Effects of Water and Ice Layer on Automotive Radar

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***Short Abstract*—This experiment is carried out at the Robert Bosch GmbH, to analyse the signal degradation of millimeter wave radar Sensors in adverse weather conditions. It reveals that, the existence of water layer on the surface of antenna lens or its radome is the main cause for performance limitation of automotive radar sensors and provides information to identify such phenomena.**

Keywords-Electromagnetic radiation effects; Millimeter wave radare; Road vehicle radar

I. INTRODUCTION

Automotive radar sensors, which fundamentally use millimeter wave signals, increasingly become one of the important comfort and collision mitigation products in the automotive market. Their performance may be affected by wetness due to adverse weather conditions unless proper antenna lens or radome design is used. The extension of automotive radar sensors from comfort to safety systems may further require intelligent features, such as detection of weather phenomena and performance controlling during adverse weather conditions. Hence, this work examines effects of water and ice on the millimeter radar performance and methods to identify such phenomena.

The wetness of antenna lens or radome surface generally affects electromagnetic wave propagation at higher frequencies and causes a considerable loss. Several studies of microwave propagation have already shown that this loss contributes a significant amount to the attenuation due to rain [1-3].

This paper presents the theoretical analysis and the measurement results of the losses due to water as well as ice layer on the surface of radome, to explore the possibility of developing a method for detecting partial or total degradation of automotive radar sensors by rainy and snowy weather conditions. Primarily it deals with losses due to water layer on the surface of radome and illustrates their dependency on the frequency, the water layer thickness and the polarization. To study these losses, the standard theoretical analysis "Fresnel formula for reflection and transmission" has been applied on multilayer wave propagation model [4, 6].

These theoretical results have been already compared with measurements, in particular for 76.5 GHz band, and they confirm limitations on automotive long range radar application during rainy and snowy weather conditions. On the other hand, ice layer on the surface of dielectric radome because of its negligible absorption coefficient [10] causes no harm to the performance of automotive radar sensors.

The automatic identification of critical performance losses and system adaptability for such changes in the propagation medium make automotive radars more intelligent and robust in adverse weather conditions like rain and snow. Based on the result of this work, the detection of performance losses is implemented in the new generation of Bosch Automotive Long Range Radar (LRR2) system [9].

II. WAVE PROPAGATION MODEL

The model is based on infinitely extended four plain dielectric layers of air, radome, water film and air again. To simplify the theoretical analysis, these dielectric media are assumed to be homogeneous and isotropic, considering a plane, time-harmonic electromagnetic wave incident upon a radome medium and propagating through the water film. In this model, a radome with optical thickness equal to multiples of half wave length in medium and with low refractive index is considered, to have a reflection free medium.

Any arbitrarily polarized plane wave may be resolved into two waves, namely perpendicular and parallel components to the plane of incidence. Since the boundary conditions at a discontinuity surface for these two waves are independent to each other, they will have different expressions for reflection and transmission of electromagnetic wave at the dielectric medium. Therefore, according to "Fresnel formula for reflection and transmission" [4, 6] and after mathematical simplification, the expression for reflectivity and transmissivity of an electromagnetic wave for the above model is given as follows:

$$R_v = \left| r_v \right|^2 = \frac{\left(\frac{\Omega}{n} - \frac{n}{\Omega} \right)^2}{\left(2\cot(\delta) \right)^2 + \left(\frac{\Omega}{n} + \frac{n}{\Omega} \right)^2}, \qquad (1)$$

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$$R_h = |r_h|^2 = \frac{\left(\frac{1}{\Omega n} - \Omega n\right)^2}{\left(2\cot(\delta)\right)^2 + \left(\Omega n + \frac{1}{\Omega n}\right)^2}, \tag{2}$$

$$R = R_h \cos^2(\psi) + R_v \sin^2(\psi), \tag{3}$$

$$T_v = |t_v|^2 = \frac{1}{\cos^2(\delta) + \left(\frac{1}{2}(\frac{n}{\Omega} + \frac{\Omega}{n})\sin(\delta)\right)^2}, \tag{4}$$

$$T_h = |t_h|^2 = \frac{1}{\cos^2(\delta) + \left(\frac{1}{2}(\Omega n + \frac{1}{\Omega n})\sin(\delta)\right)^2}, \tag{5}$$

$$T = T_h \cos^2(\psi) + T_v \sin^2(\psi), \tag{6}$$

$$\Omega = \frac{\cos(\alpha)}{\sqrt{1 - \left(\frac{\sin(\alpha)}{n}\right)^2}}, \tag{7}$$

$$\delta = \frac{2\pi}{\lambda} d \sqrt{n^2 - \sin^2(\alpha)}. \tag{8}$$

Where:

- Ω is the ratio of incidence angle to refraction angle,
- α is angle of the incidence wave,
- n is the complex index of refraction of water,
- d is the water-film thickness,
- δ is the phase term of propagated wave in medium as a function of incidence angle and water-film thickness,
- λ is the wave length of the propagated electromagnetic field,
- ψ is the polarization angle of the incidence wave
- r_v, r_h, are the reflection coefficients for perpendicular and parallel wave components respectively,
- t_v, t_h are the transmission coefficients for perpendicular and parallel wave components respectively,
- R, T are the total reflectivity and total transmissivity respectively,
- R_v, R_h are the reflectivities for perpendicular and parallel wave components respectively,
- T_v, T_h are the transmissivities for perpendicular and parallel wave components respectively.

For the practical interest of automotive radar, a linearly polarized electromagnetic wave (ψ = 45 deg), incident perpendicular to the radome i.e. α = 0 deg, $R_v = R_h = R$ and $T_v = T_h = T$, has been considered. Due to the nature of complex refractive index of water for millimetre waves and its strong dependency on frequency and temperature [5, 7, 8] the reflectivity and the transmissivity show different characteristics. As shown in Fig. 1, at a constant temperature the reflectivity from water film raises steeply for a very small thickness and reaches its maximum by a quarter of the wave length in the medium, i.e. $d = \lambda / 4n$. The absorption of electromagnetic wave in water increases with frequency as well as with water film thickness. Consequently, the reflectivity will approach a constant value, which remains below unity and decreases with increase in frequency.

Fig. 2 shows the transmissivity of a water film as a function of its thickness for three automotive radar frequencies. The water film transmits millimetre wave signals with the longer wave length and attenuates those with shorter wave length, strongly. For a 76.5 GHz signal, for example, more than 90 % of the transmitted energy will be attenuated at the water film thickness of 0.23 mm, where its reflectivity reaches a maximum of about -3 dB. This tendency of signal attenuation increases rapidly with further rise in water film thickness and absorption of almost all transmitted energy occurs with thicknesses above 1.0 mm, 0.56 mm, 0.45 mm for signals at 24 GHz, 76.5 GHz and 140 GHz respectively. The water film with thicknesses mentioned above can be easily formed in the propagation path during rain or snow and can block automotive radar functioning.

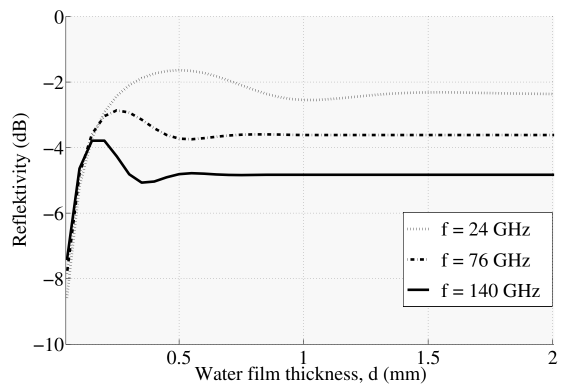

Figure 1. Reflectivity from water film at 20 °C.

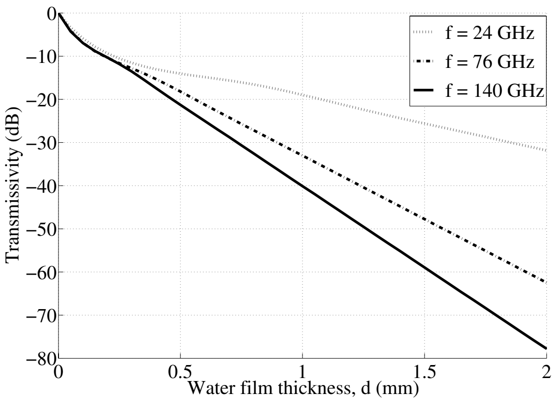

Figure 2. Transmissivity through water film at 20 °C.

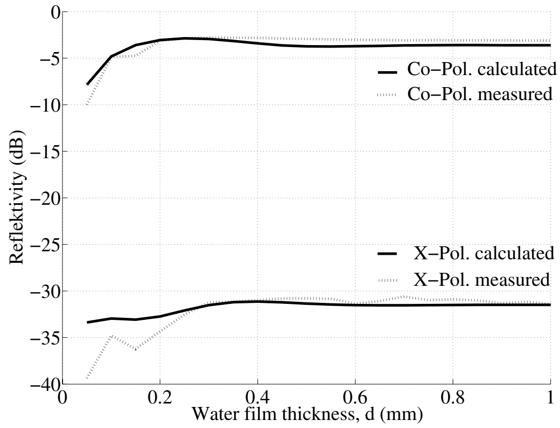

Figure 3. Reflectivity from water film at 76.5 GHz.

A layer with complex refractive index such as water film (as polar material) causes additionally a phase and amplitude difference between components of the reflected wave as well as components of the transmitted wave. Hence, the reflected and transmitted waves in the above case may be elliptically polarized depending up on the angle of incidence. The cross-polarized components, orthogonal to the polarisation of the incidence wave, for the reflected and transmitted waves can be derived from the amplitude and phase relation of the corresponding perpendicular and the parallel wave components [4, 6]:

$$p_{rX} = \frac{1}{2}\sin(2\psi)\left|r_v - r_h\right|, \tag{9}$$

$$p_{tX} = \frac{1}{2}\sin(2\psi)\left|t_h - t_v\right|. \tag{10}$$

Where p_{rX} and p_{tX} are the cross-polarization coefficients of reflected and transmitted waves respectively. Its square gives the corresponding reflectivity and transmissivity. They will have maximum values, according to (9) and (10), for a 45 deg linear polarized incident wave. They depend on water film thickness and frequency analogous to that of the corresponding co-polarized component as discussed earlier (see Fig. 1 and Fig. 2). Fig. 3 and Fig. 4 show in addition reflectivity and transmissivity of the cross-polarized components in comparison to the measured value for a 76.5 GHz wave with angle of incidence between -10 deg and +10 deg. These cross-polarized waves are considered as polarization losses due to water film unless they are received with proper antenna arrangement.

Fig. 5 and Fig. 6 show the outcome of this theoretical analysis, how the attenuation of the transmitted energy in water film could be determined automatically for radar that is designed to detect or measure the corresponding reflectivity. This concept is used to monitor maximum detection range of a target as well as object detection capability of the automotive radar during adverse weather conditions.

III. MEASURMENT

This experiment is conducted with E-band horn antennas (beamwidth: azimuth = 13.2 deg, elevation = 20.4 deg.), connected to a Vector Network Analyser via a transmission - reflection module from Anritsu operating at 22.5 MHz to 90 GHz. The two antennas are aimed at 76.5 GHz radome with a wet tissue paper arrangement mounted on mast. The measured co-polarization and cross-polarization components of the reflectivity and transmissivity have been presented in Fig. 3 and Fig. 4 respectively.

This technique offers the advantages of building a water film with a resolution of about 0.05 mm on the radome surface easily. However, one needs careful attention to avoid possible air layer between papers as well as to keep the wetness grade constant while the measurement takes place. These may be a potential cause of measurement inaccuracy and may introduce difference between the theoretical and practical results. The thickness of water film is determined from the amount of water on the tissue paper, which has been measured with a 0.1 g resolution precision balance, divided by its surface area.

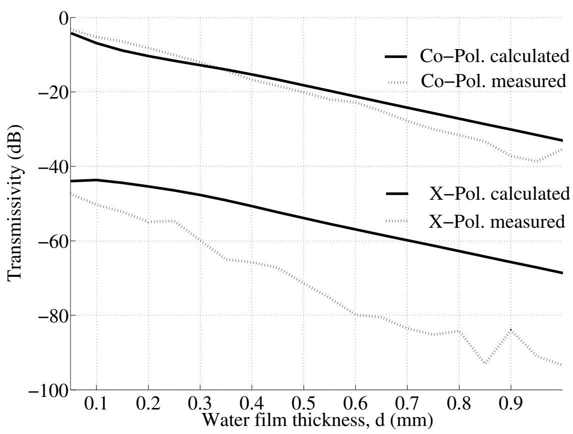

Figure 4. Transmissivity through water film at 76.5 GHz.

Furthermore, an application oriented experiment has been carried out with the new generation of Bosch Automotive long range radar sensor, which works based on Frequency Modulation Continuous Wave (FMCW) principle [9]. In the radar system a method, which measures the reflectivity from a water film on the surface of the antenna lens or its radome and assesses the degree of radar performance loss in terms of reduction in maximum detection range or object detection capability, has already been implemented. A radome with very low reflection factor has been arranged just in front of the radar sensor perpendicular to the direction of propagation. So that, in case of wet radome, reflected signals from the water film could be entirely focused on the radar antenna. It was possible to vary the degree of wetness on the radome surface by regulating the flow rate of water through a water sprayer, which has been mounted over the radar sensor. The radar vehicle is driven slowly towards a retro reflector with specified Radar Cross Section (RCS = 3.0 square meter). Based on relations between reflectivity and transmissivity of electromagnetic signals in water film the maximum detection range of the radar has been measured. Fig. 5 shows these measured results in terms of the maximum detection range for dry radome versus water film thickness and they are well in the range of the theoretical analysis. The relation between radar transmitted power and its maximum detection range of a target with a specified RCS is given in radar literature, for example, in [11].

In addition, a measurement is carried out in a constant traffic scenario by using spray water on the surface of automotive radar that uses plan-convex lens antenna without radome [9]. It has been observed that, exerted aerodynamic forces on the surface of the lens repress the formation of homogeneous water film. Therefore, the possibility of occurrence for total degradation or the so called absolute blindness of radar sensor could be minimized. Nevertheless, Fig. 6 shows strong reduction in the capability of radar object detection by wet antenna lens.

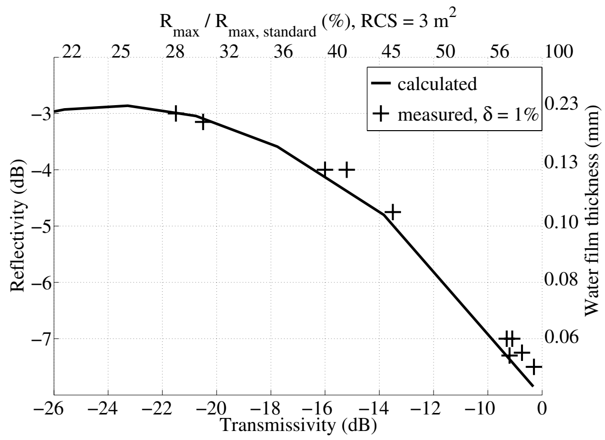

Figure 5. Maximum detection range versus reflectivity from water film on the surface of radome at 76.5 GHz.

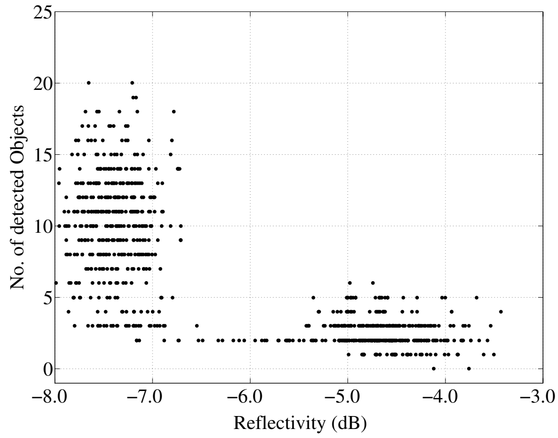

Figure 6. Correlation of radar detection capability to reflectivity from water film on the surface of antenna lens at 76.5 GHz.

IV. CONCLUSION

Water film in the propagation path of electromagnetic waves acts as signal attenuator and may lead to partial or total obstruction of radar signals in millimetre frequency range. In this paper, it has been demonstrated, in the theoretical analysis as well in the practical measurements, that the formation of water film on the surface of antenna lens or its radome causes a strong limitation on automotive long range radar performance during rainy and snowy weather conditions. Dielectric material, like ice layer with its negligible absorption coefficient, exerts generally less influence on the performance of automotive radar sensor. Therefore, the formation of water film during adverse weather conditions has to be suppressed with proper antenna lens and radome design extensively.

Further scope of this work shows that the reflected signal from the water film at the above frequencies is large enough to be recognized by any standard radar principle and so it can be utilised for the very important requirements of intelligent automotive radar, like:

- Self detection of the radar performance losses,
- System adaptability to changes of the propagation medium in adverse weather conditions like rain and snow and,
- Transfer of weather indicators to other vehicular systems.

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