 GHz.

Ice could be best detected by comparing the backscattering at TM-polarisation at 24 GHz to that at TM-polarisation at 77 GHz (Figure 8). Ice seems to increase the ratio between these backscattering coefficients at large incidence angles as compared to dry asphalt. Water increases the ratio as well, but the possibility of water can be excluded by comparing the ratio between the backscattering coefficients at TM- and TE-polarisations at 24 GHz.

V. DISCUSSION

Backscattering properties of wet asphalt differs from those of dry presumably due to change of relative permittivity of the surface. The dielectric constant of asphalt is 2.6 at microwave frequencies [8]. According to model presented in [9], the relative permittivity of 20°C water is $33 - j36$ at 24 GHz resulting into skin depth of 0.77 mm. Due to relatively small skin depth, the relative permittivity of wet asphalt is probably very close to that of the water.

According to small perturbation model [7], which is used to model backscattering from rough surfaces, the ratio of the backscattering coefficients of vertical and horizontal polarisations increases with the relative permittivity of the object. Therefore, water on the asphalt can most probably be detected because it changes the relative permittivity of the surface.

The relative permittivity of −20°C ice is approximately 3.15 at 24 GHz, according to the model presented in [10]. As the relative permittivity of ice is relatively close to that of asphalt ice must change the backscattering through other mechanisms. For example, by changing the surface shape of the asphalt, or simply by generating a two layer-structure having different kind of backscattering properties.

VI. CONCLUSIONS

In this paper, automotive radar was studied in an attempt to detect road conditions. Backscattering coefficient of dry, wet, and icy asphalt sample is measured at 24 GHz and at 77 GHz at TM- and TE-polarisations. According to measurements, both water and ice changes the backscattering coefficient of asphalt.

Several environmental variables, such as measurement distance, weather conditions and asphalt type, affect the measured backscattering. Therefore, it is preferable to use ratios between backscattering at different polarizations or frequencies for road condition detection.

The experimental results suggest that water could be detected by comparing the backscattered signal at different polarisations at 24 GHz. In addition, it could also be possible to detect ice, if backscattering is measured also at 77 GHz in addition to measurements performed at 24 GHz. Field measurement campaign is planned to obtain further proof-of-concept.

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