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Measurements of the transmission loss of a radome at different rain intensities

Mikko Kurri, Asko Huuskonen

Finnish Meteorological Institute, Helsinki (Finland)

1 Introduction

In this paper we present results on the transmission loss of a dry and wet radome as a function of rain rate, based on the work by Kurri (2006). Two different methods were used in the study. In the first method the complex permittivity of a radome was measured with a vector network analyzer and a coaxial dielectric probe. From the measured complex permittivity values the transmission loss of a dry radome was calculated. In order to calculate the total transmission loss caused by dry radome and water on radome surface, the thickness of the water layer at different rain intensities and the complex permittivity of water need to be known. The thickness of the water layer on a radome was calculated with the Gibble's formula, which predicts the water layer thickness in the case of laminar flow. The permittivity of water was calculated with a double Debye relaxation equation. As the permittivity and thickness of both the radome and water were known, the total transmission loss of a 6.7 m diameter radome was calculated with the help of the boundary conditions of Maxwell equations.

In the second method the transmission loss was measured as a free space transmission measurement with two horn antennas, a signal generator and a power meter. In order to measure and analyze the effect of precipitation on the surface of a radome a rain system was developed. With the rain system the free space measurements were carried out as a function of rain intensity in the intensity range of 2.6-22.1 mm/h. In order to examine the effects of maintenance measures of an old radome, the measurements as a function of rain intensity were performed with a dirty, cleaned and waxed radome.

All the measurements were performed with a 1.3 m^2 piece of a 14 years old orange peel A-sandwich weather radar radome at the frequency of 5.65 GHz.

Correspondence to: Mikko Kurri.

mikko.kurri@fmi.fi

The piece of radome was from a window area of the radome panel, i.e., the effects of the junctions of the panel are not included in the analysis.

As the transmission loss as a function of rain rate was measured with the piece of radome, the results were scaled in order to be valid for a complete 6.7 meter diameter radome with equal dielectric properties. Scaling was based on the ratio of the horizontal projection area of a complete radome compared to the piece of a radome used in the measurements.

2 The effect of radome on transmission loss

Electromagnetic wave transmitted and received by radar is attenuated by a sandwich type of radome by two main mechanisms (Skolnik, 1990). The first is scattering from the junction areas of the panels and the second is absorption and reflections introduced by window areas of the panels. Junction areas are normally fiberglass or composite material causing discontinuity areas compared to the layered window areas of radome panels. In addition, panels are normally attached together with metal bolts. Because of these two factors, energy transmitted by radar is scattered away from the main beam of the radiation pattern of the antenna. Junction effects on radiation pattern can be estimated by the induced field (IFR) method introduced by Rusch et al. (1976). In these measurements only the window area loss was considered as only a window area of a radome panel was available for the measurements. However, in an orange peel type of a radome the junction area blockage is quite small compared to the total area of a radome. Secondly the junction areas of the measured radome were tuned. Because of these factors the fact that junction area loss was not measured was not considered crucial.

At window areas the transmission loss is mainly caused by absorption and reflections. The main absorption mechanism at the frequency range used is orientation polarization of polar molecules (Nyfors and Vainikainen, 1989).

Mathematically absorption is described by the complex part of material's permittivity in nonmagnetic dielectric materials. When the relative permittivity $\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$ of the material is known, the attenuation constant α can be calculated from the equation of propagation constant

$$\gamma = jk = \alpha + j\beta = j\omega\sqrt{\varepsilon\mu} = j2\pi f\sqrt{(\varepsilon'_r - j\varepsilon''_r)(\mu'_r - j\mu''_r)\varepsilon_0\mu_0}\,, \qquad (1)$$

in which k is the wave number, β is the phase constant, f is the frequency, $\mu_r = \mu'_r - j\mu''_r$ is the relative permeability, ε_0 is the permittivity of vacuum and μ_0 is the permeability of vacuum. As the attenuation constant and the thickness of the material l 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 air, only a part of the transmitted power will penetrate the radome. With the assumption of a homogenous radome, there are two interfaces between air and radome causing reflections. Between these two interfaces there will be infinite amount of waves propagating backward and forward inside the radome. Total transmitted wave is the sum of all waves that penetrate the radome-air interface. The transmission coefficient for perpendicular incidence of the propagating wave can be formulated with the help of geometric series as

$$\tau = \frac{E'_{2+}}{E_{1+}} = \frac{(1+\rho_1)(1+\rho_2)e^{-\gamma l}}{1+\rho_1\rho_2 e^{-2\gamma l}}\,, \qquad (2)$$

in which E'_{2+} is the penetrated electric field at the radome-air interface, E_{1+} is the electric field at the antenna side of the air-radome interface and l is the thickness of the radome. Coefficients ρ_1 and ρ_2 are the normal incidence reflection coefficients at the air-radome and radome-air interfaces as presented by Orfanidis (2004).

3 The effect of water on the surface of a radome

According to Hendrix et al. (1989) and the measurements done by Kurri (2006), water on the surface of a radome due to rain flows down in three different forms: as a laminar sheet, as rivulets and as droplets. The form of the water flow on a spherical radome is dominated by the hydrophobic properties of the radome. The longer water stays as droplets as the rain intensity increases the better. The attenuation of droplets is smaller than the attenuation caused by a continuous film or by rivulets due to the fact that the attenuation mechanism of droplets is relatively weak scattering compared to the absorption and reflections caused by a continuous film (Manz, 2001).

In order to calculate the attenuation caused by water flowing on the surface of a radome the permittivity and the thickness of the water layer need to be known. Relative permittivity of water, which is a function of frequency, salinity and temperature, was calculated with a fit based on the double Debye relaxation equation introduced by Meissner and Wents (2004). The relative permittivity of water was calculated to be $\varepsilon_{r,w}$ = 72.02-j17.42 at the frequency of 5.65 GHz, at zero salinity and at the temperature of 30 °C.

As the attenuation is strongest in the case of continuous water film, the case of continuous film was considered. The thickness of water film was calculated with Gibble's formula as presented by Anderson (1975). Gibble's formula is valid for a laminar flow of water on a spherical radome. Despite that Gibble's formula has been used in several publications, the authors have not seen the derivation of the formula. However, the formula can be derived by combining the formula of water layer's thickness in laminar flow on a flat surface (Green, 1988)

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

and the load of rained water per unit width of radome's "latitude"

$$\Gamma = \rho_w R\frac{\pi(a\sin\varphi)^2}{2\pi a\sin\varphi} = \rho_w R\frac{a\sin\varphi}{2} \qquad (4)$$

to yield the Gibble's formula

$$l_w = \sqrt[3]{\frac{3\mu_k aR}{2g}}\,. \qquad (5)$$

In formulas (3)-(5) μ_w is the viscosity of water [kg/(ms)], g is the acceleration due to gravity, ρ_w is the density of water [kg/m^3], ρ_n is the density of surrounding medium, a is the radius of a radome [m], R is the rain rate given in m/s and μ_k is the kinematic viscosity of water [m^2/s]. Viscosity and density of water are functions of temperature. In the calculations the temperature of 30 °C was used.

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 radome and water. Total transmission loss was calculated with boundary conditions of Maxwell equations at perpendicular incidence. Electric fields at consecutive interfaces can be formulated according to Orfanidis (2004) in a matrix form as

$$\begin{bmatrix} E_{i,+} \\ E_{i,-} \end{bmatrix} = \frac{1}{\tau_i}\begin{bmatrix} e^{\gamma_i l_i} & \rho_i e^{-\gamma_i l_i} \\ \rho_i e^{\gamma_i l_i} & e^{-\gamma_i l_i} \end{bmatrix}\begin{bmatrix} E_{i+1,+} \\ E_{i+1,-} \end{bmatrix}, \qquad (6)$$

where E_{i+} and $E_{i+1,+}$ are the electric fields propagating to the positive direction at the interfaces i and $i+1$, respectively, 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 medium i, γ_i is the propagation constant of the medium i, τ_i the transmission coefficient at the interface i, and ρ_i the transmission coefficient at the interface i. As there are no returning fields after the last interface and when the electric field outside the last interface is set to one, the fields at previous interfaces can be calculated recursively and thus the transmission coefficient can be solved.

4 Transmission loss derived from permittivity measurements

The permittivity of the radome was measured with Agilent E5017B vector network analyzer and with HP 85070A coaxial dielectric probe. A coaxial probe is convenient to use as there is no need to cut a separate piece of the material under test for the measurements. The drawback is that a coaxial probe isn't capable of measuring as low complex parts of the permittivity as is needed in the case of a sandwich radome. Therefore the complex part was calibrated by measuring materials whose permittivities were known. When the relation of the measured value and of the tabulated value of the calibration material was known, it was possible to scale the complex part of the radome's permittivity. 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 was $\varepsilon''_{r,rad} = 0{,}047 \pm 0{,}005$. Results are calculated as mean of 112 independent measurements. All uncertainties in this paper are given with 95 % confidence level.

If the media before the first layer and after the last layer are the same, the transmission loss of power can be calculated in dBs with a simple formula

$$L_{tra,dB} = 10 \log_{10}\left(1 \big/ |\tau|^2 \right) \qquad (7)$$

in which τ is the transmission coefficient from equation (2). With equations (1),(2) and (7), and with measured thickness of 12.7±0.04 mm of the radome the transmission loss of a dry radome was calculated to be

$$L_{tra,dB} = 0.34 \pm 0.26 \text{ dB.}$$

5 Transmission loss by free space measurements

Free space transmission loss measurements were done using two identical pyramidal horn antennas. Transmitting antenna was fed with a HP 83731A signal generator at the frequency of 5.65 GHz at the power level of 20 dBm. Receiving antenna was connected to a HP8484A power sensor and a HP 436A power meter. With a 22.5° phase error assumption the far field distances of the antennas were 1.66 m. The radome was placed in the middle of the antennas at 1.8 meter distance from the apertures of the antennas. At the distance of 1.8 m the diameter of the Fresnel ellipsoid was one half of the shortest dimension of the radome piece. This was considered to be enough to discard the effect of diffraction around the radome sides.

All the antenna measurements were performed as relative measurements. At first free space between the antennas was measured as a reference after which the piece of a radome was put in place and the measurement was repeated. Because of a standing wave between the antennas all the measurements were done as function of distance by moving the transmitting antenna. As the distance of the antennas was changing, the chance in free space attenuation was first cancelled and then a fit was established for the reference and radome measurements. Mean values of the measurements were derived from the fits and the transmission loss was calculated by subtracting the mean values in dBs from each other. The final result was calculated as a mean of eight independent measurement sets. The transmission loss measured as a free space measurement was

$$L_{rad,dB} = 0.35 \pm 0.07 \text{ dB.}$$

In order to measure the total transmission loss as a function of rain rate a rain system was developed. Main parts of the system were two parallel connected flow meters, a feeding hose, a nozzle, a nozzle holder and an electric motor for rotating the nozzle. The nozzle consisted of 2 mm diameter hose into which holes of diameter 0.2-0.45 mm were stuck. The rain system was calibrated by weighing the water collected to containers with known areas at given time unit. Linear fits were done for the measurements and as a result a lookup table, which connects the readings of the flow meters and the rain intensity in mm/h, was established. Results of the calibration, the fits and the prediction intervals at the confidence level of 95 % are shown in figure 1.

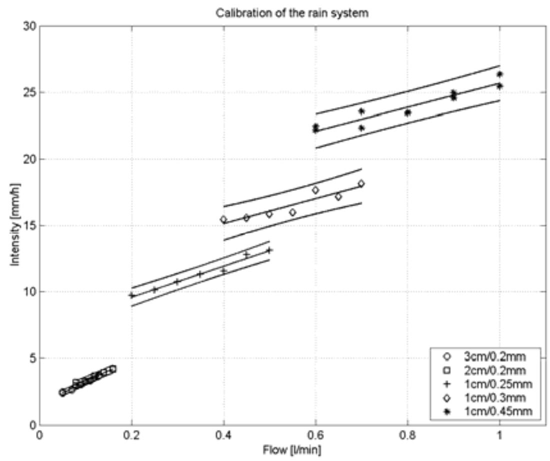

Fig. 1. Calibration results of the rain system.

The nozzle was placed above the piece of a radome at 3.2 meters height. Measurements were done as in the case of dry radome with the exception that the dry radome was used as a reference measurement. Measurements were performed with the same piece of a radome as dirty, as cleaned and as waxed. Results of the one way losses of combined dry radome transmission loss and extra loss caused by water on the piece of a radome are shown in figure 2. As is seen in the figure, there are no significant differences between a dirty and a cleaned radome. In both 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 little as the rain intensity was increased. The steeper increase of the attenuation at intensities around 20 mm/h is explained by the fact that as the spherical radome was placed vertically, there was more water reaching also the area underneath the "equator" of the radome as the intensity was increased thus causing more beam blockage. This in turn implies that at higher antenna elevations transmission loss will increase.

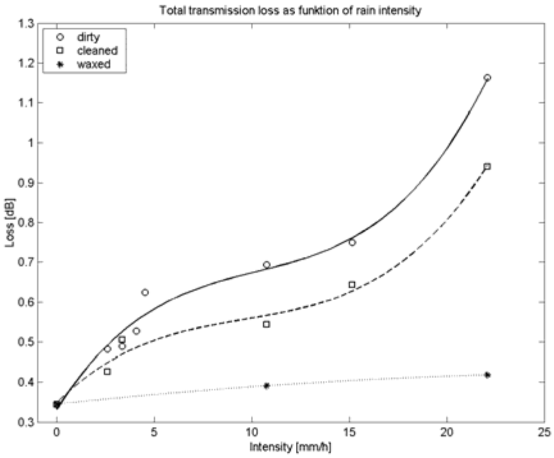

Fig. 2. The effect of water sheet on a surface of a radome.

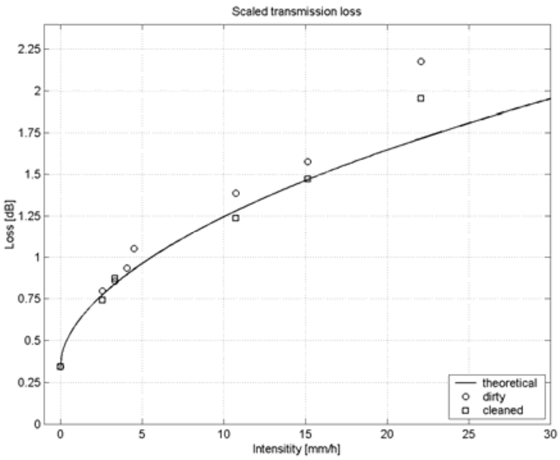

Fig. 3. Antenna measurements scaled to be valid with a 6.7 m diameter's radome.

6 Scaling of the free space measurements

Because of 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. Thus the transmission loss is also higher for a full radome. It is possible to scale the present results to a complete radome by modifying the Gibble's formula to take into account the different horizontal projection areas of the piece of radome and of the complete radome. The ratio of the projection areas *K* was inserted into Gibble's formula to yield the thickness of water layer in the form

$$l_w = \sqrt[3]{\frac{3\mu_k aRK}{2g}} \quad . \qquad (8)$$

When calculating the transmission loss with equations (6) and (8), the theoretical transmission loss as function of rain rate will be scaled down to the same level of the antenna measurements. As the theoretical transmission losses of the complete radome and of the piece of radome are now known, the difference of theoretical losses given in dBs will be the amount of loss which has to be added to the results of antenna measurements. One way transmission losses scaled to be valid with a 6.7 m diameter's radome are shown in figure 3. As seen in figure 3, the measured and scaled losses are fitted rather well to the theoretical attenuation of a complete radome. Attenuation values of the waxed radome are not shown, because scaling is only valid for laminar flow. Uncertainties with confidence level of 95 % were also calculated for the scaled values (Kurri, 2006).

7 Conclusions

Transmission losses of a dry radome derived by antenna measurements and derived by permittivity measurements were in good agreement. Difference between the two methods was only 0.01 dB. Water running on a surface of a radome appeared to have a great impact on transmission loss. A 3 dB two way transmission loss of a dirty radome is achieved at the rain intensity of 15.1 mm/h. Measurements also showed that it is possible to reduce the effect of water by waxing the radome. As seen in figure 2, at the rain intensity of 22.1 mm/h the effect of rain is 1.5 dB lower with the waxed radome than with the dirty radome when two way loss is considered. In the case of a complete radome the effect of waxing would most likely to be greater.

References

Anderson, I., 1975: Measurements of 20-GHz transmission through a radome in a rain. *IEEE Transactions on Antennas and Propagation*, vol. 23, no. 5, p. 619-622.

Green, D. (edit.), 1988: *Perry's Chemical Engineers' Handbook*. McRaw-Hill Book Co.

Hendrix, C. E., McNally, J. E., Monzingo, R. A., 1989: Depolarization and attenuation effects of radomes at 20 GHz. *IEEE Transactions on Antennas and propagation*, vol. 37, no. 3, March, p. 320-328.

Kurri, M., 2006: Determining transmission loss of a weather radar's radome by dielectric and horn antenna measurements. Master's Thesis of Radio Engineering, Helsinki University of Technology, Radio Laboratory, 81 p.

Manz, A., 2001: Radome Influence on weather radar systems - principles and calibration issues. AMS workshop radar calibration, Albuquerque, NM, USA. www.gematronik.com/website/selex/pdf/pubs/2001_6.pdf

Nyfors, E., Vainikainen, P., 1989: *Industrial Microwave Sensors*. Norwood, MA, Artec House, Inc., 351 p.

Orfanidis, S. J., (2004): Electromagnetic waves and antennas. www.ece.rutgers.edu/~orfanidi/ewa.

Rusch, W .V. T., Appel-Hansen, J., Klein, C. A., Mittra, R., 1976: Forward scattering from square cylinders in the resonance region with application to aperture blockage. *IEEE Transactions on Antennas and Propagation*, vol. 24, no. 2, p. 182-189.

Skolnik, M. (edit.), 1990: *Radar Handbook,* second edition. McGraw-Hill, Inc.