THE COMBINED ATTENUATION OF RAIN AND WIND OF PARABOLIC ANTENNA AT KU-BAND FREQUENCIES

by

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LIST OF SYMBOLS

α	A constant that fit the data using the least square method.
β	A constant that fit the data using the least square method
ρ	The density of water
μ	The viscosity of water
ε	The dielectric constant of the medium
μ	The permeability of the medium
σ	The conductivity of the medium
θ	The inclination angle
θ_o	The angle of incidence
θ_1	The angle of refraction in water
η	The intrinsic impedance of the medium
γ	Scaling ratio for antenna attenuation
γ_1	The propagation constant in water.
γ_o	The propagation constant in air
ω	The angular frequency
ϕ	The polar angle of a data point
τ	The relaxation time
ε'	Dielectric constant of water
$\Gamma_{\chi\text{-}\chi}$	The flow rate, i.e., the rain rate
Γ_{eq}	The equivalent reflection coefficient
ε''	Conductivity of water
ϕ_0	The angle of the ITU-R "line,"

A_a	The antenna attenuation
A_m	Measured attenuation
A_p	The path attenuation
$\boldsymbol{A_r}$	"**a**" matrix of the radome
$\boldsymbol{A_w}$	***"a"*** matrix of the water sheet
A_{wet}	Wet antenna attenuation in dB.
C	The highest value of measured antenna attenuation in the experiments
d	A parameter to be determined from the observations and results
D	Parabolic antenna diameter
E	The electrical field
F	Focal length
f	Frequency
G_r	Receiver antenna gain
G_t	Transmitter antenna gain
g	The gravitational force
H	The magnetic field
h	The thickness of the water sheet
l	The thickness of the medium
L	The two-way transmission loss in dB due to radome wetting
L1	Represents the region only affected by path losses
L2	Represents a water cell located on the antenna dish
L3	Represents a water cell falling between the feed horn and the dish
L4	Represents a water cell on the feed horn
L_{ref}	Wet reflector los
L_{rx}	Los of the received signal

L_{tx}	Los of the transmitted signal
n	Positive parameter
P_{rdry}	Received power for dry antenna in dBm.
P_{rwet}	Received power for wet antenna in dBm
R	The rainfall rate in mm/h
s	The scattering matrix
s_{11}	Scattering matrix parameter
s_{12}	Scattering matrix parameter
s_{21}	Scattering matrix parameter
S_m	Scaling ratio for measured attenuation
S_p	Scaling ratio for path attenuation
$\vec{S}_k^{\pm}$	The Poynting vector
x	The S-band reflectivity over the X-band wet radome
y	The length of the flat plate.
y	The average wet radome attenuation.
Z_1	The impedance of water.
Z_o	The impedance of air.

LIST OF ABBREVIATIONS

ACTS	Advanced Communication Technology Satellite
AFC	Antennas for Communications
APT	ACTS propagation terminal
CASA	Center for Collaborative and Adaptive Sensing of the Atmosphere
CW	Continuous wave
dBZ	Disables of Z, where Z is radar Reflectivity
EDF	Exceedence Distribution Function
EHF	Extremely High Frequency
ITU-R	International Telecommunication Union Radio communication sector
KLIA	Kuala Lumpur International Airport
LOS	Line Of Sight
MEASAT	Malaysia East Asia Satellite
NASA	National Aeronautics and Space Administration
NPOL	NASA polarimetric radar
SHF	Super High Frequency
SMC	Sheet moulding composite
SWR	Standing Wave Ratio
UHF	Ultra High Frequency
USAT	Ultra Small Aperture Terminal
UTC	Coordinated Universal Time
VSAT	Very Small Aperture Terminal
WSR- 88D	Weather Surveillance Radar - 1988, Doppler

GABUNGAN ATENUASI HUJAN DAN ANGIN ANTENA PARABOLA PADA FREKUENSI JALUR-KU

ABSTRAK

Dalam sistem komunikasi wayarles, khususnya komunikasi satelit dan bumi, radar dan sistem penginderaan jarak jauh, kesan daripada akumulasi air hujan pada permukaan antena (reflektor dan tetingkap suapan) semasa hujan yang lebat terutama pada frekuensi yang tinggi perlu diambilkira. Kesan ini dikenali sebagai pelemahan antena basah dan berbeza dalam mekanisma pelemahan hujan yang disebabkan oleh hujan di laluan perambatan. Pelemahan antena basah adalah salah satu daripada banyak faktor lain yang boleh merendahkan prestasi sistem di jalur frekuensi yang lebih tinggi seperti Ku-band.

Disertasi ini adalah berkaitan dengan masalah pelemahan untuk antena parabola penerima yang basah pada frekuensi Ku-band. Hubungan jarak pandang gelombang mikro yang dekat telah dibina dengan memancarkan isyarat melalui antena hon. Isyarat tersebut diterima menggunakan antena parabola dan kekuatan isyarat yang diterima diukur dan dirakam dengan menggunakan penganalisis spektrum. Dalam rangka untuk mensimulasi hujan dengan berbagai tingkat curahan hujan pada penerima, pengsimulasi hujan telah dibina. Untuk mengukur pengaruh angin terhadap pelemahan antena yang basah kipas terarah industri telah digunakan untuk menghasilkan simulasi angin yang boleh bertiup ke arah antena dari arah yang berbeza dan dengan kelajuan angin yang berbeza. Tiga antena parabola dengan rekabentuk dan saiz yang berbeza telah digunakan dalam simulasi percubaan hujan sebagai antena penerima. Kebergantungan pelemahan antena basah pada frekuensi,

sudut elevasi dan tahap curahan hujan telah diselidiki dan hasil eksperimen telah dianalisa. Telah direkodkan bahawa pelemahan antena basah meningkat secara berperingkat di semua frekuensi Ku-band ketika tahap curahan hujan meningkat. Namun demikian frekuensi yang lebih tinggi mengalami pelemahan lebih tinggi. Sudut elevasi reflektor antena juga mempunyai kesan yang jelas pada pelemahan antena yang basah. Perilaku tiga antena parabola yang basah berbeza dari segi pelemahan walaupun untuk frekuensi yang sama dan intensiti curahan hujan. Ini menunjukkan bahawa rekabentuk antena, secara jelasnya mempengaruhi fenomena ini.

Kesan kelajuan dan arah angin juga diselidiki dengan mendalam dalam eksperimen dan analisa. Didapati bahawa keadaan angin juga mempunyai pengaruh terhadap pelemahan antena basah. Disebabkan hujan sering disertai angin, oleh itu kesan angin perlu juga diambilkira dalam menganggarkan pelemahan antena basah. Dalam rangka menjaga ketersediaan minimum sistem, pelemahan antena basah pada Ku band harus dipertimbangkan dan ditambah ke jidar hubungan khususnya di zon hujan tropika.

THE COMBINED ATTENUATION OF RAIN AND WIND OF PARABOLIC ANTENNA AT KU-BAND FREQUENCIES

ABSTRACT

In wireless communication systems, especially satellite and terrestrial communications as well as in radar and remote sensing systems the effect of the rain water accumulated on the antenna surfaces (reflector and feed window) during the rain event is considerable especially at higher frequency bands. This effect is known as wet antenna attenuation and it differs in its mechanism from the rain attenuation which is caused by rain on the propagation path. Wet antenna attenuation is one of many other factors that can degrade the system performance at higher frequency-bands such as the Ku-band.

This dissertation is dealing with the issue of wet antenna attenuation for the receiving parabolic antenna at Ku- band frequencies. A short LOS (Line Of Sight) Ku- band link was set up so that microwave signals were generated by a signal generator and transmitted via horn antenna. The signals were received using parabolic antenna and the received power level was measured and recorded using spectrum analyzer. In order to simulate the rain with wide range of rainfall rates at the receiver site only, a rain simulator was constructed. To measure the influence of the wind on the wet antenna attenuation an industrial directional fan was used to produce simulated wind which can blow toward the antenna from different directions and with different wind speeds. Three parabolic antennas with different designs and sizes were used in simulated rain experiments as receiving antennas. The dependency of wet antenna attenuation on the frequency, the elevation angle and the rainfall rate was experimentally investigated and experimental data were analytically evaluated. It

was noted that the wet antenna attenuation increases gradually at all Ku-band frequencies when the rainfall rate increases. But higher frequencies experience more wet attenuation. The elevation angle of the antenna reflector also has a clear impact on the wet attenuation. The behavior of the three parabolic antennas during the wetting was different in terms of wet attenuation values even for the same frequency and rainfall rate. This indicates the impact of the antenna design on this phenomenon. The effect of both wind speed and direction was carefully treated in the experimental and in the analytical phase. It was found that the wind condition has a reasonable influence on the wet antenna attenuation. Since the rain is often accompanied by wind, so the effect of the wind should be taken into account when estimating the expected wet antenna attenuation caused by rain. In order to maintain the required minimum system availability, wet antenna attenuation at Ku band frequencies should be taken into account and added to the link margin especially at tropical rain zones.

CHAPTER 1

INTRODUCTION

1.1 Background

Due to the overcrowding in the C-band frequency in many wireless communication applications such as satellite and radar systems, as well as the growing demand for wideband services with a large capacity, it has become necessary to move to the higher frequency bands such as Ku- and Ka- bands.

The performance of wireless communication and radar systems as well as remote sensing systems operating at higher frequency bands such as Ku-band and higher is reasonably influenced by many atmospheric propagation impairments such as rain, snow, fog, clouds, and so on.

Rain is the most serious attenuation factor for microwave signals propagated in the atmosphere especially at higher frequency bands. In addition, other impairments such as cloud attenuation, gaseous and water vapor absorption, melting layer attenuation, and scintillation become increasingly important with increasing operating frequency. Rain can affect the microwave propagation in two different mechanisms. One is as path rain attenuation which results from absorbing and scattering caused by raindrops on the propagation path, and the other one is the wet antenna attenuation which is caused by accumulation of rain water on the antenna surfaces during the rain event.

Several models are already in existence for predicting the path rain attenuation for satellite and terrestrial communications depending on geographical rain statistics but it has been observed from many direct measurement activities of rain attenuation that the predicted rain attenuation differs from the measured attenuation. One main reason for the difference between predicted and measured rain attenuation is the additional wet antenna attenuation, which is not taken into account by most of these rain attenuation models. Losses due to the antenna wetting are required to be subtracted from the measured rain attenuation in order to predict the propagation losses accurately. Therefore some research activities dealing with rain attenuation have proposed some approaches to correct the measured rain attenuation data for the wet antenna effect.

The need for investigating wet antenna issue separately was discovered by many of rain attenuation researchers in the last two decades. Several research activities pertaining to wet antenna attenuation are discussed in Chapter 2.

The basic concept of the wet attenuation could be linked to the dielectric properties of the water as a propagation medium for the microwave signals. Water drops and water film formed on the antenna surfaces during the rain event can cause both the scattering and the absorbing of the microwave signal, which could lead to signal attenuation. The wet attenuation can be influenced by many parameters such as rain intensity, speed and direction of the wind, operating frequency, material and design of the antenna, elevation angle and so on. Therefore the effect of these parameters on the wet attenuation characteristics has been experimentally investigated in this research.

1.2 Basic background of parabolic antennas and the wet attenuation

Antennas are essential components or subsystems of any wireless communication link. The antenna is the interfacing component between a guided and free space electromagnetic wave. Because of the wide variety of applications, different types of antennas in terms of sizes and shapes can be found. There are many categories of antennas, such as horn antennas, reflector antennas, wire antennas, aperture antennas, array antennas, printed and conformal antennas, and so forth (Kraus, 1988, Kraus and Marhefka, 2001, Milligan, 1985, Siwiak, 1998, Stutzman and Thiele, 1981, Balanis, 2005, Chen and Luk, 2009). In this research, the concern is focused only on reflector antennas especially the parabolic antenna.

1.2.1 The parabolic reflector antenna

A parabolic reflector, known as a parabolic dish, is a reflective device commonly formed in the shape of a paraboloid of revolution. If a beam of parallel rays is incident upon a reflector whose geometrical shape is a parabola, the radiation will converge (focus) at a spot which is known as the focal point. In the same manner, if a point source is placed at the focal point, the rays reflected by a parabolic reflector will emerge as a parallel beam. This is one form of the principle of reciprocity, as shown in Figure 1-1.

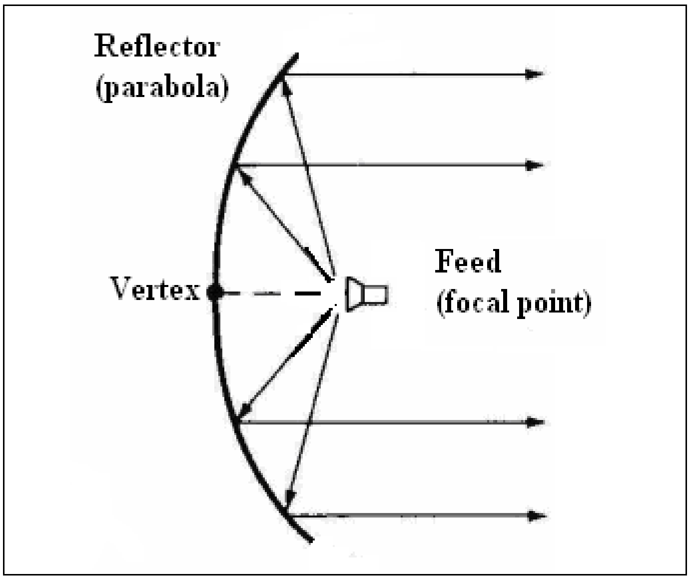

Figure 1-1 Geometrical configurations for parabolic reflector

According to Love, (1989), the world's first parabolic reflector antenna was constructed by Heinrich Hertz in 1888. The antenna had an aperture of 1.2 meters wide, a focal distance of 0.12 meters, and was used at an operating frequency of about 450 MHz. The reflector was made of zinc sheet metal supported by a wooden frame, and had a spark-gap excited dipole along the focal line. With two such antennas, one used for transmitting and the other for receiving, Hertz successfully demonstrated the existence of the electromagnetic waves which had been predicted by James Clerk Maxwell some 22 years earlier (Love, 1989).

The radiation pattern of a parabolic antenna contains a major lobe, which is directed along the axis of propagation, and several small minor lobes. Very narrow beams are possible with this type of reflector. However the antenna feed and its supports produce blockage in the antenna field of view, which can cause shadowing and produce diffraction lobes in the antenna pattern. An offset feed parabolic antenna can be utilized to minimize the blockage effect of the feed and its supports. Offset parabolic antennas are preferred in the direct broadcast satellite TV service such as Astro in Malaysia.

1.2.2 The wet antenna attenuation characteristics

Most of the applications of parabolic antennas are in the long distance links such as satellite- and terrestrial communications as well as radar systems. Antennas of such links are often subjected to earth's atmospheric phenomena such as rain and wind. The performance of the parabolic antenna operating at higher frequency bands such as Ku- band and above is strongly affected by the antenna wetting. The antenna wetting which in most cases caused by rain is considered to be a serious attenuation factor in many wireless microwave link applications. The wet antenna issue is of increasing concern to microwave propagation researchers and antennas designers (see Chapter 2). The basic theoretical concept of the wetting effect could be separated into two main concepts:

- Electromagnetic waves propagation characteristics in water.
- The water distribution mechanism on the antenna surfaces.

1.2.2.1 Electromagnetic waves propagation through water

During the rain event, water drops accumulate on the antenna reflector surface and on the feed window radome, consequently a water sheet could be formed on the antenna surfaces. The thickness of the water layer is mainly dependent on the rain intensity, antenna surface properties and the elevation angle as well as the wind condition. However, the electromagnetic wave, which passes through the water layer, will be attenuated according to its wavelength (frequency) and the thickness of the water layer. As an example, consider that propagation through water at 30 GHz attenuates as much as 15.7 dB per millimeter (Klein and Swift, 1977). Moreover the water temperature has also an impact on the signal attenuation.

The basic theoretical concept underlying the wet antenna issue is the propagation of electromagnetic waves through multiple dielectric interfaces (air- water- conductor). Equivalent reflection and transmission coefficients of the propagating signal are key factors for calculating of expected wet attenuation.

The situation of a uniform water layer covering a conductor can be demonstrated as shown in the Figure 1-2. In the figure, $\vec{S}_o^+$, $\vec{S}_o^-$, $\vec{S}_{1a}^+$, $\vec{S}_{1a}^-$, $\vec{S}_{1b}^+$ and $\vec{S}_{1b}^-$ refer to the Poynting vectors of the form $\vec{S}_k^\pm = \vec{E}_k^\pm \times \vec{H}_k^\pm$. The subscript 0 denotes the wave in air at the air-water boundary, subscript 1a denotes the wave in water at the air-water boundary, and 1b refers to the wave in water at the water conductor boundary. The superscripts + and - refer to the wave propagating in the positive and negative *z*-direction, respectively. The thickness of the water layer is $d1$. The angle of incidence is θ_o and θ_1 is the angle of refraction in water. The permittivity of the water is denoted by ε_1

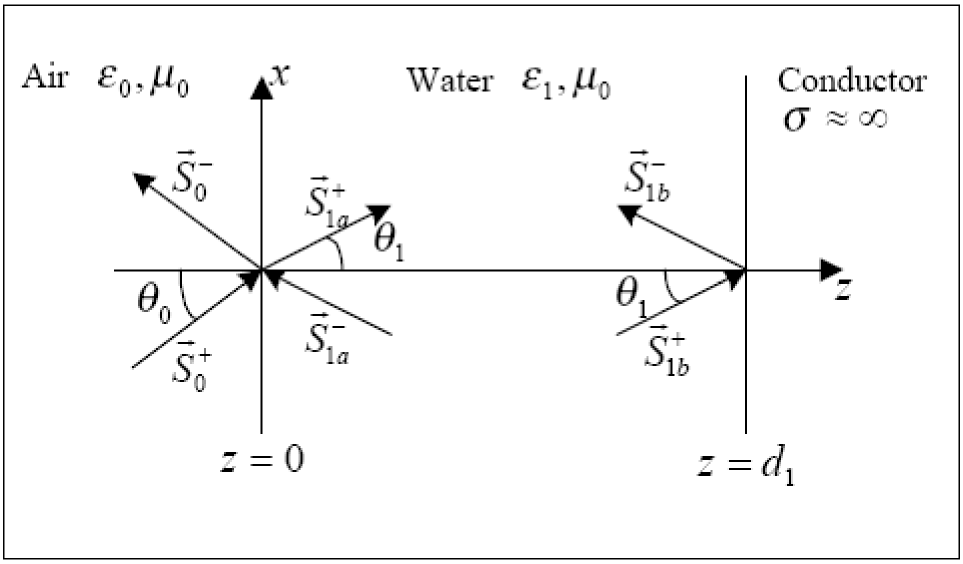

Figure 1-2 Water layer on conductor

The equivalent reflection coefficient, Γ_{eq} at the air-water boundary is

$$\Gamma_{eq} = \frac{E_o^-}{E_o^+} \tag{1-1}$$

where

E_0^- is the reflected electrical field.

E_o^+ is the incident electrical field.

The effect of the water layer on a reflector surface can be modeled as

$$G = \frac{E_{o,water}^-}{E_{o,air}^-} \tag{1-2}$$

where

$E_{0,water}^-$ is the reflected E-field when the reflector is wet.

$E_{o,air}^-$ is the reflected E-field when the reflector is dry.

The attenuation in dB can be calculated from

$$\text{Attenuation (dB)} = -20\log_{10}(\text{G}) \tag{1-3}$$

Expressions for G can be found in (Balanis, 2009, Borsholm, 1999a, Shen and Kong, 1995).

Applying the boundary conditions $E_{\tan}\approx 0$ for a good conductor in the propagation equation and solving for equivalent reflection coefficient Γ_{eq} gives,

$$\Gamma_{eq} = \frac{E_o^-}{E_o^+} = \frac{Z_1 \tanh(\gamma_1 d_1 \cos\theta_1) - Z_o}{Z_1 \tanh(\gamma_1 d_1 \cos\theta_1) + Z_1} \tag{1-4}$$

This yields,

$$G = \frac{E_{o,water}^-}{E_{o,air}^-} = -\frac{Z_1 \tanh(\gamma_1 d_1 \cos\theta_1) - Z_o}{Z_1 \tanh(\gamma_1 d_1 \cos\theta_1) + Z_1} \exp(2\gamma_o d_1 \cos\theta_o) \tag{1-5}$$

Where

γ_1 is the propagation constant in water.

γ_o is the propagation constant in air.

Z_1 is the impedance of water.

Z_o is the impedance of air.

1.2.2.2 Water distribution on the antenna surface

During the rainfall, the water accumulates on the antenna surface first in the form of droplets and/or rivulets and then a water sheet will be formed. The thickness of the water sheet depends on the rainfall rate, the reflector surface properties, and the elevation angle of the reflector as well as the wind condition. However, it is difficult to determine the water layer thickness because the reflector surface is curved. The result is a water layer of non-uniform thickness on the reflector which will cause attenuation to the incident electromagnetic signals. Therefore, the thickness of the water layer is an important factor that needs to be determined in order to estimate the wet attenuation. Since the thickness of the water layer varies due to hitting of raindrops, this implies that the wet attenuation also varies.

1.3 Problem statement and motivation

During its propagation between the transmitting and receiving systems, microwave electromagnetic signals are subjected to loss. For long distance wireless communication links operating at high frequency bands such as earth- satellite links, the main signal degradation factor is the free space loss. This loss can be considered as being constant and it can be calculated based on the frequency and distance. On the other hand, there are some other contributions of a dynamic loss along the propagation path such as signal impairments due to the change in atmospheric conditions. In order to maintain the predefined link availability, the link budget must be calculated accurately. A link budget accounts for the gains and losses from the transmitter, through the medium (in this case free space) to the receiver in a communication system. Rain is the main contributor of the signal loss in the atmosphere. The effect of rain on radio wave propagation can be considered in two different conditions:

1) Signal loss due to rain on the propagation path.

2) Signal loss due to rain water on the antenna.

The second case is otherwise known as the wet antenna attenuation, and it is the main objective of this research. The need for investigating wet antenna attenuation is of great interest in many applications of wireless communication systems such as satellite and terrestrial communication systems as well as radar and remote sensing systems. Rain water accumulating on the antenna surfaces during the rain event can cause signal loss. The magnitude of the loss is dependent on many factors such as rain intensity, operating frequency, elevation angle, wind condition, antenna design, and so on. The impact of the signal loss on the system performance differs depending on the system application. For example in the satellite direct broadcasting TV, signal weakness due to rain can cause system interruption for several minutes (see Appendix B). In radar and remote sensing systems, the signal degradation due to rain water on the antenna (when not taken into account) can lead to serious measurements error. For all these reasons, the wet antenna issue needs to be more researched and investigated in order to reveal all possible factors that can affect it, which is the major focus of this research.

1.4 Objectives

The main objectives of this research can be summarized as follow:

- To study the effect of simulated rain on the performance of the receiver parabolic antenna at Ku-band frequencies in order to estimate the signal attenuation caused by the antenna wetting during the natural rain. In order to achieve this goal, there is a need to design and implement a proper rain simulator which can produce a wide range of rain intensities for conducting the required experiments. The rain intensity, operating frequency and elevation angle of the antenna reflector are considered as the major parameters for investigating the wet attenuation. Other parameters such as the antenna design, antenna material and antenna surface condition must also be investigated in order to estimate their effects on the antenna wetting condition and consequently on the wet antenna attenuation.
- To investigate the influence of the wind condition during the rain event on the wet antenna attenuation characteristics of the parabolic antenna. The wind is assumed to be a considerable impact factor on the antenna wetting condition. Therefore a simulated wind with different wind speeds and wind directions is required to investigate its effect on the antenna wetting and consequently on the wet attenuation characteristics.
- To obtain and analyze experimental data about antenna wetting effects on the performance of the receiving parabolic antenna at Ku-band frequencies. The obtained experimental measurements of the received signal power under various conditions of rain and wind have to be analyzed in order to determine the magnitude of wet attenuation and its dependence on the particular

parameters such as rain intensity, frequency, elevation angle, wind speed, wind direction and antenna design.

1.5 Thesis Organization

This thesis consists of six chapters as follows:

Chapter one gives an introduction about this research. It consists of the background of the wet antenna issue, followed by the problem statement, objectives of the thesis and thesis organization.

Chapter two presents a literature review about the wet antenna attenuation. It highlights the most recent research efforts in the issue of wet antenna attenuation in many communication systems applications.

Chapter three describes methodologies of measurement and analyses used in this dissertation. It describes the Ku-band link design and its components, which include transmitter and receiver systems as well as antennas. It also gives an overview of the rain simulation and rain rate measurements, the wind simulation and wind speed measurements, the wet attenuation calculation and data analysis.

In Chapter four the wet antenna attenuation in absence of the wind has been discussed. The dependence of wet attenuation on the frequency and rain intensity has been experimentally investigated. The effect of the elevation angle of the reflector on the wet attenuation values for different frequencies has been analyzed.

Chapter five deals with the impact of wind on the characteristics of wet antenna attenuation. Different wind conditions such as wind speeds and wind directions were simulated synchronously with simulated rain in order to measure and analyze the impact of wind conditions on the wet attenuation. Measurements of the received signal level were carried out for three different wind speeds and for two wind directions during the simulated rain event.

And lastly, Chapter six presents the final conclusions and gives recommendations for future works.

1.6 Chapter Summary

The theoretical basics and concepts of the wet antenna issue have been introduced. Background of parabolic reflector antenna and its utilization in many communications systems are also reviewed. This chapter also explains and discusses the problem statement and motivation of this research and gives the objectives of the dissertation. Thesis organization, followed by the chapter summary has been also included in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The wireless radio waves experience attenuation when propagating through the atmosphere as a result of absorption and scattering. These two effects are frequency dependent and both can be caused by rain (Bean and Dutton, 1968, Hall and Barclay, 1989, Pratt et al., 2003, Dybdal, 2009). Satellite and terrestrial communication systems designers need to know the expected probability distribution for signal level changes. Not all the changes in signal level are caused by the propagation medium. Water on the surface of the antenna or on the antenna feed window as well as on the antenna radome can also produce signal attenuation. Prior observations have shown that rain can reduce the signal level by more than 30 dB for frequencies in the 20–30 GHz range (Crane, 1996). Rain can affect the microwave propagation in two different mechanisms. The first one is the path rain attenuation, which increases with the rain intensity, the size of the rain drops, and the length of the path through the rain (Blaunstein and Christodoulou, 2007) and the other one as wet antenna attenuation. This chapter is devoted to the latter case in particular.

2.2 Wet radome effects

It is common practice in radar systems and terrestrial microwave links to protect the radar components and antenna from the environment using radomes (radar domes). In general the radome is considered to be a constant source of attenuation, but on a closer look the radome performance reveals a function depending on variables such as radome material and rainfall rate. A water sheet on a radome produces signal attenuation, which depends on frequency, temperature and water layer thickness (Crane, 2003). As an example, consider that propagation through water at 30 GHz attenuates as much as 15.7 dB per millimeter (Klein and Swift, 1977). Wet radome effects due to rain were discovered and investigated in the early application of microwave frequencies above 4 GHz in wireless communications and radar systems, where the antennas were often covered with domes to protect them against adverse weather conditions.

One of the early attempts to study and model the wet antenna attenuation was by (Blevis, 1965) who reported that the effects of thin layers of water on radome and feed surfaces due to rainfall have been largely neglected when measurements and analysis of rain attenuation were conducted. The Blevis's brief theoretical study had aimed to determine losses due to rainfall on a radome enclosing a large parabolic reflecting antenna. Then to what extent losses would be expected to impair the performance of systems operating at frequencies above 2 GHz. Blevis's analysis was basically based on the assumption that a uniform water layer on a perfect conductor, but in real situation the thickness of the water layer is an unknown parameter and varies across the parabolic reflector depending on many factors. The power reflection and transmission coefficients were calculated for a plane wave in air incident on an infinite-plane dielectric sheet of uniform finite thickness. For a water layer on a parabolic reflector, it is assumed that the situation may be approximated by a plane wave normally incident on a water layer laying on a perfectly reflecting plane surface, and so the power reflection coefficient was calculated according to this assumption. A model proposed by (Gibble, 1964) was used here to predict the thickness of water layer formed on a spherical radome during rainfall. This model predicts that the thickness is fairly constant over the upper hemisphere in the absence of wind. Here an early indication of the impact of the wind on the distribution of water on the radome surface can be noted.

However, the effect of water on radome in the form of small drops rather than an evenly distributed layer was not considered here. Blevis had concluded that the transmission losses in water layers formed on radomes during heavy rainfall are likely to be significant at all frequencies considered, and especially at the higher frequencies. Furthermore Blevis assumed that losses due to water layer formed on reflector surface if no radome is used are much smaller and will be negligible. Nonetheless the validity of this assumption cannot be verified without an experimental test which had not been done by Blevis. Moreover this assumption has also been severely criticized by (Crane, 2002) who reported “A mythology for system design has developed from the earlier work: radomes may produce unacceptable increases in attenuation when exposed to rain, but a wet reflector causes little additional attenuation”. Similar calculations of the transmission and reflection coefficients due to a thin water film on radome have also been carried out by (Ruze, 1965).

Wet radome influence on weather radar systems was the subject of the theoretical and experimental study carried out by (Manz, 2001). According to Manz’s study, the water layer formed on the antenna radome due to rain can cause an attenuation of several dB of the signal, leading to significant measurement errors and underestimation of the precipitation intensity. Although a radome provides complete elimination of precipitation from all the antenna surfaces, the system performance during rain will be determined by the quantity and form of the water on the radome outer surface. This effect can be minimized by using hydrophobic coating, which allows water beading to occur, and then this will directly encourage rapid shedding of the water from the surface. The form of the water beading on a typical high quality hydrophobic surface is shown in Figure 2-1.

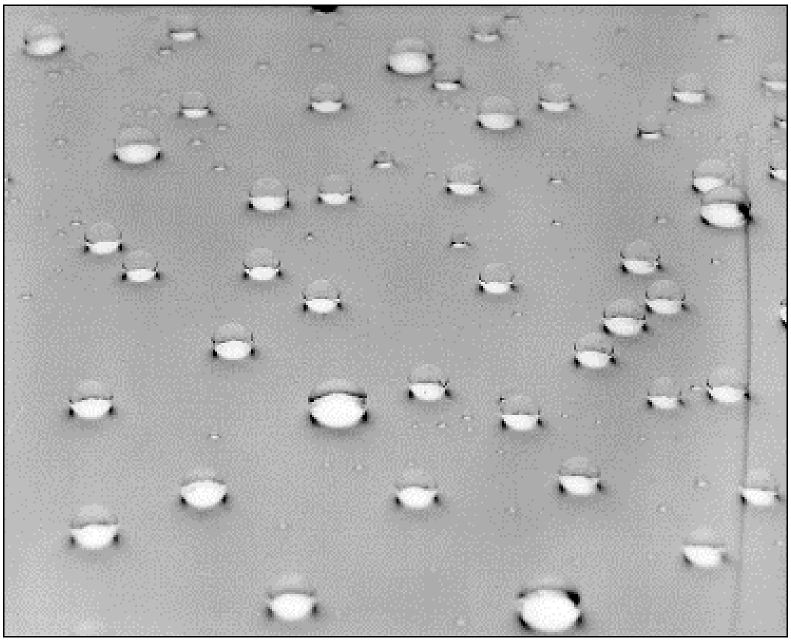

Figure 2-1 Water Droplets on a Hydrophobic Coating. (Manz, 2001)

Manz has concluded that wet radome attenuation is always depending on the specific rain rate, the wind conditions and the radome surface conditions. Factors contributing to the variability within the water cover on the radome include the precipitation rate, the viscosity of the hydrometeors, the direction and velocity of the wind, the angle of incidence, the slope of the radome surface, and the hydrophobic properties of the surface (Germann, 2000).

According to (Germann, 1999) a cover of water, wet snow and/or ice on the radome may cause serious signal attenuation. He reported that for qualitative work, such as detecting and tracking precipitation areas, the reduction of the signal may be acceptable, whereas for quantitative precipitation estimation it may have unacceptable consequences. Estimation for radome attenuation has been done under natural conditions using radar measurements of precipitation. Reflectivity measurements before, during and after rain on the radome are compared. The average signal loss within the precipitation area gives a quantitative estimate of the phenomenon. Radome attenuation ranges up to 5.4 dB in moderate rain, and thus reduces the precipitation estimates to less than half (Germann, 2000).

According to (Cohen and Smolski, 1966) it is found that the water flow, due to rain on the surface of a radome, is partly laminar and partly in the form of rivulets. Laminar flow is characteristic of a wetting surface and rivulet flow is characteristic of a non-wetting surface. However Hendrix, et al. (1989), reported that the water on the surface of a radome due to rain flows down in three different forms: a laminar sheet, rivulets and as droplets. The form of the water flow on a spherical radome is dominated by the hydrophobic properties of the radome (Hendrix et al., 1989).

(Anderson, 1975) has measured rapidly increasing losses while the snow or ice on the radome was melting. He has found a considerable degradation of the non-wetting surface properties of the radome of a satellite communication antenna, both by observing the water cover as well as by measuring the transmission loss. The non-wetting nature of the radome surface significantly degraded with time, and this was accompanied by a large increase in the 20-GHz transmission loss during periods of rain. The losses were in the range of 6-8 dB for rain rates of 3-40 mm/h. Within the first half year of the experiment one-way attenuation at a rain rate of 10 mm/h increased from below l dB up to about 7 dB (transmission frequency was 20 GHz). Assuming a homogeneous water layer at 5.5 GHz this corresponds to below 1dB up to about 3.5 dB. After that no further degradation has been observed. This suggests that already in the first few months of operation, atmospheric pollution and weathering may seriously change the hydrophobic properties of a radome.

A recent study dealing with wet antenna issue in weather radar service has been carried out by (Trabal et al., 2008). A method to correct CASA (Center for Collaborative and Adaptive Sensing of the Atmosphere) X-band radar data for wet radome attenuation was developed by the use of a contiguous WSR- 88D S-band radar. The method is based on the comparing between area-averaged data from the X-band radar and the S-band radar data. The method aims to obtain a data fit that relates the amount of rainfall over the X-band wet radome to the average attenuation in the X-band radar data. Results show an exponential fit that relates the amount of rainfall over the X-band wet radome to the wet radome average attenuation expected in the X-band data as following: (Trabal et al., 2008)

$$y = \alpha \exp(\beta x) \qquad (2\text{-}1)$$

Where:

α and β are constants that fit the data using the least square method.

x is the S-band reflectivity over the X-band wet radome.

y is the average wet radome attenuation.

It is showed that the best exponential fit to estimate the wet radome attenuation from the X- and S-band data comparison method has constants $\alpha = 0.03$ and $\beta = 0.10$, which is valid for reflectivity thresholds up to 20 dBZ.

A comparison of non-logarithmic reflectivity between the CASA X-band and the S-band radars averaged over an area of 750 km^2 is shown in Figure 2-2 (a). The reflectivity estimated over the X-band radar wet radome by the S-band radar is also shown in Figure 2-2 (b). A period of severe radome attenuation is clearly identified during the half hour ranging from 6 to 6.5 time UTC, with a maximum observed attenuation of 7.5 dBZ. Moreover, the Figure shows the high correlation between the maximum reflectivity intensity over the X-band wet radome with the time period of severe radome attenuation.

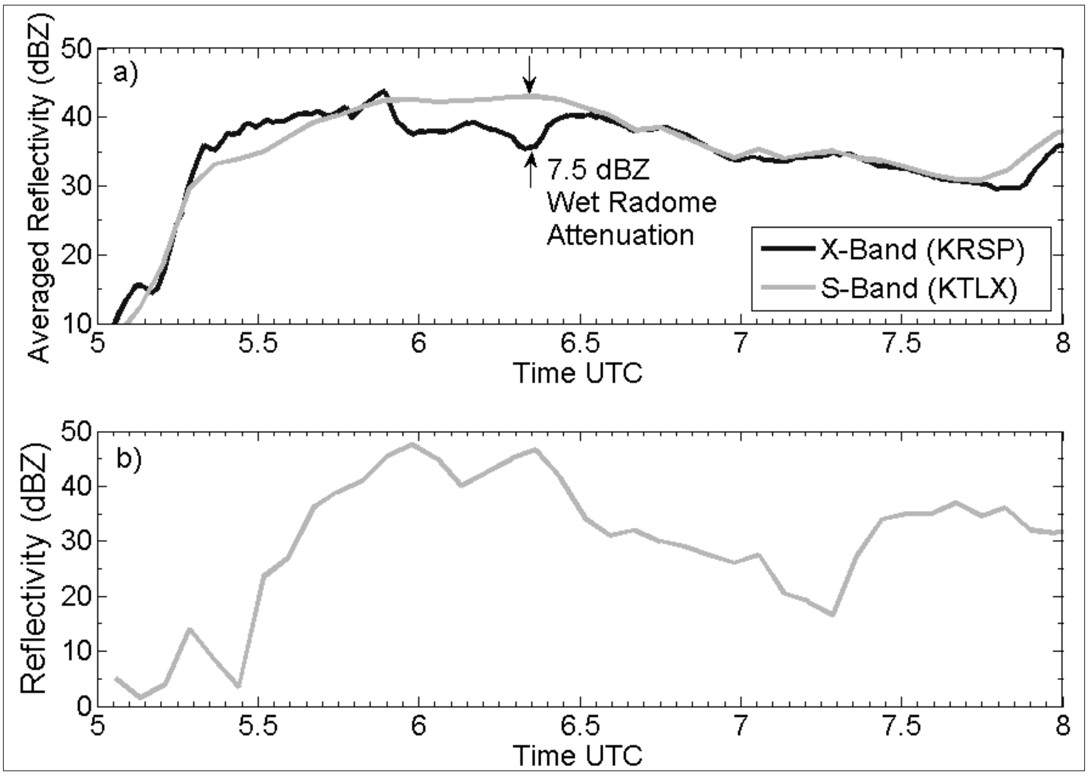

Figure 2-2 Averaged reflectivity for the X- and S-band radars within the precipitation area vs. time (a), and S-band reflectivity over the X-band wet radome during the same time (b) (Trabal et al., 2008)

According to my knowledge the only study so far that takes into account the effect of the wind on the wet radome attenuation was carried out by (Gang et al., 2000). In their study of the effect of rain on microwave link performance at 38 GHz in Singapore, they have observed that the rain attenuations derived from the measured received levels are much greater than those predicted using the ITU-R models. They suggested that water on the antenna radome could be a possible reason for the higher measured attenuation. Tests of simulated rain on the radome were conducted to evaluate the effects of water on the antenna radome. Four different wetting conditions which can occur simultaneously on a radome in a rain event were chosen:

a) Fine water droplets.

b) Water rivulets.

c) A thin film of water.

d) A thicker water sheet.

The obtained results for the transmission loss due to water on the radome are shown in Figure 2-3.

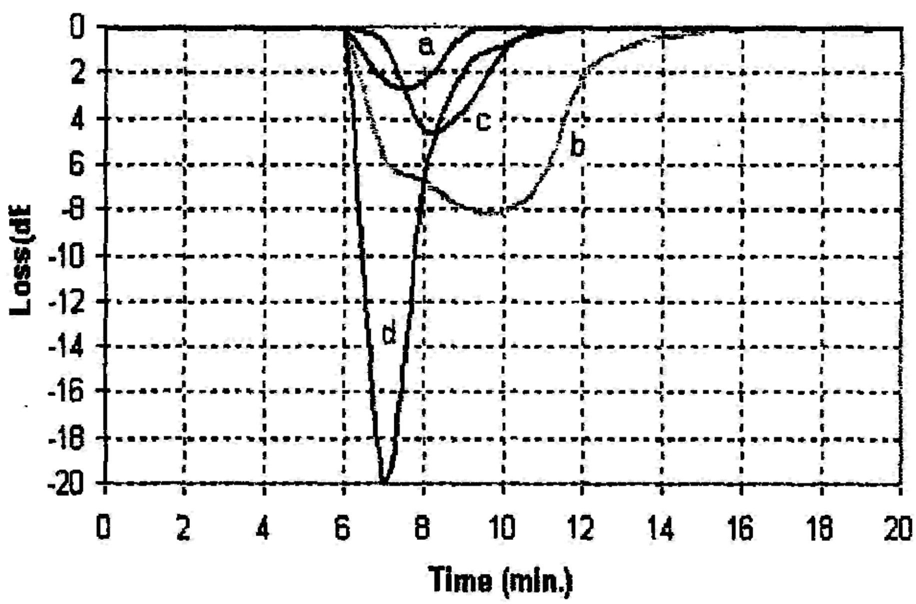

Figure 2-3 The transmission loss due to water on the radome under four wetting conditions: a) Water droplets. b) Water rivulets. c) A thin film of water. d) A thicker water sheet. (Gang et al., 2000)

For the water droplets condition the reduction of the received signal with time can be seen in Figure 2.3. The maximum signal loss due to fine water droplets on the radome is about 3 dB. For the water rivulets condition loss of nearly 8 dB is recorded. To produce the thin film of water condition a wet cloth is used to wet the surface of the radome. The thicker the film stands on the surface of radome, the more serious attenuation can be measured. The maximum attenuation in this condition is about 4.46 dB. The thicker water sheet condition was created using a watering can. The spray from the watering can was corresponding to a rainfall rate of 300 mm/hr. The maximum attenuation recorded for this case is 19.81 dB. Two methods, called Correlation and Equi-probability method, were developed to separate the attenuation due to rain along the path and that due to water on the antenna radome. In the correlation method, the difference between the measured attenuation and the predicted attenuation is taken as the loss due to water on the radome. In the second method, the monthly cumulative distributions of the rainfall rate and the total measured received signals are computed. For each probability value, a set of total measured attenuation and the rainfall rate is obtained.

The effect of the wind condition during the rain event on the wet radome attenuation has been also observed in this study. The relationship between the wet radome attenuation and the rainfall rate in natural rain events for the months May, July, August and December 1998 in Singapore is shown in Figure 2.4 for the 38 GHz radio link. According to (Gang et al., 2000), December is Northeast Monsoon season in Singapore where the direction of wind is mainly in Northeast and the maximum wind speed is 24.1 km/hr. July and August belong to the Southwest Monsoon season, where the wind direction is often in the southeast or southwest. The maximum wind speed averaged by one minute can be up to 35.4 and 37 km/hr. May is the pre-

Southwest monsoon season, where the wind strength is generally lighter than that of other seasons and the direction of wind is variable. Figure 2-4 shows that the highest wet radome attenuation has occurred in August while the lowest in December. A possible reason for that could be the change in the wind direction between two different monsoon seasons. However this study lacked some details about the position of the antenna according to the wind direction as well as the details about the wind speed for each particular case.

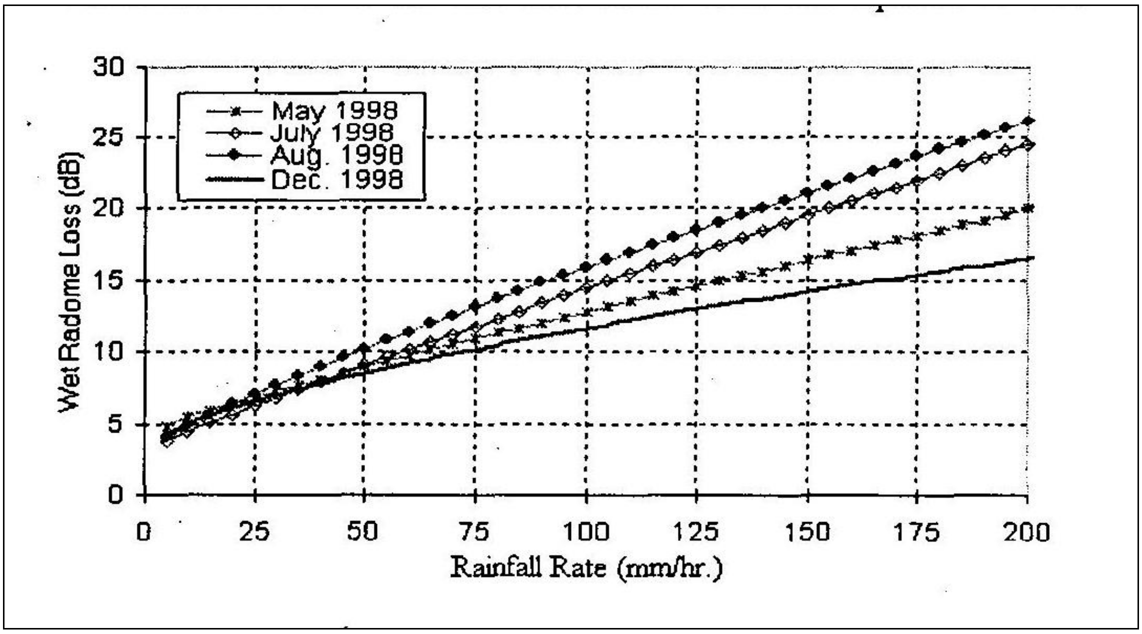

Figure 2-4 The variation of wet radome loss in the months May, July, August and December 1998 (Gang et al., 2000)

Also in automotive radar sensors, which fundamentally use millimeter wave signals, wet antenna issue gains an increasing interest. It observed that, the existence of water film on the surfaces of the antenna or its radome is the main cause for weak performance of radar sensors in rainy and snowy weather conditions (Arage et al., 2006, Arage Hassen, 2007). A theoretical analysis and measurement results of the losses due to wet radome in automotive radar sensors have been presented by (Arage et al., 2006). Mainly it deals with the losses due to water film on the surface of radome and illustrates their dependency on the frequency, the water film thickness and the polarization. The theoretical analysis is based on the "Fresnel formula for reflection and transmission" (Born and Wolf, 2003). The wet radome was modeled as infinitely extended four plain dielectric layers of air, radome, water-film and air again. As shown in Figure 2-5, 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 waves 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.

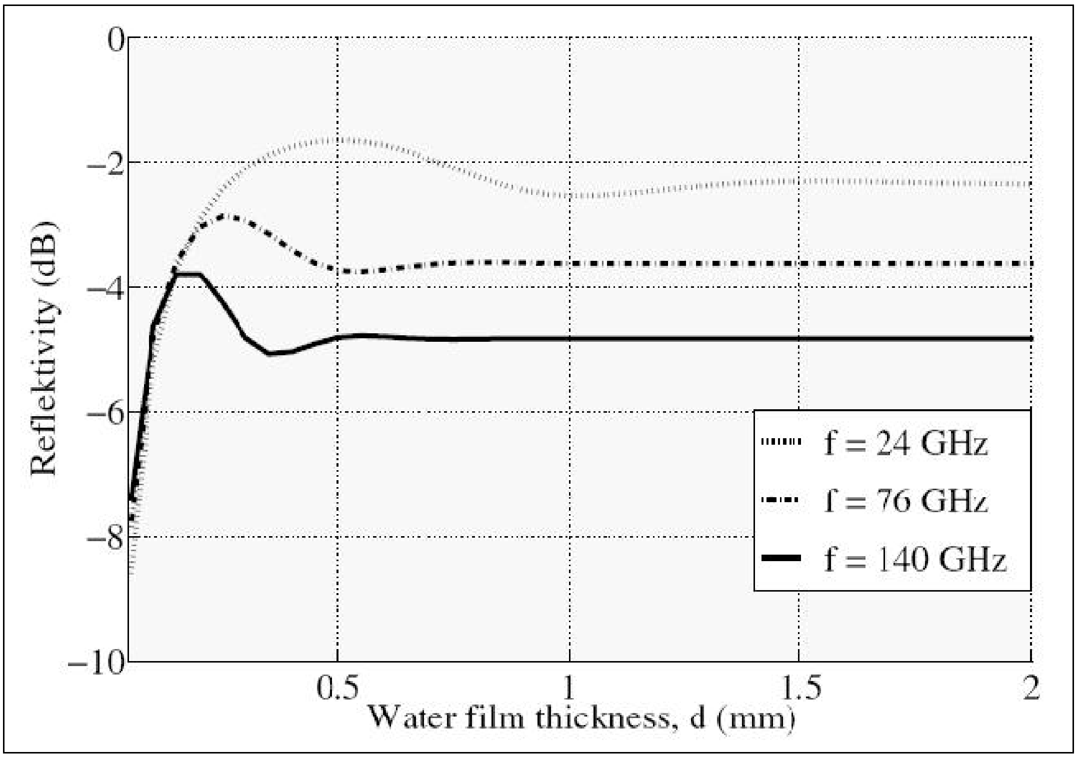

Figure 2-5 Reflectivity from water film at 20 °C. (Arage et al., 2006)

The transmissivity of a water film as a function of its thickness for three automotive radar frequencies is shown in Figure 2-6. The water film attenuates millimeter wave signals with shorter wave length strongly. The 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.

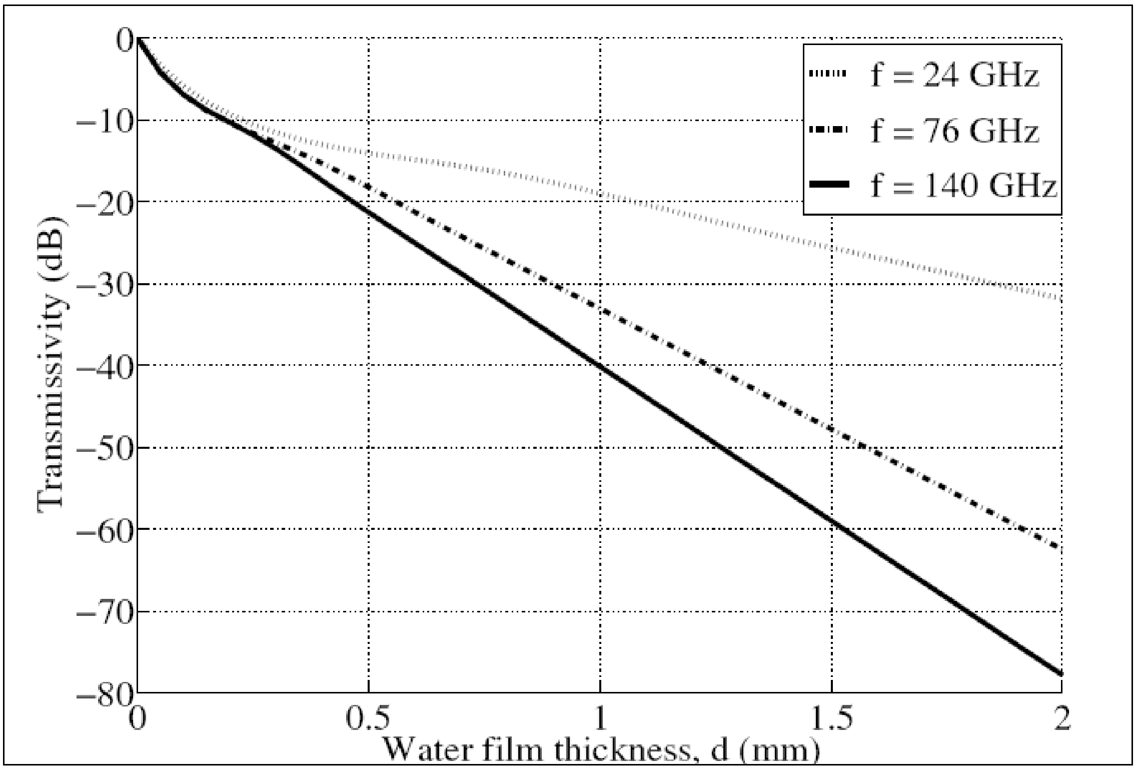

Figure 2-6 Transmissivity through water film at 20 °C (Arage et al., 2006)

As result from Arage's study, it has been proved, in the theoretical analysis as well as in the practical measurements, that the existence of water film on the surface of the antenna lens or its radome causes a strong limitation on automotive long range radar performance during rain and snow.