A CONCEPT FOR EVALUATING THE PERFORMANCE OF WET RADOMES FOR PHASED-ARRAY WEATHER RADARS

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Abstract— **A novel analytical method for evaluating the electrical performance of a flat, tilted radome for a dual-polarized phased-array antenna under rain conditions is presented. Attenuation, reflections and induced cross-polarization are evaluated for different rainfall conditions. A new radome model is presented which takes into account the properties of the skin surface, area, inclination, radome structure, and rainfall rate. The radome is modeled as consisting of multiple layers, including a wet layer. Attenuation and propagation effects through the radome are characterized using a transmission line equivalent circuit model. Knowledge of the rainfall rate and surface properties of the radome is used to determine the radome performance. Calculated results are compared with radar data obtained with the NEXRAD and CASA systems, where good agreement between measurements and simulations was found.**

Index Terms— **Index Terms— Radome, Phased-arrays, Atmospheric Remote Sensing, Electromagnetic Modeling**

I. INTRODUCTION

The influence of water accumulation on radome surfaces has been extensively studied in terms of additional attenuation and depolarization effects in RF communication systems [1,2,3,4] and meteorological radar systems [5,6,7]. Because it is difficult to accurately model the electromagnetic effects of water accumulated on radome surfaces, evaluation of radome performance has involved experimental measurements and computer simulations. Early models estimate the distribution of rain based on laminar flow and surface tension on the radome, and do not include hydrophobic surface properties [1,4]. Currently most antenna radomes for meteorological applications include hydrophobic material on their surfaces to mitigate the negative impact of the rain on radome performance. Experimental measurement has been the most trustworthy method to evaluate radome performance under the influence of rain. Although experimental methods can provide a better understanding of physical phenomena, this approach nonetheless has significant drawbacks, including: the requirement of a large space for deployment, the need for expensive RF equipment (e.g., disdrometer, network analyzer, generator, calibrated antennas, etc.), and the need to deal with measurement uncertainties in the testing process [7].

This paper proposes a simple and inexpensive approach to model a wet radome using an analytical approach implemented in Matlab. Even though the proposed radome model is implemented for a flat, tilted antenna at X-band, the model can be modified to fit other types of radome geometry (e.g., spherical and cylindrical shapes), as well as different frequencies and wall material structures. The model requires prior knowledge of the characteristics of the radome surface and rainfall rate. With these values, it then estimates surface water distribution and calculates the attenuation, reflection and depolarization of radio signals issued.

II. MODEL

The model is subdivided into four parts, as illustrated in Figure 1. The first part estimates the drop size distribution (DSD) of a rain event. In this approach, the DSD is assumed to follow a Gamma distribution. Drop spectra $n(D)$ are calculated as follows:

$$n(D){=}N_o D^u e^{-\Lambda D} \quad (0 < D < D_{\max}) \tag{1}$$

where D represents the drop diameter, and u, Λ, N_o are model fit parameters defined in [8,9].

Based on this rain-rate dependent DSD, the second part of the model estimates the distribution of liquid water droplet sizes $n_R(D)$ over the flat tilted radome surface area (A_u):

$$n_R(D){=}\frac{n(D)}{v(D)A_u\cos(\theta_t)T\Delta D}.10^6 \quad (0 < D < D_{s-\max}) \tag{2}$$

where $v(D)$ is the terminal velocity of the water droplet in air [9], ΔD is the bin-width of each drop-size class, T represents the integration time, and θ_t the inclination angle of the radome surface [9].

To evaluate the DSD modeled in (1), a random number generator is used to create a distribution of droplets. To estimate the DSD in a tilted radome surface using (2), properties of the radome skin, such as surface tension and contact angle hysteresis, are required.

The third part of the model includes both surface tension and contact angle hysteresis. It was formulated by Nilsson and Rothstein [10], and describes the critical angle required to initiate water droplet motion occurring when gravitational forces overcome droplet surface tension on a flat, tilted radome surface.

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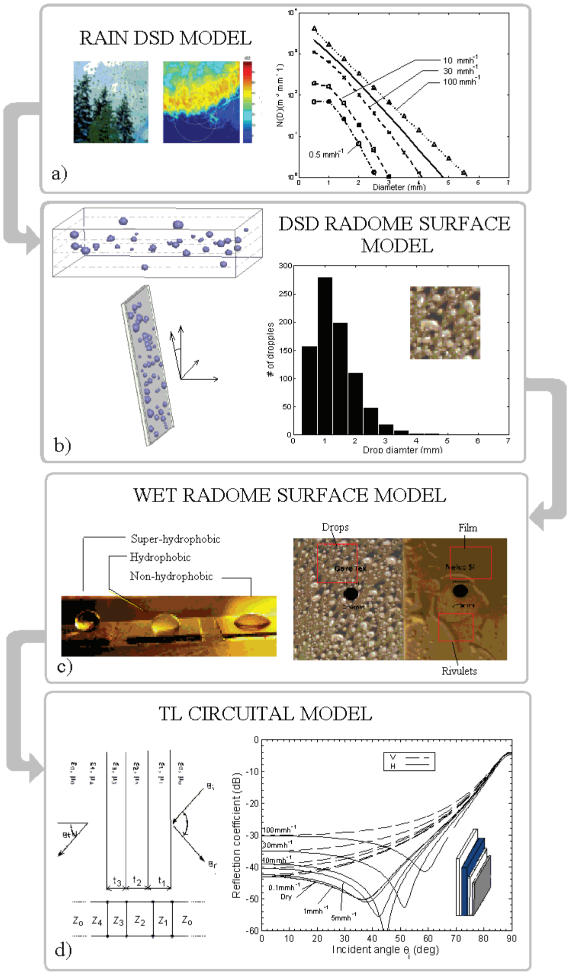

Fig. 1. Representation of a wet radome model proposed a) Rainfall rate and rain DSD is used as a function of drop diameter. b) DSD at radome surface. c) Model for droplets, rivulets and film water formation. d) A transmission line circuit model is used to estimate the scattering performance of the wet radome surface.

This critical angle is represented as follows:

$$\alpha_{crit}=\sin^{-1}\left[\frac{6k^{-2}\sin\left(\pi\text{-}\frac{1}{2}\sin\theta_H\right)\left(\cos\theta_R\text{-}\cos\theta_A\right)}{D^2}\right] \quad (3)$$

where θ_R is the receding angle and θ_A is the advancing angle. $\theta_H = \theta_R - \theta_A$ represents the hysteresis angle, and k^{-1} is the capillarity length, which is 2.7 mm for water.

Figure 2 illustrates the critical angle versus drop diameter for different hydrophobic (Teflon and GoreTex) and super-hydrophobic (TeflonS240, Hirec100 and Cytonix WX2100) material surfaces. Figure 2 illustrate the advancing, receding and hysteresis angles of 6 samples were obtained based on the drop expansion and contraction process in the Fluid Dynamic Laboratory at University of Massachusetts, Amherst [10]. From (3), the maximum diameter of a droplet for a given tilted angle (critical angle D_{s-max}) was used to adjust the DSD estimated using (2).

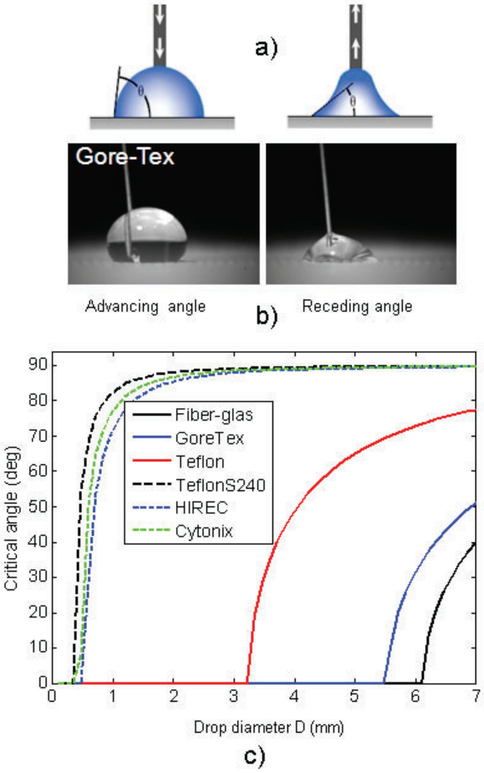

Fig. 2. Critical angle versus drop diameter for non hydrophobic (Fiber Glass), hydrophobic(GoreTex and Teflon) and Super-hydrophobic (Hirec,Teflon-S240 and Cytonix.

Once the drop spectra on the radome surface has been calculated, the next step is to estimate the effective dielectric constant of the wet surface. In the case of drop formation, since the droplets are small compared with wavelength, the Maxwell-Garnet mixing formula in (4) is used [11], as follows:

$$\varepsilon_{eff} = \varepsilon_2 + \frac{3f\varepsilon_2(\varepsilon_1 - \varepsilon_2)}{\varepsilon_1 + 2\varepsilon_2 - f(\varepsilon_1 - \varepsilon_2)}.10^6 \quad (4)$$

where, f is the fractional volume of the inclusions of water droplets with dielectric constant (ε_1) over the radome surface with dielectric constant (ε_2).

When the radome is not treated with water repellent, water sheeting occurs. In this case the formulation in [11] for a water laminar flow on an inclined surface can be used. Using this formulation, the thickness of the water film on a flat tilted radome surface as function of rain intensity and radome surface characteristics is described by:

$$t_f = \sqrt[3]{\frac{2\mu R}{W\rho g\sin\theta_t}} \quad (5)$$

where, R represents the volumetric flow rate of rain in m/s, running on a radome surface of width W in meters; μ is the kinematic viscosity of the water in kg/m.s; ρ is the density of the water in kg/m^3; and g is the gravitational acceleration in m/s^2.

The fourth and last part of the model consists of estimating the scattering parameters of a flat radome for any angle of incidence (in the azimuth plane) and polarization mode (vertical and horizontal). This model was formulated using the equivalent transmission line method, represented in Figure 1(d). Each layer is constructed of a homogeneous material with dielectric constants (ε_n) that represent the different layers of the radome material. In the case of a wet radome, the first layer (n_1) represents the water accumulated on the radome surface.

III. VALIDATION AND PRELIMINARY RESULTS

Between September and October of 2011, samples of different radome surfaces were exposed to three rain events. Intervals between 5 minutes to 3 hours were used to evaluate the characteristics of water accumulated on each surface. Non-hydrophobic, hydrophobic and super hydrophobic materials, with different inclination angles (-10 °, 0 °, and 10 °) were considered. Pictures and videos of water accumulation were used to estimate the drop size distribution for each specific sample. The estimated drop size distribution for given sample was later compared with calculated values from the model proposed. Figure 3 shows the comparison of estimated and measured drop size distributions on a hydrophobic radome sample (GoreTex), tilted 10 °, during a rain event of September 21, 2011. The rainfall rate was estimated from the reflectivity of S-band (NEXRAD) radar using the Z-R relationship given in [5]. Although there is not a perfect match between the estimated and measured distributions, the median values of the drop diameter differ by 0.01 mm.

Figure 4 shows the corresponding calculated and measured values of the two-way attenuation radar signals for a reflectivity range between 0 dBZ to 50 dBZ. The scatter data was obtained by comparing the difference between the S- and X-band wet radome. Area was averaged over the rain gauge network location with a size of 20 km by 32 km. The calculated data (dashed line) was estimated using the radome characteristics and geometry for a rain intensity equivalent to a reflectivity between 0 dBZ to 50 dBZ, in intervals of 5 minutes. A good fit existed between measured and calculated values, which suggests that the model proposed can be used to estimate the two-way losses of a wet radome surface.

Table I, provides information comparing radome design specification (given by the manufacturer) and calculated values based on the model proposed. It also shows comparison with radar data measured by Trabal et. al., [5] in dry conditions, and also for 10 mmh^{-1} and 30 mmh^{-1}. Small differences existed between specified and estimated values of two way losses using this model for dry and wet conditions.

TABLE I

SUMMARY RESULTS FOR TWO-WAY ATTENUATION IN THE CASA IP1 X-BAND ANTENNA DISH RADOME.

Parameter	Specified	Calculated	Measured [5]
Two-way loss (dry)	0.8 dB	0.50 dB	No data
Two-way loss (at 10mmh^{-1})	1.6 dB	1.18 dB	1.11 dB
Two-way loss (at 30mmh^{-1})	2.0 dB	1.82 dB	1.96 dB

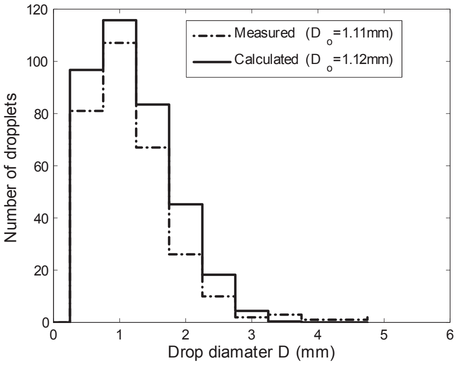

Fig. 3. Comparison of estimated and measured drop size distribution collected on a hydrophobic radome sample (5cm x 5cm). The measured data corresponds with data obtained in experiment of September 21, 2011.

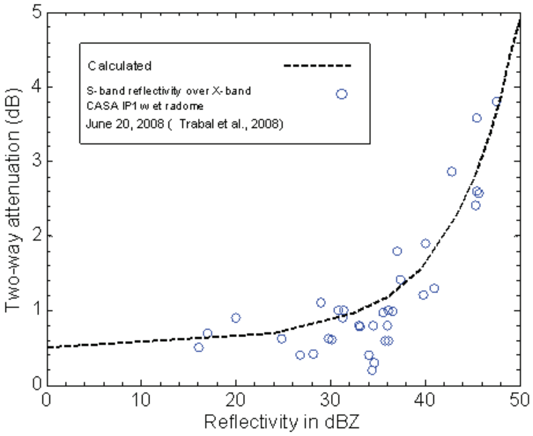

Fig. 4. Calculated and measured two-way attenuation versus reflectivity values in a CASA IP1 weather radar network (June 20, 2008)

Figures 5, 6 and 7 show the estimated results for one-way reflections, attenuations, and induced depolarization corresponding to a flat sandwich radome with a hydrophobic surface that is tilted at 34 ° and affected by rain intensities between 0.1 mmh^{-1} to 100 mmh^{-1}. The wall radome structure used for this example was designed for 10 GHz. The struture is composed of a low core dielectric of Rohacell foam (ε_r=1.046, tanδ=0.0017, t=250 mil) and a thin skin hydrophobic layer of Goretex (ε_r=1.55, tanδ=0.0017, t=12 mil). Considering a scanning range from 0 ° to 60 ° (in the azimuth plane), the dry radome presents an attenuation below -0.3 dB, reflections below -30 dB and an induced cross-polarization below -50 dB. However when the radome is wet, rain intensity of 100 mmh^{-1}, the attenuation (one-way) increases to -1.5 dB, the reflections to -15 dB and the depolarization to -19 dB. Those results are more realistic that results obtained using the film water model, which estimates for same radome and rain conditions, an attenuation of -4.5 dB, reflections of -2 dB and induced depolarization of -14 dB.

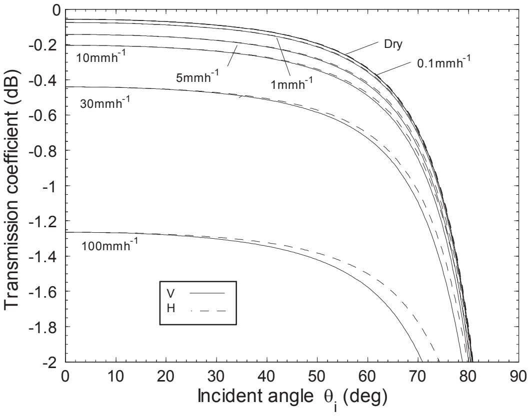

Fig. 5. Transmission coefficient versus incident angle (in azimuth plane) for different rain intensity and polarization H and V when the radome is tilted 34 deg.

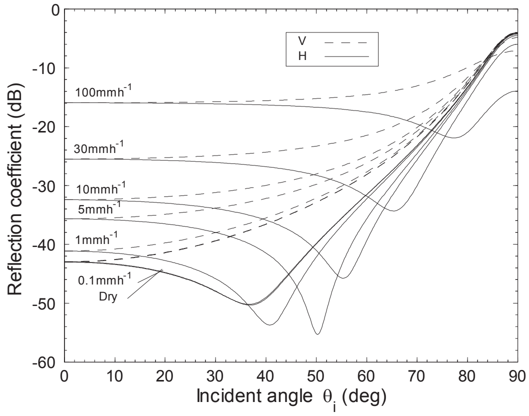

Fig. 6. Reflection coefficient versus incident angle (in azimuth plane) for different rain intensity and polarization H and V when the radome is tilted 34 deg.

IV. CONCLUSIONS

A new analytical model to evaluate and characterize the performance of a wet radome was presented. The proposed model offers a better estimation of the radar signal attenuation than a conventional models based on water film. In addition it provides information about reflections and depolarization. The model can be used for various types of radome and material surfaces (including super hydrophobic surfaces). It estimates the water distribution of an inclined flat surface for different types of water formation (water film, rivulets and drops) and then calculates the scattering parameters of the wet radome. The method requires prior knowledge of the characteristics of the radome surface and rainfall rate. The model was validated using numerical simulation in HFSS and also using experimental data from operational CASA IP1 and NEXRAD radars systems, where good agreement was found.

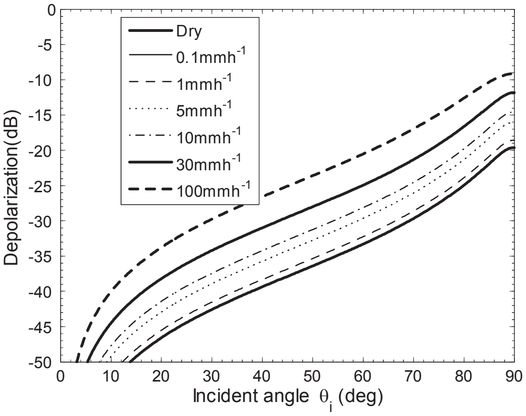

Fig. 7. Depolarization ration versus incident angle (in azimuth plane) for different rain intensity and polarization H and V when the radome is tilted 34 deg.

V. ACKNOWLEDGMENTS

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