Measurements of the Transmission Loss of a Radome at Different Rain Intensities

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ABSTRACT

Results on the transmission loss of a dry and a wet C-band weather radar radome at different rain intensities are presented. Two methods were used in the study, both carried out under laboratory conditions. In the first method, the complex permittivity of a dry radome is measured and the transmission loss calculated. To analyze the transmission loss of a wet radome, the thickness of a continuous water layer on the surface of a radome at different rain intensities and the complex permittivity of water are calculated. In the second method, the transmission loss is measured as a free space transmission measurement with a 1.3-m² piece of a radome panel. The piece is measured as dry and as doused by a rain system designed for the measurements. The measurements are performed with a dirty, cleaned, and waxed radome to examine the effects of maintenance measures with an old radome on the transmission loss. Because the transmission loss as a function of rain intensity is measured with a small piece of radome, a method is developed to scale the free space measurements for a complete 6.7-m-diameter radome with equal dielectric properties. Results of the one-way transmission loss of a dry radome with the permittivity and free space measurements are in a good agreement (0.34 and 0.35 dB, respectively). According to the analysis, a continuous water layer on a radome has a significant influence on the transmission loss. A 3-dB two-way transmission loss caused by a dirty radome is observed at a rain intensity of 15.1 mm h⁻¹. Waxing gives promising results in reducing the wet radome loss because the waxing prevents the formation of a continuous water layer on the surface of the radome.

1. Introduction

Radomes are needed to protect the weather radar antenna and the receiving and transmitting chains from weather conditions. Even though radomes enable a continuous operation of the weather radar even in severe weather, they have a negative influence on measurement accuracy. One of the biggest concerns is the additional transmission loss caused by a radome. If the transmission loss of a dry radome is known, it can be compensated for by taking it into account in the calibration of the radar. If water or wet snow precipitates onto a radome, the situation is more complicated because the transmission loss changes as a function of the rain intensity. The wet radome transmission loss has been discussed, for instance, by Blevis (1965), Cohen and Smolski (1966), Anderson (1975), Effenberger et al. (1986), Dietrich and West (1988), Hendrix et al. (1989), Fenn (1997), Manz et al. (1999), and Crane (2002). Blevis (1965) presented theoretical calculations of the wet radome attenuation at different water layer thicknesses. At 3.65 GHz with a 0.254-mm water layer thickness, the one-way radome transmission loss was 2.6 dB, suggesting a strong influence on the radar performance. Anderson (1975) conducted continuous measurements for 15 months with a piece of a radome at 20 GHz. Anderson concluded that a nonwetting radome surface is essential if a small transmission loss in rain is desired and that the hydrophobic property of the radome surface will degrade with time. After 6 months, the transmission loss at a rain intensity of 10 mm h⁻¹ had risen by about 6 dB. Dietrich and West (1988) conducted measurements in artificial rain between 13 and 20 GHz with used and new radome panels. The old panels had 2–3 dB higher losses compared to the new ones at a rain intensity of 10.5 mm h⁻¹. The addition of hydrophobic paint on used panels dropped the maximum loss to 0.25 dB at rain intensities between 2.5 and 29 mm h⁻¹. Hendrix et al. (1989) carried out measurements of attenuation with radome panels of two different materials in dry conditions and in artificial mist, rivulet flow, and sheet flow conditions at 20 GHz. An
estimate of the transmission loss for a complete radome was calculated to be 3.9 dB lower for the radome with better hydrophobic properties at a rain intensity of 48.8 mm h⁻¹. Fenn (1997) conducted measurements of the transmission loss of an air-supported radome in artificial rain at 19.5 GHz. At a rain intensity of 10 mm h⁻¹, one-way transmission loss of 1.1 dB was observed for the hydrophobic radome.

Even though the studies mentioned above show the influence of water on the radome surface to the transmission loss, only Cohen and Smolski (1966), Effenberger et al. (1986), Manz et al. (1999) and Crane (2002) discussed the wet radome loss at the C band. Cohen and Smolski (1966) carried out measurements in artificial rain with a 16.8-m-diameter metal space frame radome at a frequency of 6.7 GHz. They concluded that the transmission loss was about 0.5 dB at a rain intensity of 10 mm h⁻¹. At a rain intensity of 40 mm h⁻¹, the wet radome loss dropped from 1.5 to 0.3 dB after applying a hydrophobic coating. Effenberger et al. (1986) carried out an analysis which took into account both the water film and the droplet conditions on flat polytetrafluoroethylene (PTFE) coated fiberglass radome panels and polyvinyl fluoride (PVF) film laminates. The analysis showed that as long as water stays as droplets on the radome surface, the transmission loss is less than that under continuous water film conditions. At a 6 GHz frequency and 10 mm h⁻¹ rain intensity, the loss caused by droplets can be 3.3 dB less than the loss at water film conditions. Manz et al. (1999) presented results of measurements carried out at the C band with a CW signal source and a radar equipped with a 6.7-m-diameter radome. Around 10 mm h⁻¹ a one-way transmission loss of approximately 1.3 dB was measured for a cleaned radome. Crane (2002) presented theoretical calculations of the wet radome attenuation at 5.5 GHz for a 5.2-m-diameter radome. One-way transmission loss of 2.8 dB was calculated for a nonhydrophobic radome and 0.8 dB for a hydrophobic radome at a rain intensity of 10 mm h⁻¹.

The C band, specifically from 5.6 to 5.65 GHz, is commonly used by weather radars in Europe and thus is also the frequency range of interest in our study. Radomes of C-band weather radars are usually self-supporting spherical sandwich structures assembled from many panels connected together to form joints. The joint areas are typically of fiberglass or composite material, whereas the middle part of a panel, the window area, consists of a multilayer sandwiched wall structure. A broadly used sandwich structure is the A-sandwich structure, which is also the wall structure analyzed in this study.

In this paper we present results of calculations and measurements of the transmission loss of a dry and wet radome at a frequency of 5.65 GHz. All the measurements are performed with a 14-yr-old 1.3-m² piece of a radome in controlled conditions in the laboratory. The piece is a part from a window area of a complete 6.7-m-diameter orange-peel-geometry radome. Two different approaches are used in the study. In the first approach, the complex permittivity of a radome is measured with a vector network analyzer and a coaxial dielectric probe, and the transmission loss of a dry radome is calculated based on the permittivity measured. The transmission loss of a wet radome at different rain intensities is calculated assuming a continuous water film flowing on the surface of a radome. For the wet radome calculations, the thickness of the water layer and the complex permittivity of water are deduced. In the second method, the transmission loss is measured as a free space transmission measurement with two horn antennas, a signal generator, and a power meter. To measure and analyze the effect of the precipitation on the surface of a radome, a rain system is developed with which the free space measurements can be carried out as a function of rain intensity. The effects of maintenance measures for an old radome on transmission loss are studied by carrying out the measurements with a dirty, cleaned, and waxed radome at the different rain intensities. To get an estimate of the wet radome loss of a complete radome, a method is developed to scale the measurements of the radome piece to be valid for a complete radome.

2. Theory

According to Skolnik (1990), an electromagnetic wave transmitted and received by a radar is affected by a sandwich type of radome with two main mechanisms: the scattering from the junction areas of the panels and the absorption and reflections introduced by the window areas of the panels. Because the dielectric properties of the joints and the window areas are different, there will be an impedance mismatch between the joints and the window areas. In addition, the panels are normally attached with metal bolts and nuts. Because of these two factors, the energy transmitted by a radar is scattered away from the main beam of the radiation pattern of the antenna. Despite the recognized influence of the joints to the transmission loss, the scattering of the joints is not analyzed in this study because the main focus is on the effects of a wet radome.

At the radome’s window areas, the transmission loss is mainly caused by the absorption and reflections. The main absorption mechanism at the C band is the orientation polarization of polar molecules (Nyfors and
Vainikainen (1989). Mathematically, the absorption is described by the complex part of the material's permittivity in a nonmagnetic dielectric medium. When the relative permittivity \( \varepsilon_r = \varepsilon'_r - j\varepsilon'_r \) of an isotropic material is known, the attenuation constant \( \alpha \) can be calculated from the equation of the propagation constant \( \gamma \); that is,

\[
\gamma = jk = \alpha + j\beta = j\omega \sqrt{\varepsilon_r \mu_r},
\]

\[
= j2\pi f \sqrt{\varepsilon_r' \mu_r' - j\varepsilon_r'' \mu_r' - j\mu_r'' \varepsilon_r' \mu_r'}, \tag{1}
\]

where \( k \) is the wavenumber, \( \beta \) is the phase constant, \( f \) is the frequency, \( \mu_r = \mu_r' - j\mu_r'' \) is the relative permeability, \( \varepsilon_r \) is the permittivity of the vacuum, and \( \mu_0 \) is the permeability of the vacuum. When the attenuation constant and the thickness of the material are known, the absorption can be calculated for a plane wave by using a solution of the Helmholtz equations.

Because of mismatches of the wave impedances between the radome and the air, only a part of the transmitted power will penetrate the radome. With the assumption of a homogenous radome, there are two interfaces between the air and the radome causing reflections. Between these two interfaces there will be an infinite amount of waves propagating backward and forward inside the radome. The total transmitted wave is the sum of all the waves that penetrate the radome–air interface. When a layer of water is present on the surface of a radome, there is one more medium and one more interface for the transmitted wave to penetrate. Because of an extra layer, there are now multiple reflections inside the radome, inside the water layer, and across the interface between the radome and water. The total transmission loss is calculated with the boundary conditions of the Maxwell equations at the perpendicular incidence, taking into account absorption and reflections with a plane wave approximation and assuming a homogenous layer of water and a homogenous wall structure of the radome. Electric fields at the consecutive interfaces can be formulated in a matrix form as (Orfanidis 2004)

\[
\begin{pmatrix}
E_{i,+} \\
E_{i,-}
\end{pmatrix}
= \frac{1}{\tau_i} \begin{pmatrix} e^{\gamma_i l_i} & \rho_i e^{-\gamma_i l_i} \end{pmatrix} \begin{pmatrix}
E_{i+1, +} \\
E_{i+1, -}
\end{pmatrix}, \tag{2}
\]

where \( E_{i,+} \) and \( E_{i+1,+} \) are the electric fields propagating to the positive direction and \( E_{i,-} \) and \( E_{i+1,-} \) are the electric fields propagating to the negative direction at the interfaces \( i \) and \( i + 1 \), respectively; \( l_i \) is the thickness of the medium \( i \); \( \gamma_i \) is the propagation constant in the medium \( i \); \( \tau_i = 1 + \rho_i \) is the transmission coefficient at the interface \( i \); and \( \rho_i \) is the reflection coefficient at the interface \( i \). When the radar pulse is transmitted, the electric fields at the water–air interface (indicated by subscript wa) are related by the equation

\[
\begin{pmatrix}
E_{wa,+} \\
E_{wa,-}
\end{pmatrix}
= \frac{1}{\tau_{wa}} \begin{pmatrix} 1 & \rho_{wa} \end{pmatrix} \begin{pmatrix}
E'_{wa,+} \\
0
\end{pmatrix}, \tag{3}
\]

where \( E'_{wa,+} \) is the penetrated electric field at the water–air interface. Because there are no returning fields after the last interface, the fields at previous interfaces can be calculated recursively with Eqs. (2) and (3), and thus the transmission coefficient can be solved as a ratio of the transmitted electric field after the last interface and the incident electric field before the first interface. If the media before the first layer and after the last layer are the same, the transmission loss of power can be calculated in decibels with the formula

\[
L_{\text{tra,dB}} = 10 \log_{10} \left( \frac{1}{|H|^2} \right). \tag{4}
\]

To calculate the attenuation caused by a continuous water film flowing on the surface of a radome, the permittivity and the thickness of the water layer need to be known. The relative permittivity of water, which is a function of the frequency, the salinity, and the temperature, is calculated with a fit based on the double Debye relaxation equation introduced by Meissner and Wentz (2004). The salinity is set to zero because the water droplets in rain can be considered to be practically without any salinity concentration. The temperature of the water droplets can vary from supercooled water temperatures to tropical temperatures. Theoretically, the highest imaginable temperature in Finland is estimated to be 30°C. When the temperature of water goes down, the attenuation will increase because the imaginary part of the permittivity will rise (as can be seen from Table 1). Because of the negative temperature dependency of the attenuation of water, the measurements and the analysis are performed at a water temperature of 30.5°C to give a conservative limit for the attenuation. The thickness of the water film was calculated with Gibble’s formula as presented by Anderson (1975). Gibble’s formula,

\[
l_w = 3 \frac{3\mu_0 a R}{2g}, \tag{5}
\]

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Relative permittivity of water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td>64.36 – 37.20i</td>
</tr>
<tr>
<td>10°C</td>
<td>70.71 – 29.37i</td>
</tr>
<tr>
<td>20°C</td>
<td>72.62 – 22.56i</td>
</tr>
<tr>
<td>30°C</td>
<td>72.07 – 17.42i</td>
</tr>
</tbody>
</table>

Table 1. Relative permittivity of water at different water temperatures at a frequency of 5.65 GHz.
is valid for a laminar flow of water on a spherical radome. It can be derived by combining the equation of water layer’s thickness in laminar flow on a flat surface (Green 1988),

$$l_w = \sqrt{\frac{3 \Gamma \mu_w}{g \rho_w (\rho_w - \rho_n) \sin \varphi}},$$

(6)

and the equation of the load introduced by the precipitating water per unit width of the radome’s “latitude,”

$$\Gamma = \rho_w R \frac{\pi (a \sin \varphi)^2}{2 \pi a \sin \varphi} = \rho_w R \frac{a \sin \varphi}{2} ,$$

(7)

where $\mu_k$ is the kinematic viscosity of water, $a$ is the radius of the radome, $R$ is the rain intensity given in meters per second, $g$ is the acceleration due to gravity, $\mu_w$ is the viscosity of water, $\rho_w$ is the density of water, $\rho_n$ is the density of the medium surrounding the water (air in this case), and $\varphi$ is the inclination angle with the vertical measured from the center of the radome. The density of the air $\rho_a$ is set to zero as required by Eq. (5). The viscosity and density of water are functions of the temperature; that is, they affect the thickness of the water layer and thus have to be taken into account when the thickness of the layer is calculated using the formulas presented above. Because of the greater surface area, there will be more water running on a surface of a full-scale radome than on a piece of a radome at the same rain intensity. As can be seen from Eq. (7), Gibble’s formula is dependent on the horizontal projection area from which the precipitation is collected. From this area, water is flown down across the arc of a small circle defined in the denominator of the first form of Eq. (7). If a defined width $L$ is given to the arc of the small circle at an inclination angle $\varphi$, the horizontal projection area from which water is flown across the given width $L$ is

$$A_h = \frac{L a \sin \varphi}{2} .$$

(8)

When the ratio $K$ of the horizontal projection areas of the piece to the complete radome with the same arc width $L$ is calculated and inserted into Eq. (5), Gibble’s formula will be modified into the form

$$l_{w,m} = \sqrt{\frac{3 \mu_k a R K}{2g}} .$$

(9)

Equation (9) scales the thickness of the water layer on a complete radome to the thickness of the water layer on a piece of a radome with an arc width of $L$. A schematic picture of the projection area of a complete radome is presented in Fig. 1.

The method used in this study to scale the free space measurements to a complete radome is based on the calculation of the transmission loss with Eqs. (2)–(4) using two water layer thicknesses deduced from Eq. (9), valid for a piece of radome, and Eq. (5), valid for a complete radome. The difference of the transmission losses is then added to the free space measurements of the transmission loss to scale the measurements made on a piece of radome to be valid for a complete 6.7-m-diameter radome with equal dielectric properties.

Attention is paid in this study to deriving the uncertainties for the measured and the calculated values. Uncertainties are calculated as root sum square (RSS) uncertainties at the 95% confidence level. All the variables in the uncertainty analysis are expected to be uncorrelated. Combined uncertainties related to measured values are calculated by taking the square root of the sum of the squares of the analyzed standard uncertainties. Combined uncertainties related to calculated values are calculated with a formula

$$U = \sqrt{\sum_{i=1}^{n} \left[ \frac{\partial f}{\partial x_i} u(x_i) \right]^2} ,$$

(10)

in which $u(x_i)$ is the standard uncertainty of the input estimate $x_i$. Because the distribution of all of the variables is not known, a uniform distribution is assumed in the undetermined cases. Finally, the central limit theorem is invoked to calculate the uncertainties by multiplying the combined uncertainty by a coverage factor associated with a given confidence level.
3. Experiments and results

a. Transmission loss based on permittivity measurements

The permittivity of the radome is measured from the window area of the panel with an Agilent E5017B vector network analyzer equipped with a Hewlett-Packard (HP) 85070A coaxial dielectric probe and the measurement software provided with the probe. The permittivity measurements and the calibration of the vector network analyzer are carried out in the laboratory at 21°C. A coaxial probe is convenient to use because there is no need to cut a separate piece of the material being tested for the measurements. The drawback in the method is that the derivation of the permittivity is based on a reflectivity measurement. A reflectivity measurement is not optimal for measuring multilayer sandwich structures because one cannot be sure whether all of the layers are actually affecting the reflection coefficient or not. It is possible to distinguish four main layers in the panel used: the fiberglass inner skin, the polyvinyl chloride (PVC) foam core, the fiberglass outer skin, and the hydrophobic gelcoat outer coating. Each of these layers has different dielectric properties and thicknesses and thus contributes to the overall reflection coefficient. If the material under test is too thin compared to the penetration depth of the electromagnetic wave in that material, the reflection from the back side of the material can bias the measurements. The adequacy of the radome wall thickness was checked by placing a metal plate to the back side of the measurement area. No variation was observed between measurements carried out with and without the metal plate. Another drawback in using a coaxial probe is that the probe is not capable of measuring complex parts of the permittivity as low as are needed in the case of a low-loss A-sandwich radome. Therefore, the imaginary part was calibrated by introducing a calibration constant with which the bias in the measured imaginary part of the radome’s permittivity was removed. The calibration constant was based on the ratio of the tabulated and measured value of the permittivity of polyamide (Ertalon 6SA). The complex permittivity of polyamide is given by von Hippel (1995) at a frequency of 3 GHz and temperature of 25°C. The measured imaginary part of the permittivity of the polyamide differed by 5.3% from the measured imaginary part of the radome’s permittivity; thus, the material was considered adequate to be used in the calibration constant for bias removal in the measurements carried out at 5.65 GHz.

According to the measurements, the real part of the relative permittivity of the radome was \( \varepsilon'_{r,rad} = 3.613 \pm 0.062 \) and the imaginary part \( \varepsilon''_{r,rad} = 0.047 \pm 0.005 \).

The permittivity was calculated as a mean of 112 independent measurements. The thickness of the radome wall was measured with a micrometer gauge from different positions of the radome’s window area. The mean thickness given by 30 measurements was 12.7 ± 0.04 mm. Insertion of these parameters into Eqs. (2)–(4) results in a transmission loss of a dry radome of \( L_{tra,dB} = 0.34 \pm 0.26 \) dB.

The wet radome transmission loss for a 6.7-m radome is calculated by inserting the measured parameters and the calculated thickness and permittivity of the water layer into Eqs. (2)–(4). The transmission loss at 5.65 GHz as function of the rain intensity at the water temperatures of 0°C, 10°C, 20°C, and 30°C is given in Fig. 2.

b. Free space measurements with a dry radome

The free space transmission loss measurements are performed using two identical pyramidal horn antennas at horizontal polarization. The transmitting antenna was fed with an HP 83731A signal generator at a frequency of 5.65 GHz and a power level of 20 dBm. The receiving antenna was connected to an HP 8484A power sensor and an HP 436A power meter. The measurement setup is shown in Fig. 3. With a 22.5° phase error assumption, the far field distance of the antennas was 1.66 m. The radome was placed vertically in the middle of the antennas at a 1.8-m distance from the apertures of the antennas. At this distance the 3-dB beamwidth of the antennas was 0.7 m. Because the shortest horizontal and vertical dimensions of the piece were 1.1 and 1.0 m, respectively, the piece was considered to be large enough to discard the effect of diffrac-
tion around the sides of the piece. The piece was put vertically in place in such a way that the normal of the surface, located at the center of the spherical piece, was aligned with the line of sight of the antennas. The measurement setup was thus analogous to the real radar measurements with zero antenna elevation.

All the antenna measurements were performed as relative measurements. At first, free space between the antennas was measured as a reference; afterward the piece of the radome was put in place and the measurement was repeated. Because of the standing wave between the antennas all the measurements were carried out as function of distance by moving the transmitting antenna. The effect of the standing wave is clearly visible in Fig. 4. Mean values of the measurements were derived from the fits, and the transmission loss was calculated by subtracting the mean value of the radome measurement from the mean value of the reference measurement in dBm. The measured values and the fits needed for the derivation of the transmission loss can be seen in Fig. 4. The measured transmission loss was $L_{\text{rad,dB}} = 0.35 \pm 0.07$ dB, calculated as a mean of eight independent measurement sets, which each consisted of 31 measurements. The largest contribution to the uncertainty originates from the orientation of the radome piece. The eight measurement sets allowed us to estimate the effect of the orientation on the uncertainty.

c. Free space measurements with a wet radome

To measure the total transmission loss as a function of the rain intensity, a rain system was developed. Main parts of the system are two parallel connected flow meters enabling flow rates between 0.01 and 1.13 L min$^{-1}$, a feeding hose, a nozzle, a nozzle holder, and an electric motor for rotating the nozzle. The nozzle consists of a 2-mm-diameter hose into which holes of diameter 0.2–0.45 mm with a separation of 10–30 mm were stuck. The diameters and separation of the holes were experimentally tested to adjust the nozzle to a certain flow rate area. Five different nozzles were needed to cover the rain intensities between 2.4 mm h$^{-1}$ and 25.7 mm h$^{-1}$. Small diameters of the nozzles and of the holes caused the water to be sprayed from the holes as small droplets, thus producing a more uniform rain field than would have been possible to produce with single larger droplets. Despite the spraying effect, uniform areas of rain intensities smaller than 10 mm h$^{-1}$ were difficult to produce with a static system. Smaller intensities were reached through adding a motor of wind screen’s wiper to the axel of the nozzle. With the motor the nozzle was rotated back and forth in a 90° sector. The nozzle was placed above the piece of the radome at a 3.2-m height. At this height the droplets do not reach their terminal velocities, but this had to be accepted because the measurement site did not allow for a higher installation of the nozzle.

The rain system was calibrated by weighing the water collected in two containers, each of 0.205-m$^2$ area, at a given time unit. Linear regression fits were derived for the measurements, and as a result a lookup table connecting the readings of the flow meters (L min$^{-1}$) and the rain intensity (mm h$^{-1}$) was established. The results of the calibration, the fits, and the prediction intervals at a confidence level of 95% are shown in Fig. 5. The nozzle used at rain intensities between 3.1 and 4.2 mm h$^{-1}$ is omitted for clarity.

The wet radome measurements were carried out as relative measurements; the dry radome measurement...
was used as the reference measurement. At each rain intensity, one set of 31 measurements was carried out and the attenuation was calculated as described above in section 3b. Repeated measurement sets to estimate the uncertainty of the placement of the radome piece were not done; instead, the uncertainty derived from the dry radome measurements was used in the uncertainty estimation. All the wet radome measurements were performed in the laboratory in conditions of no wind. As shown by Bechini et al. (2006), wind can introduce a great bias in the wet radome loss as a function of azimuth angle. Analysis of the wind effects on wet radome loss requires a full radome and thus was beyond the scope of our study carried out with a piece of a radome.

Measurements were performed with the same piece of the radome as dirty, as cleaned, and as waxed. Ethanol, xylene, dishwasher detergent, and acetone were tested in cleaning the radome. The result of cleanness was inspected visually. No major difference was found between the effectiveness of the different detergents. Because the cleaning was done by polishing the radome by hand with a piece of cloth, the biggest difference appeared to be the effort put into cleaning. Acetone gave the best results with the least effort, but the dishwasher detergent (an effective and less expensive alternative) produced an almost equally good cleanness. Waxing was performed also by hand with a wax designed for gelcoat surfaces.

Results of the wet radome one-way transmission loss measurements combined with the dry radome loss are shown in Fig. 6. The figure shows that there are no significant differences between a dirty and a cleaned radome at different rain intensities. The calculated uncertainty of the free space measurements remained under ±0.08 dB; that is, the differences between transmission losses of a dirty and cleaned radome are covered by the given uncertainty. In both those cases, the water stayed as a continuous film on the surface of the radome; with a waxed radome, the water remained as droplets at all rain intensities measured. As a consequence the transmission loss increased only a little as the rain intensity was increased.

The results of Fig. 6 are applicable only to a radome piece with equal size and at horizontal antenna elevation. Because the objective of this study was to define the wet radome transmission loss of a complete radome, the method described in section 2 was used to derive the transmission loss of the full 6.7-m-diameter radome. The results of the scaled measurements and the theoretical attenuation based on Gibble’s formula, given in Eq. (5), are shown in Fig. 7. The transmission loss of the waxed radome is not shown because the scaling of the measurements is based on the modified Gibble’s formula that is valid only for a laminar flow of a continuous water sheet. The one-way transmission losses and associated uncertainties at the 95% confidence level are also given in Table 2. Uncertainties are calculated as RSS uncertainties, with Eq. (10) taking into account the uncertainties in the free space measurements and the uncertainties related to the scaling of the measurements.

4. Discussion

As seen in Fig. 7, the theoretical attenuation given by Gibble’s formula and the scaled free space measure-
ments are in a good agreement at a water temperature of 30.5°C, at which our measurements and calculations have been carried out. Figure 2 shows that the attenuation increases with decreasing temperature quite considerably, and therefore our results are not directly applicable to most climatic conditions. However, the results give a lower limit for the attenuation. For lower temperatures, more commonly encountered in real-life applications, the attenuation can be calculated using the formulas presented in this paper provided that the water stays as a continuous sheet on the radome surface.

Table 2 shows that nearly ±0.8-dB variability in the transmission loss has to be accepted. Because the uncertainties of the free space measurements shown in Fig. 6 are less than ±0.08 dB, almost all of the uncertainty results from the scaling of the measurements. Even though the uncertainty of the scaled transmission loss can be large, the behavior of the loss as a function of the rain intensity is similar to the results given by Fenn (1997), Manz et al. (1999), and Crane (2002). Because of different frequencies, radome materials, and methods used in these studies, a direct comparison of the transmission loss is meaningful only with the results of Manz et al. (1999), whose measurements were carried out with a full radome at the C band. According to Manz et al. (1999), as interpreted from the figure in the article, the one-way transmission loss of a cleaned radome at 10 mm h⁻¹ was approximately 1.3 dB, which is 0.06 dB more than the attenuation achieved in this study at 10.8 mm h⁻¹. At 4 mm h⁻¹ they reported approximately 0.9-dB attenuation for a dirty radome, whereas 0.94-dB attenuation was observed at 4.1 mm h⁻¹ for a dirty radome in our study. Even though Manz et al. (1999) did not specify the wall structure of the radome or the temperature of water used in the experiment, they note that the radome was covered with a gelcoat coating, which was probably similar to that used in our study. This could explain the similarity in transmission losses at the rain intensities compared.

We did not analyze joint effects in this study despite the known negative effects of joints on transmission loss (Skolnik 1990). The complete orange-peel radome (the source of the panel used in the measurements) consists of top panels and of six identical wall panels forming six vertical joints. When the top panels were neglected, the combined joint area was about 6% of the total wall area of the radome. Because the total area of the joints was relatively small, the fact that junction area loss was not measured or analyzed was not considered crucial in estimating the radome loss of horizontally polarized weather radar.

According to Hendrix et al. (1989) and Fenn (1997), water on the surface of a radome flows down in three different forms: as a laminar sheet, as rivulets, and as droplets. The form of the water flowing on a spherical radome is dominated by the hydrophobic properties of the outer surface of the radome. Measurements done by Cohen and Smolski (1966), Anderson (1975) and Hendrix et al. (1989) showed that the transmission loss is smaller if water stays as rivulets instead of a continuous film. In our study, water stayed as a sheet above the equator of the vertical radome piece and as rivulets underneath the equator in the measurements carried out with the dirty and cleaned piece. At the lowest intensity, 2.6 mm h⁻¹, the continuous sheet covered about 30% of the surface area from the top toward the equator, and at the highest rain intensity, 22.1 mm h⁻¹, about 65% of the surface area from the top toward the equator of the piece. Underneath the continuous water film area, water flowed down in rivulets

<table>
<thead>
<tr>
<th>Rain intensity (mm h⁻¹)</th>
<th>Dirty radome (dB)</th>
<th>Cleaned radome (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
<td>0.80 ± 0.64</td>
<td>0.74 ± 0.65</td>
</tr>
<tr>
<td>3.4</td>
<td>0.86 ± 0.66</td>
<td>0.87 ± 0.65</td>
</tr>
<tr>
<td>4.1</td>
<td>0.94 ± 0.66</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>1.05 ± 0.65</td>
<td></td>
</tr>
<tr>
<td>10.8</td>
<td>1.39 ± 0.71</td>
<td>1.24 ± 0.74</td>
</tr>
<tr>
<td>15.1</td>
<td>1.58 ± 0.74</td>
<td>1.47 ± 0.76</td>
</tr>
<tr>
<td>22.1</td>
<td>2.17 ± 0.72</td>
<td>1.95 ± 0.76</td>
</tr>
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</table>
mostly along the old and darker paths. In our measurements we never observed a situation where the water was flowing merely as rivulets. As the rain intensity increases, more water reaches the area beneath the equator in the form of a continuous sheet, thus causing more attenuation. This is the most probable explanation for the steep rise of the transmission loss in Fig. 6 at 22.1 mm h$^{-1}$, which in turn implies that at higher radar antenna elevations the transmission loss would be higher. The experiments carried out by Dietrich and West (1988) also suggest this kind of behavior as a function of the elevation angle.

After waxing, the behavior of water on the surface of the radome piece changed dramatically and the transmission loss of the waxed radome was hardly measurable. Water stayed as droplets on the whole capture area at the rain intensities measured and also flowed down as separate droplets. By visual inspection, the droplets grew in size as the rain intensity increased, causing them to fall more rapidly than at the lower rain intensities. This can probably explain the surprisingly small 0.03-dB rise of the transmission loss as the rain rate increased from 10.8 to 22.1 mm h$^{-1}$. Because the water stayed as droplets on the surface of the radome piece, it is not possible to calculate the effects of waxing on a complete radome; the method used in our study is only valid for a laminar flow of a continuous water film. However, when the nonscaled free space measurements of a dirty and a waxed radome are compared, the two-way transmission loss of the waxed radome piece is 1.5 dB less at a rain intensity of 22.1 mm h$^{-1}$. With a complete radome, the difference between a waxed and nonwaxed wet radome would most likely be even greater. First, the greater amount of water collected by a complete radome would run down more rapidly than in the nonwaxed case. Second, the waxed surface would keep the water as droplets on the surface of the radome, and at higher rain intensities the waxed surface would cause the water to flow down as separate rivulets rather than a continuous film. These assumptions are supported by Cohen and Smolski (1966), who observed that many narrow rivulets were formed, thereby allowing fast shedding of water after the hydrophobic treatment, and by Effenberger et al. (1986), who claimed that there was no significant difference in drop distribution on a hydrophobic panel when held at 30° from vertical at rain intensities between 10 and 50 mm h$^{-1}$. Despite the fact that waxing a full radome is a laborious task and the durability of waxing can be questionable, waxing is an appealing way to enhance the performance of an old radome. On the other hand, according to the measurements the benefit of cleaning the radome seems to be insignificant. Even though the radome was 14 yr old, it was relatively clean and there was no sign of firm dirt that could collect moisture or water. If the radome had had to withstand harsher circumstances (e.g., in the vicinity of salty waters), cleaning could have had a bigger effect on radome performance.

5. Conclusions

We have measured the transmission loss of a dry radome by the free space measurements and derived the loss from the permittivity measurements and have found that the results are in a good agreement (0.35 and 0.34 dB, respectively). We have developed a method to scale the free space measurements made with a piece of a radome to be valid for a complete radome. This has enabled us to get results of the loss, valid for a 6.7-m radome, as a function of rain intensity. We obtained a 3-dB two-way transmission loss of a dirty radome at a rain intensity of 15.1 mm h$^{-1}$. This is a significant factor and greatly affects the derivation of the rain intensities, which is even more important now that the quantitative precipitation estimation by a radar is becoming increasingly significant. Even though the uncertainties of the wet radome loss are relatively high and direct comparison of the prior results is difficult, the transmission losses are similar to results derived by Manz et al. (1999) and comfortably in between the results derived for a hydrophobic and for nonhydrophobic radome by Crane (2002). We also tested the effect of cleaning and waxing to find out how these measures could enhance the transmission performance of an old radome in rain. Cleaning showed no big improvement in the performance, probably because the radome was already relatively clean despite 14 yr of continuous operational use. Waxing, however, showed promising results: measurements carried out with a piece of the radome showed a 1.5-dB improvement in two-way transmission loss at a rain intensity of 22.1 mm h$^{-1}$ when compared to an untreated dirty radome piece. Our scaling method is not usable in the case of a waxed radome and hence we are not able to estimate how large the improvement for a full-scale radome would be, but we expect that the effect of waxing is most likely even greater than that for the piece of radome.

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