PRECIPITATION SCATTER INTERFERENCE ON COMMUNICATION LINKS WITH EMPHASIS ON THE MELTING-SNOW LAYER

by

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Abstract

A geometrical model has been developed to calculate hydrometeor interference between different microwave systems sharing the same frequency. The model is capable of calculating the interference for any combination of transmitter-receiver geometry and the program is flexible enough to allow for many assumptions related to the spatial and vertical structure of the rain cell. Furthermore, it can easily accommodate different attenuation and scattering models.

The study also focuses on the melting-snow layer and it is found that this layer plays a significant role in the interference calculations. The melting layer significantly increases the interference in the 1–8 GHz range, and moderately in the 8–12 GHz. On the other hand, the melting layer results in a significant decrease in the interference level at higher frequencies, especially in the 30–40 GHz range.

The study also examines the effect of the ice/snow region above the melting layer and it is concluded that this region plays an important role in the interference calculations, especially at higher frequencies.

Three examples of interference geometries are examined in Chapter 4. The first deals with the interference from an up-link to terrestrial links in the near-forward direction, the second deals with the interference from an up-link to terrestrial links in the near-backward direction and the third deals with the interference from an up-link to a satellite in the forward direction.

A comparison is made between two rain-cell models in Chapter 5. The COST 210 rain-cell model, which is adopted by the CCIR (International Radio Consultative Committee), is compared with the more physical Capsoni rain-cell model.

A new empirical attenuation formula for rain and melting-snow has been developed, which, unlike previous formulae, has the frequency as a separate parameter. For detailed analysis, refer to Appendix D.

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$\bar{a}$	=	representative rain drops radius.
a_{mi}	=	melting-snow particles radius.
a_{Ri}	=	rain drops radius.
dc	=	diameter of the COST 210 rain-cell.
f	=	frequency.
f_r	=	the resonant frequency of the melting-snow particle.
g	=	low-frequency polarizability.
g_e	=	high-frequency polarizability.
$g_r(\hat{\varphi})$	=	normalized radiation pattern of the receiving antenna at an angle $\hat{\varphi}$ from the main lobe axis.
$n(\bar{a})$	=	the raindrop-size distribution.
p_i	=	fraction of the volume of rain V_R composed of the rain drops of radius a_{Ri}.
r_o	=	the distance at which the rainfall rate decrease by a factor of 1/e (Capsoni rain cell).
r_{eff}	=	effective Earth radius.
$\bar{r}_m$	=	the truncated Capsoni rain cell radius.
r_{rt}	=	link length between transmitter and receiver.
v_{mi}	=	fall velocity of the melting-snow spheres of radius a_{mi}.
v_{Ri}	=	fall velocity of the rain drop of radius a_{Ri}.
(x_c, y_c, z_c)	=	the rectangular coordinates of the bottom of the rain cell.
(x_r, y_r, z_r)	=	the rectangular coordinates of the receiver.
(x_t, y_t, z_t)	=	the rectangular coordinates of the transmitter.
z	=	sum of the sixth powers of the diameters of all hydrometeors per unit volume (reflectivity)
A_a	=	Attenuation coefficient due to atmospheric gases.
A_n	=	the normalized melting-snow attenuation.

A_p	=	Attenuation coefficient due to precipitation.
G_r	=	receiving antenna gain.
G_t	=	transmitting antenna gain.
Hc	=	the rain cell height.
Hm	=	rain height; also the height of the top of the melting layer.
K	=	a parameter connected with the receiver normal radiations pattern. It determines the gain level of the side lobe of the antenna.
L	=	transmission loss.
N	=	number of representative rain drops of radius $\bar{a}$ per unit volume.
N_m	=	number of melting-snow particle per unit volume (rain drop density).
$\bar{P}_r$	=	average interference power received.
P_t	=	transmitted power.
R	=	rain rate.
R_r	=	distance from the common volume to receiver.
R_{min}	=	the rain rate where the Capsoni rain cell is truncated.
R_t	=	distance from the transmitter to the common volume.
R_M	=	the peak rain rate at the centre of the rain cell (Capsoni rain cell).
S	=	ratio of the melted to the total volume in the melting-snow particle.
S_a	=	surface area of the narrow beam antenna perpendicular to the main beam axis (also known as the 3dB foot-print).
T	=	melting-snow layer thickness.
V_R	=	volume of rain.
(α_1, α_2)	=	parameters connected with the receiver normal radiations pattern.
β	=	phase coefficient due to precipitation.
$\gamma(R_t, R_r)$	=	the propagation loss due to precipitation and atmospheric gases along the path $R_t + R_r$.

δ	=	skin depth of water.
ϵ	=	complex permitivity of water.
ϵ_o	=	complex permitivity of free space.
η_r	=	receiver loss factor.
η_t	=	transmitter loss factor.
θ_{1h}^2	=	double-sided half power beamwidth of the narrow beam antenna.
(θ_r, ϕ_r)	=	the rectangular coordinates of the receiver main lobe axis relative to the receiver coordinate axes.
(θ_t, ϕ_t)	=	the spherical coordinates of the transmitter main lobe axis relative to the transmitter coordinate axes.
λ	=	wavelength of the transmitter electromagnetic wave.
ρ	=	the rain cell radius.
ρ_s	=	the density of snow in the melting-snow particle.
$\sigma\left(\hat{\theta}, \hat{\phi}\right)$	=	bistatic scattering cross section in the direction of $\hat{\theta}$ and $\hat{\phi}$ (Figure C.1).
$\sigma_{bi}\left(\hat{\theta}, \hat{\phi}, \bar{a}\right)$	=	the bistatic cross section of a drop of equi-volume radius $\bar{a}$ in the direction of $\left(\hat{\theta}, \hat{\phi}\right)$.
σ_s	=	Rayleigh scattering.
Γ_R	=	attenuation outside the COST 210 rain-cell.

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Chapter 1 Introduction

The ever increasing demand on a limited radio-frequency spectrum has necessitated the sharing of frequencies by a number of services. This frequency sharing increases the possibility of interference. In system planning, an engineer has to be able to establish a reliable system which can distinguish between the incoming signal and interference caused by other systems using the same frequency. To do this, it is necessary to estimate the mutual interference between the different radio systems. This is by no means an easy task (and is getting harder with the increasing congestion of the radio-frequency spectrum).

There are many mechanisms that can cause interference [6]:

— line of sight;

— diffraction over isolated obstacles;

— diffraction over irregular terrain;

— tropospheric forward scatter;

— superrefraction, with or without reflection;

— ducting;

— scatter from hydrometeors;

— reflections from aircraft.

Microwaves are scattered by hydrometeors such as rain, snow, melting-snow, and ice particles. This scattering is one of the possible causes of interference between communication links operating at the same frequency. It becomes then necessary to quantify this interference in order to be able to design more reliable communication links.

Recently, considerable work has been done on interference caused by hydrometeor [1,2,7]. So far, however, the issue of the melting-snow layer has not been considered, even though the presence of the melting layer tended to be a significant source of error in radar measurement of rain rate [17]

The purposes of this study are:

1. to develop a general geometrical model which can be used in conjunction with any attenuation and scattering model;
2. to develop a "universal" program to calculate the interference for a wide range of geometries and variables;
3. to study the effect of those variables and geometries on interference due to rain, and
4. to study the effect of the melting-snow layer on the interference problem.

The possible geometries involved in the interference calculations are numerous. To overcome this, a "universal" model-program has been developed. While this program is capable of calculating the interference for all geometries and variables, only the most likely scenarios (which are still very numerous) will be considered (e.g., geometries involving the interference from up-link to satellite, interference from up-link to terrestrial link and variables such as antenna gain, rain rate and rain-cell structure).

Chapter 2 Hydrometeors: Structure and Characteristics

2.1 Hydrometeor Structure

Hydrometeor scattering is observed when a rain cell overlaps with the common volume of transmitting and receiving antennas. This scattering and the subsequent interference depends on the rain cell, its rain intensity, height, radius, etc. It thus becomes very important to model the rain cell as accurately as possible for interference calculations. Many models have been developed to describe rain processes [eg. 3,6,7]; the most realistic is that of Capsoni [3]. The Capsoni model will be the basis for the spatial distribution of rain in the present work.

2.1.1 Rain cells

The horizontal pattern of the rain cell has been represented by an analytical expression with an exponential shape having rotational symmetry [2]:

$$R_{(x,y)} = R_M e^{\left(\frac{-\tilde{r}}{r_0}\right)} \tag{2.1}$$

where $\tilde{r}$ is the distance of the point (x, y) from the rain cell centre, r_0 is the radius at which rainfall rate decreases by a factor of 1/e, and R_M is the peak rain rate at the centre of the cell (Figure 2.1)

The rain cell is truncated at a certain distance $\tilde{r}_m$ where the rain rate is R_{min} [2]:

$$R_{min} = R_M e^{-\tilde{r}_m/r_o} \tag{2.2}$$

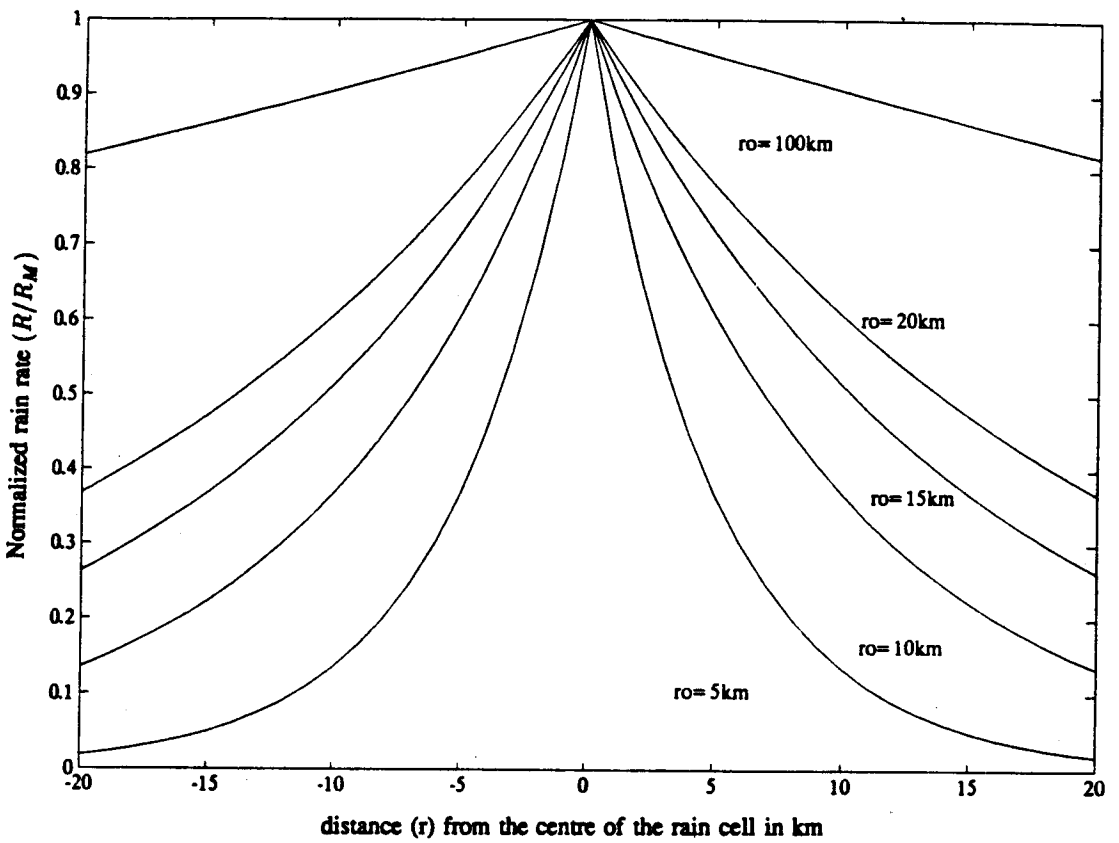

Figure 2.1 Rain rate distribution in a 20 km radius rain-cell for different r_o

Beyond this point, we assume that the effect of rain is negligible. Equation 2.2 can now be rewritten as:

$$r_o = \tilde{r}_m / ln(R_M / R_{min}) \tag{2.3}$$

The radius of the rain cell is given by:

$$\tilde{r}_m = 10 - 1.5 \times \log_{10} R_M \tag{2.4}$$

where $\tilde{r}_m$ is in km and R_M is in mm/h.

2.1.2 Spatial structure of rain

Two rain-cell structures are considered. The first is a rain-only medium. The other is when snow forms and then melts introducing a melting-snow layer.

2.1.2.1 The Melting-snow layer (Bright Band)

When it is warm enough for the snow to melt before reaching the ground, there is often observed a layer of high reflectivity just below the 0^oC isotherm. This phenomenon was observed as far back as the forties and it became known as the radar "bright band." The melting-snow layer is the region in which the precipitation changes from snow to rain (Figure 2.2). As snowflakes descend into the melting-snow layer, they become highly "reflective."

The most important reason for the increase in reflectivity is that the dielectric constant of water is four times higher than that of ice [19]. Another reason for the high reflectivity is the large size and low velocity of the melting-snow particles relative to those of rain drops. Continuing to melt while descending, the snowflakes become smaller in size and

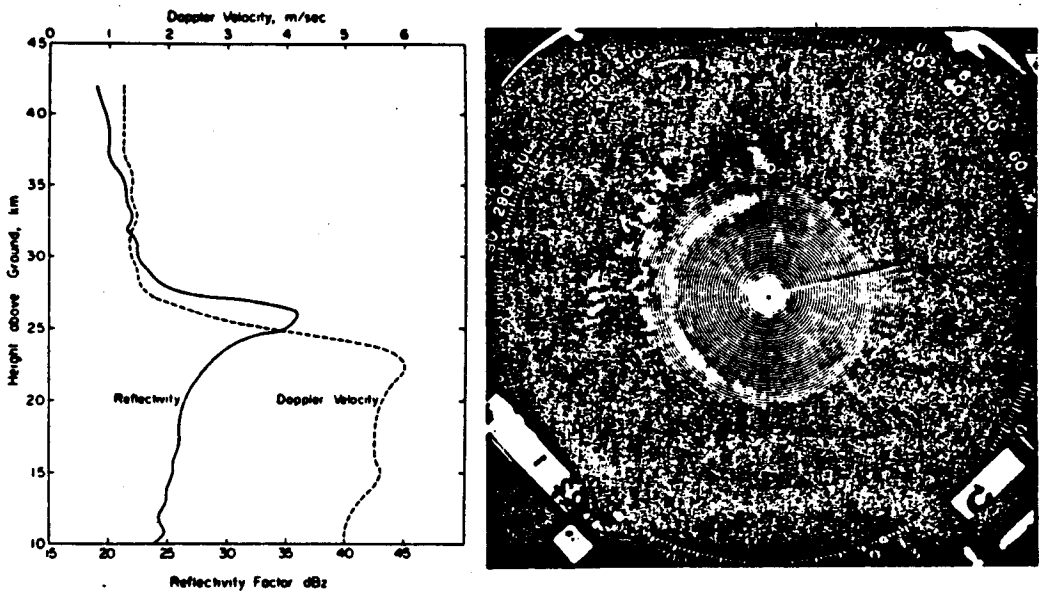

Figure 2.2 Two views of the radar bright band: at the left a vertical profile of reflectivity and Doppler velocity as measured with vertically pointing Doppler Radar; at right a PPI map at 8° elevation on which the melting layer appears as a bright ring at about 12 miles. [Rogers]

faster with less concentration. This will cause a decrease in the reflectivity as the rain medium is approached.

A formula for the melting layer thickness (in meters) has been suggested by Klassen [13]:

$$T = 100z^{0.17} \tag{2.5}$$

where z is the reflectivity as given in [6]:

$$z = 400R^{1.4} \tag{2.6}$$

where R is the rain rate in mm/h. The melting layer disappears at high rain rates; it is usually assumed that it disappears above a rain rate of 30 mm/h.

2.2 Electromagnetic wave propagation in Hydrometeors

The most accurate method to model melting layer scattering and attenuation is through the use of Mie scattering techniques for spherical rain droplets [11]. The advantage of using this technique is obvious — its accuracy. This method is quite complicated and thus undesirable in computer models. Another technique is to have the data for scattering and attenuation stored in files. Unfortunately, such files occupy a very large chunk of memory and they slow the system considerably. New models, that are simpler, but less accurate, have been developed in order to model hydrometeor scattering and attenuation [6, 10, 11, 12].

2.2.1 Hydrometeor scatter

A Hydrometeor scattering model has been developed by Kharadly [11]. This model is both simple and relatively accurate in the 1–40 GHz range. A thorough description of

the model is given in Appendix C. The model has "good" agreement with the "exact" results calculated by Kishk using Mie scattering [11]. At the top of the melting layer (S=0, where S is the ratio of the melted to the total volume in the melting-snow particle), the reflectivity is assumed to be the same as that of rain (S=1). The reflectivity then decreases by −6.5 dB per kilometer.

2.2.2 Hydrometeor attenuation[1]

Attenuation plays an important role in the interference problem. On one hand, an increase in attenuation may decrease the interference. On the other hand, it may force the transmitting station to increase its transmitting power thus further aggravating the interference. Since attenuation affects the incident and scattered signals and since this attenuation varies as a function of rain rate and melting ratio (S), accounting for it occupies much of the computer time in the interference calculations. It is then desirable to use models that are reasonably accurate and simple. The models developed by Kharadly [10, 12] are simple and flexible; they can readily accommodate changes in physical assumptions relating to drop-size distributions, rain drop shapes, the density of the snow in the melting-snow particle, etc. An empirical formula has also been developed (Appendix D). While this formula is simpler, it is not flexible.

2.2.1 Kharadly 1st model for attenuation [10]

The melting-snow particles are considered to be spherical, of the same number and (relative) size distribution as the resulting rain drops. The radius of the representative particle is calculated using equation A.4.

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1 For a thorough analysis refer to the Appendix A and B (Kharadly's models [10, 12]) and Appendix D for empirical model.

2.2.2 Kharadly 2nd model for attenuation [12]

The above model does not satisfy the conservation of mass criterion since it does not take into account the effect of the changing velocities of the melting-snow particles on the number density and hence the drop-size distribution. This model has been amended to include the effect of the velocity.

2.2.3 Kharadly 3rd model for attenuation [12]

Because of the deviation of the results of the 1st model from that of the exact values for the melting-snow layer, Kharadly introduced a correction factor that brought the results of the model closely to the exact attenuations calculated using Mie scattering. The correction factor is given by [12]:

$$\text{Factor1} = \left\{ \frac{n\left[(2+S)\frac{f}{f_r}+1\right]}{\frac{f}{f_r}+2-S} \right\} \times \left\{ \frac{2-S}{2+S} \right\}^{(1-S)} \tag{2.7}$$

where f is the frequency in GHz, f_r is the resonant frequency of the melting-snow particle, S is the melting degree , defined as the melted to the total volume in the representative melting-snow particle, and n is defined in Appendix B.

2.2.4 Kharadly 4th model for attenuation

Because of the deviation of the results of the 2nd model from that of the exact values for the melting snow layer, Kharadly introduced a correction factor that brought the results of the model closely to the exact attenuations calculated using Mie scattering. The factor is given by:

$$\text{Factor2} = \left[\{n + S(1-n)\} \left\{ 1 + \frac{n^2\bar{a}(1-S)}{2\delta} \left[1 + \frac{(1-5S)f}{5f_r} \right] \right\} \right]^{(1-S)} \tag{2.8}$$

where $\bar{a}$ is the radius of the representative particle, δ is the skin depth of water = $\frac{100}{Real[f \times C_1 \times \sqrt{-\epsilon}]}$, with C_1 = 20.958, f is the frequency in GHz and ϵ is the complex permittivity of water as given in Appendix B.

The range of applicability of Kharadly formulas is between 1–40 GHz

Although the above formulas were developed with the assumption that the density of the snow core in the melting layer (ρ_s) is 0.1, they still apply with a reasonable degree of accuracy for a wide range of ρ_s (typically between 0.1 and 0.3). Figure 2.3 shows how close the 3rd and the 4th attenuation models are to the "exact" results for this range. We also note that Kharadly 3rd model yields the best results.

2.2.5 Empirical model

Since the frequency stays constant during the interference calculations, it would be useful to have an equation where the frequency variable is separable from all other variables, which is not the case in any of the above models. This has been achieved through the development of an empirical formula for attenuation based upon the exact values [12] and is given by:

$$A_p = A_{n(R,S)} \times \alpha R^{\beta} \tag{2.9}$$

where,

$$A_{n(R,S)} = M_1 S^{a_1 - 1} e^{-b_1 S^{a_1}} + M_2 S^{a_2 - 1} e^{-b_2 S^{a_2}} + M_3 e^{-b_3 S} + 1 \quad \text{with } S \leq 1 \tag{2.10}$$

with,

$$M_{1(R)} = C_0 + C_1 R^{0.003} + C_2 R^{0.0002}$$
$$M_{2(R)} = D_0 + D_1 R^{0.003} + D_2 R^{0.0002} \tag{2.11}$$

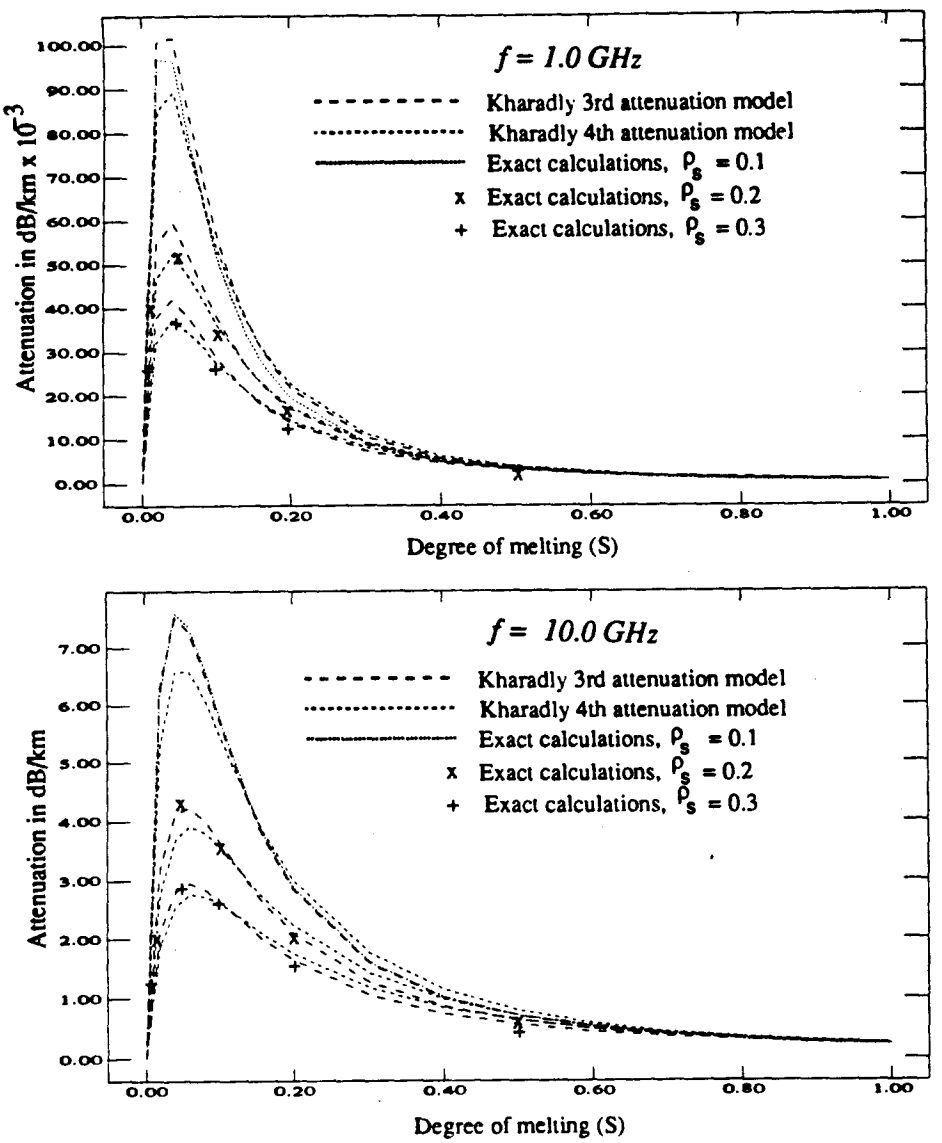

Figure 2.3(a) A comparison of the attenuation profile of the melting layer between Kharadly 3rd and 4th attenuation models, and the Exact calculations for R (rain rate) = 12.5 mm/h, f (frequency) = 1.0 and 10.0 GHz and ρ_s = 0.1, 0.2, 0.3

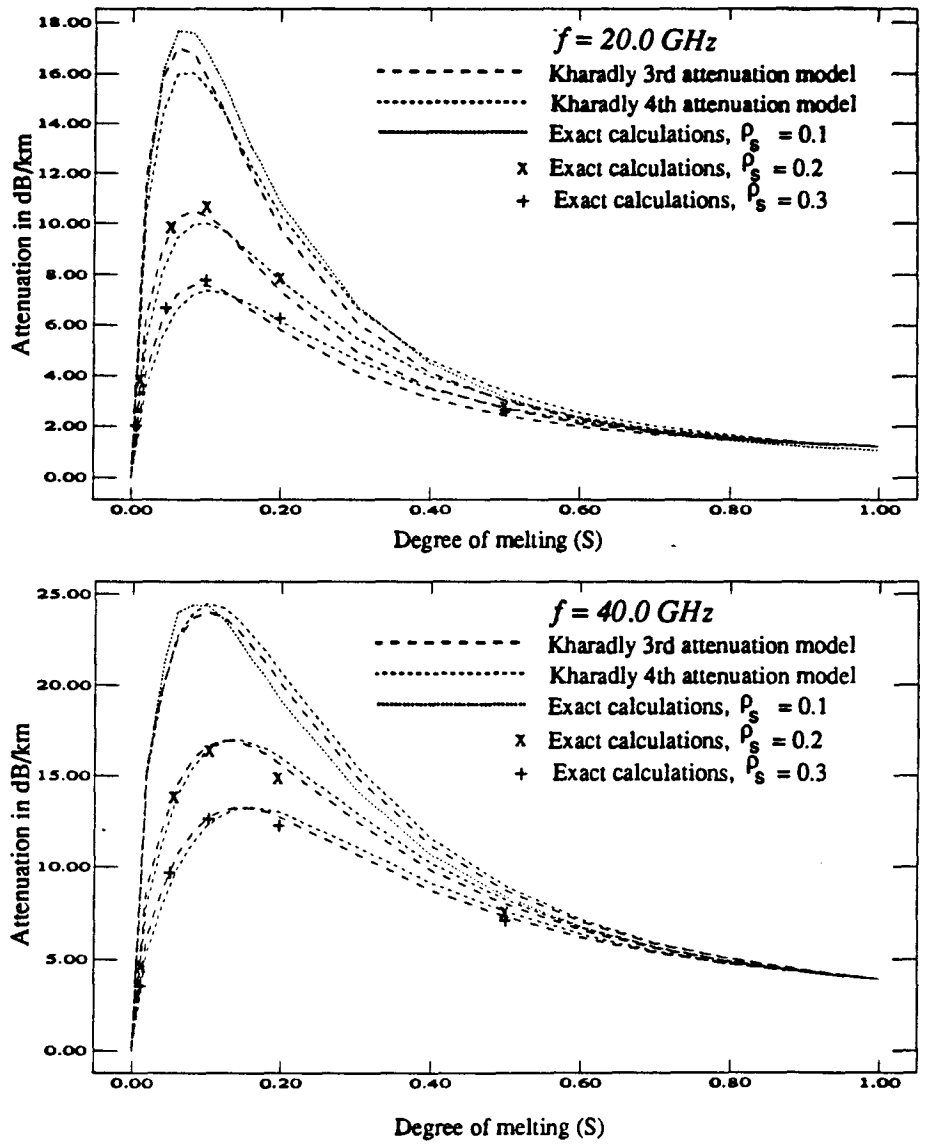

Figure 2.3(b) A comparison of the attenuation profile of the melting layer between Kharadly 3rd and 4th attenuation models, and the Exact calculations for R (rain rate) = 12.5 mm/h, f (frequency) = 20.0 and 40.0 GHz and ρ_s = 0.1, 0.2, 0.3

$C_0, C_1, C_2, D_0, D_1, D_2, a_1, \alpha, \beta$ are frequency dependent constants.

$A_{n(R,S)}$ approaches unity when S = 1.

The advantage of this formula is its simplicity and ease of use. Its disadvantage is that the formula does not, so far, take into account the average density of the snow in the melting-snow particle. The formula does represent the attenuation "quite well" from 1–100 GHz, however (Figure 2.4(a,b)). For a complete description, refer to Appendix D.

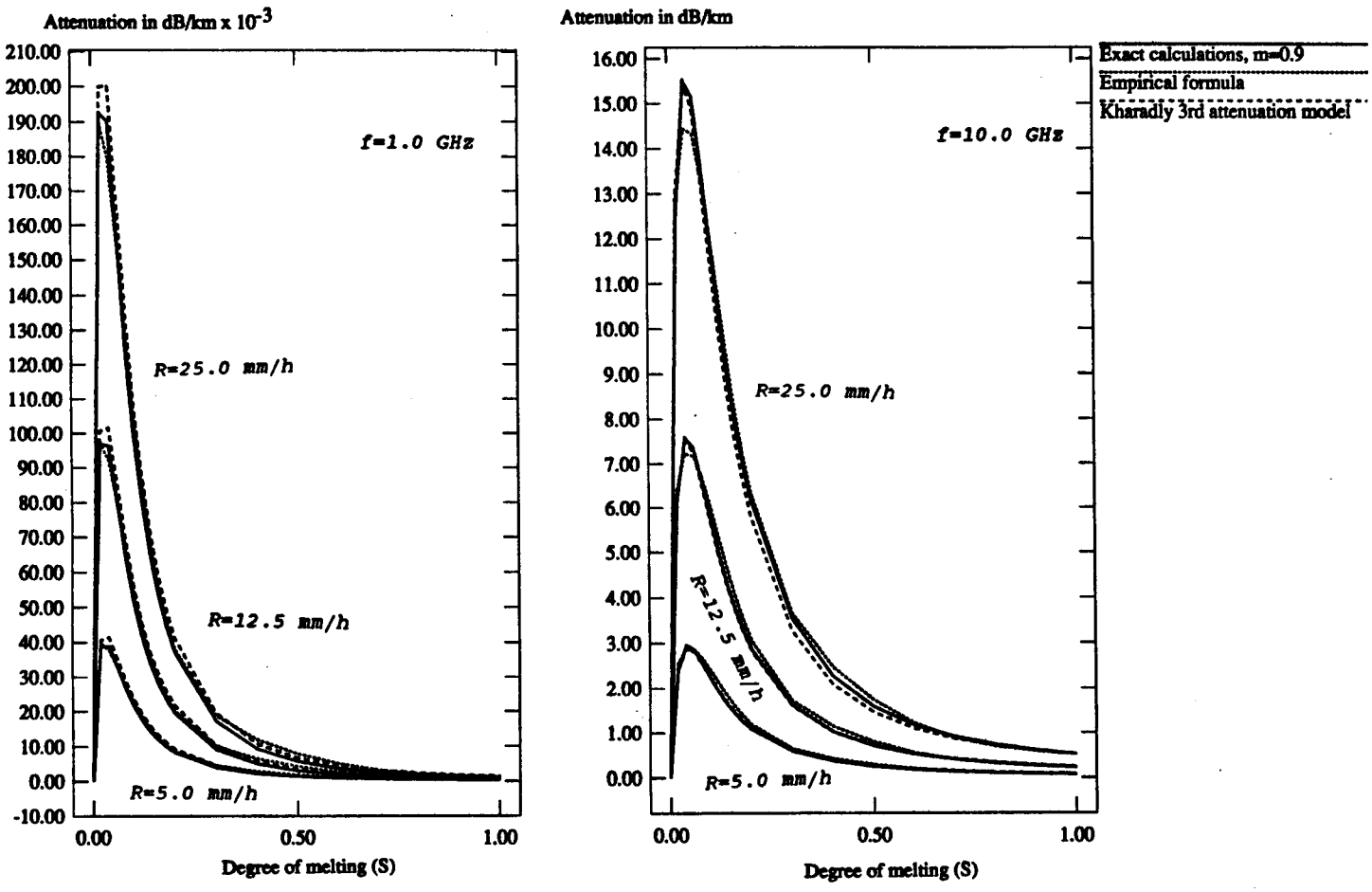

Figure 2.3.(a) A comparison of the attenuation profile of the melting layer between Kharadly 3rd attenuation model, Empirical model, and the Exact calculations for f (frequency) = 1.0 and 10.0 GHz (ρ_s = 0.1).

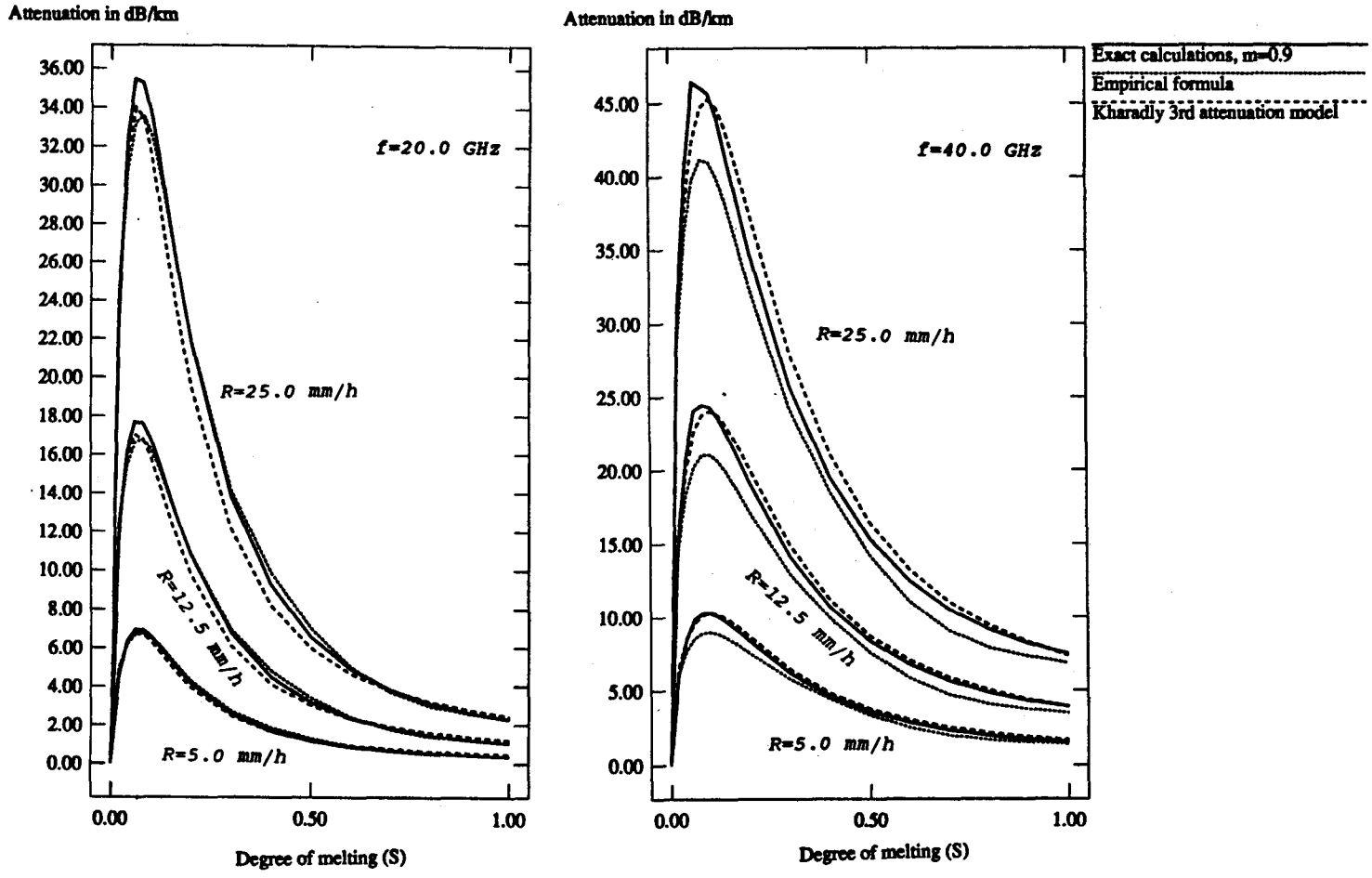

Figure 2.3.(b) A comparison of the attenuation profile of the melting layer between Kharadly 3rd attenuation model, Empirical model, and the Exact calculations for f (frequency) = 20.0 and 30.0 GHz (ρ_s = 0.1).

Chapter 3 The Interference Model

3.1 Approximate Radar equation

The interference power received by an antenna due to the scattering of the electromagnetic wave by precipitation is given by [1] [8]:

$$\frac{1}{L} = \frac{\bar{P}_r}{P_t} = \frac{\lambda^2 G_t G_r \eta_t \eta_r}{(4\pi)^3} \int_{Vol} \frac{g_t\left(\hat{\psi}\right) g_r(\hat{\varphi}) \sigma\left(\hat{\theta}, \hat{\phi}\right)}{\mathrm{R_t^2 R_r^2}} \gamma(\mathrm{R_t}, \mathrm{R_r}).dV \tag{3.1}$$

Where

L	=	transmission loss
$\bar{P}_r$	=	average interference power received
P_t	=	transmitted power
G_t	=	transmitting antenna gain
G_r	=	receiving antenna gain
$g_t\left(\hat{\psi}\right)$	=	normalized radiation pattern of the transmitting antenna at an angle $\hat{\psi}$ from the main lobe axis
$g_r(\hat{\varphi})$	=	normalized radiation pattern of the receiving antenna at an angle $\hat{\varphi}$ from the main lobe axis
η_t	=	transmitter loss (loss factor < 1) - for simplicity assume 1 (no loss)
η_r	=	receiver loss (loss factor < 1) - for simplicity assume 1 (no loss)
R_t	=	distance from the transmitter to dV
R_r	=	distance from dV to receiver
λ	=	wavelength of the transmitter electromagnetic wave

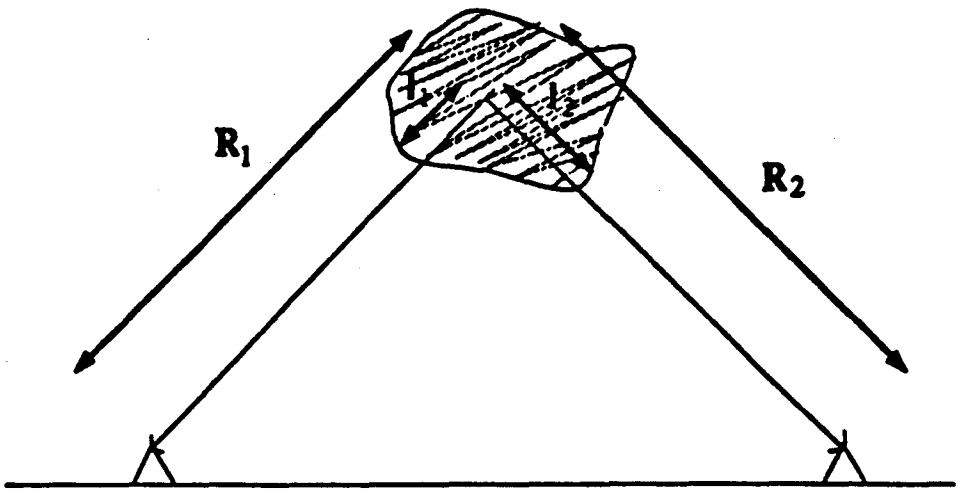

Figure 3.1 General Interference geometry

$\gamma(R_t, R_r)$	=	the propagation loss due to precipitation and atmospheric gases along the path $R_t + R_r$
$\sigma\left(\hat{\theta}, \hat{\phi}\right)$	=	bistatic scattering cross section in the direction of $\hat{\theta}$ and $\hat{\phi}$ (Figure C.1)

The propagation loss γ is given by [1]:

$$\gamma = 10^{-0.1 \int_0^{l_t+l_r} A_p dr - 0.1 \int_0^{R_t+R_r} A_a dr} \tag{3.2}$$

where,

A_p	=	Attenuation coefficient due to precipitation
A_a	=	Attenuation coefficient due to atmospheric gases. For simplicity we will assume that the attenuation due to gases is negligible (A_a = 0)
l_t, l_r	=	the distances that the electromagnetic wave traverses the rain cell along the transmitter and receiver directions, respectively

The bistatic cross section $\sigma\left(\hat{\theta}, \hat{\phi}\right)$ is given by

$$\sigma\left(\hat{\theta}, \hat{\phi}\right) = \sum \sigma_{bi}\left(\hat{\theta}, \hat{\phi}, \bar{a}\right) = \int_0^{a_{max}} n(\bar{a}) \sigma_{bi}\left(\hat{\theta}, \hat{\phi}, \bar{a}\right) d\bar{a} \tag{3.3}$$

where $n(\bar{a})$ is the raindrop-size distribution, $\bar{a}$ is the radius of the raindrop, and $\sigma_{bi}\left(\hat{\theta}, \hat{\phi}, \bar{a}\right)$ is the bistatic cross section of a drop of equi-volume radius $\bar{a}$ in the direction of $\left(\hat{\theta}, \hat{\phi}\right)$.

In order to simplify the Radar equation, the narrow beam approximation to either one of the antennas may safely be introduced. Since the transmitter and receiver parameters

are interchangeable, we will assume that the antenna with the narrow-beam approximation has the subscript '1' and the other antenna has the subscript '2' as shown below:

$$\frac{1}{L} = \frac{\bar{P}_r}{P_t} = \frac{\lambda^2 G_t G_r}{(4\pi)^3} \int_{Vol} \frac{g_1\left(\hat{\psi}\right) g_2(\hat{\varphi}) \sigma\left(\hat{\theta}, \hat{\phi}\right)}{\mathrm{R}_1^2 \mathrm{R}_2^2} \gamma . dV \tag{3.4}$$

Using the narrow-beam approximation, $dV = S_a dr$(where S_a is the 3dB circular surface area perpendicular to the main beam axis), equation 3.4 becomes

$$\frac{1}{L} = \frac{\bar{P}_r}{P_t} = \frac{\lambda^2 G_t G_r \theta_{1h}^2}{256\pi^2} \int_{r_0}^{r_c} dr \frac{g_2(\hat{\varphi}) \sigma\left(\hat{\theta}, \hat{\phi}\right)}{\mathrm{R}_2^2} \times 10^{-0.1 \int_0^{l_1+l_2} A_r dr} \tag{3.5}$$

3.2 Antenna gain pattern [7]

The standard method for representing the main lobe of an antenna is through the Gaussian-shaped pattern [7]:

$$G_{1(\theta)} = e^{-4ln\left(\frac{\theta}{\alpha_1}\right)} \tag{3.6}$$

where $G_{1(\theta)}$ is the gain at angle θ from the main axis and α_1 is the double-sided half-power bandwidth.

In order to represent the secondary lobe, we also assume a Gaussian-shaped pattern, but with a larger half-power bandwidth and a gain of **K** dB below the main lobe (Figure 3.2) :

$$G_{2(\theta)} = 10^{0.1\mathrm{K}} \times e^{-4ln2\left(\frac{\theta}{\alpha_2}\right)} \tag{3.7}$$

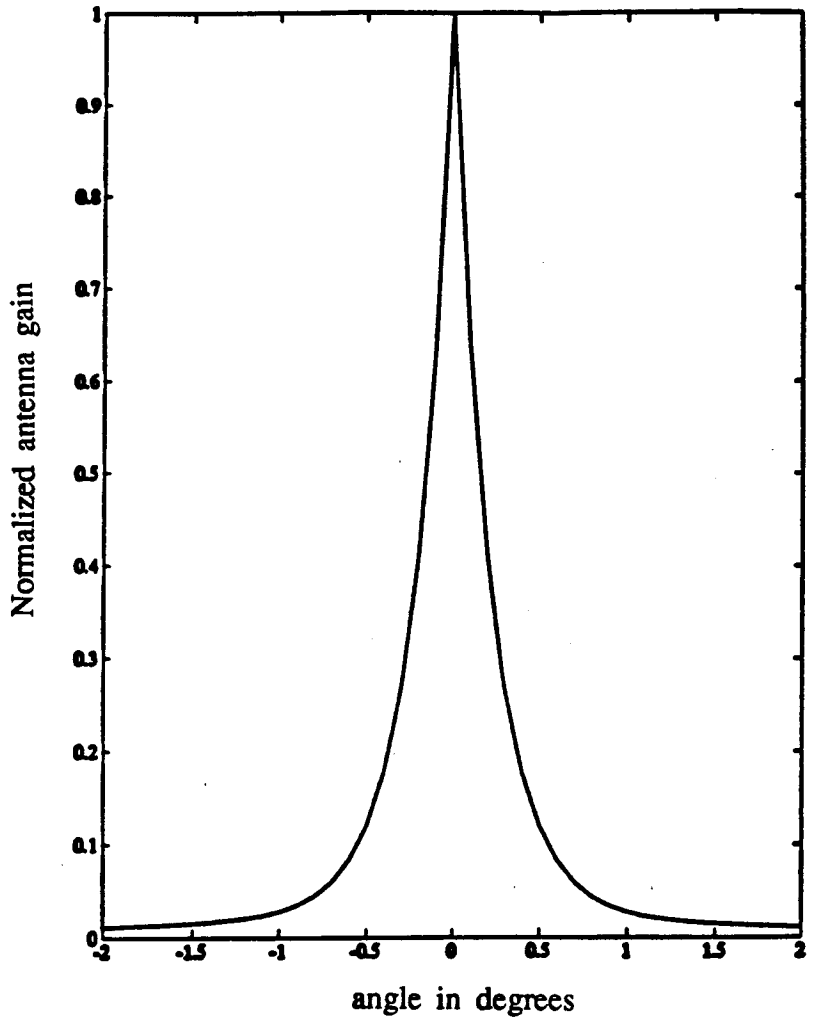

Figure 3.2 Simulation of the gain of an antenna with K=-15, $\alpha_1 = 0.6$, $\alpha_2 = 5.5$.

The total radiation pattern thus becomes:

$$G_{(\theta)} = \frac{G_{1(\theta)} + G_{2(\theta)}}{1 + 10^{0.1\mathrm{K}}} \tag{3.8}$$

3.3 The "Universal Model"

A program have been developed to implement the above equations. This program can calculate the interference for any configuration of transmitter-receiver geometry. It accepts the following input variables:

1. the rectangular coordinates (x_t, y_t, z_t) of the transmitter. Initially, we will consider that the transmitter is located at the centre of the main coordinate system, and hence the coordinates of the transmitter are (0,0,0)
2. the spherical coordinates (θ_t, ϕ_t) of the transmitter main lobe axis relative to the transmitter coordinate axes
3. the rectangular coordinates (x_r, y_r, z_r) of the receiver
4. the spherical coordinates (θ_r, ϕ_r) of the receiver main lobe axis relative to the receiver coordinate axes
5. the polarization of the transmitter[2]
6. the transmitter and receiver gains
7. the transmitter double-sided half-power bandwidth
8. the parameters connected with the receiver normal radiations pattern $(\alpha_1, \alpha_2, \mathrm{K})$
9. the rectangular coordinates (x_c, y_c, z_c) of the bottom of the rain cell
10. the rain cell radius (ρ) and Height (Hc)

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[2] We assume that the receiver accepts input electromagnetic wave regardless of polarization

11. the height (Hm — T) and the thickness (T) of the melting snow layer. Thickness will be zero in the absence of a melting snow layer
12. the rain rate at the centre of the rain cell R_M and the distance (r_0) at which rainfall rate decrease by a factor of 1/e
13. the integration steps which largely determine the accuracy of the program
14. the frequency used
15. the density of the snow in the melting snow particle ρ_s
16. the scattering and attenuation model to be used in the calculations. For scattering, we are limited to Kharadly's model. For attenuation, we can choose from Kharadly's 1st, 2nd, 3rd, 4th models and the empirical formula.

Also note that:

1. The z-axis for all the above mentioned coordinate systems is in the direction of the vertical edge of the rain cell, in the direction opposite to the rain fall.
2. In order for the program to work correctly, at least one of the antennas has to satisfy the narrow-beam approximation.

The program can also compute the interference for different melting layer profiles. However, a different subroutine is needed for each profile. Another method, which has not yet been implemented, is to have an external data file that contains the shape of the melting layer. The advantage is to avoid changing the program and recompiling it every time we introduce a different profile. The disadvantage of this procedure is that using an external file will add to the computation time.

Chapter 4 Interference Calculations

4.1 Introduction

4.1.1 Scattering in the ice/snow region

Rayleigh scattering is generally assumed for the ice/snow region above the melting-snow layer in the rain cell. The scattering cross section per unit volume at the top of the melting layer is given by [7]:

$$\sigma_s = \frac{\pi^4}{\lambda^4}\left|\frac{\epsilon - 1}{\epsilon + 2}\right|^2 z \times 10^{-18} \qquad m^2/m^3 \tag{4.1}$$

where ϵ = complex relative permittivity of water, λ is the wavelength, and z is the sum of the sixth powers of the diameters of all hydrometeors per unit volume. The magnitude of z is also given by the following empirical formula [6]:

$$z = 400R^{1.4} \qquad mm^6m^{-3} \tag{4.2}$$

where R is the rain rate. The scattering decreases by -6.5 dB/km as we move higher into the ice/snow region.

On the other hand, the attenuation in the ice/snow region is negligible and is assumed to be zero.

Several transmitter-receiver systems will be considered below, in our study of interference caused by the rain and melting-snow. It will seem that the interference will vary depending on several factors, which will include frequency, rain rate, the height of the melting snow layer, its thickness, and the density of the snow in the melting-snow particle.

4.2 Interference from up-link to terrestrial links in the near-forward direction

4.2.1 Description

The calculations are performed for an experimental link which is part of the European COST 210 project [7] dealing with the influence of the atmosphere on interference between radio communication systems. The Chilbolton-Baldock (England) path [7] has been chosen because of the availability of the measured transmission loss. The geometry of interference is shown in Figure 4.2.1. A radio wave transmitted by an up-link toward a satellite is scattered by rainfall. The scattered electromagnetic wave interferes with a terrestrial receiving station operating at the same frequency and sharing a common volume. In this case the main lobe axes of the two antennas intersect. In order to maximize the interference, the centre of the rain cell is positioned at the intersection of antenna beam axes. The parameters used in the calculations are listed below, in Table 4.1. The measured (experimental) transmission loss of the path for 11.2 GHz frequency

Chilbolton-Baldock path	
Station separation in km (r_{rt})	131 km
Scatter geometry	Vertical plane
Transmitting antenna gain in dB	59.0 dB
Receiving antenna gain in dB	40.5 dB
Transmitting antenna 3dB Beamwidth in degrees	0.18 degrees
Receiving antenna 3dB Beamwidth in degrees	1.6 degrees
Transmitting antenna elevation angle in degrees	20.0 degrees
Receiving antenna elevation angle in degrees(ϵ_r)	1.0 degrees
Transmitting antenna height from sea level in km (h_t)	0.12 km
Receiving antenna height from sea level in km (h_r)	0.086 km

Table 4.1 Chilbolton-Baldock path parameters [7]

(Graph not to scale)

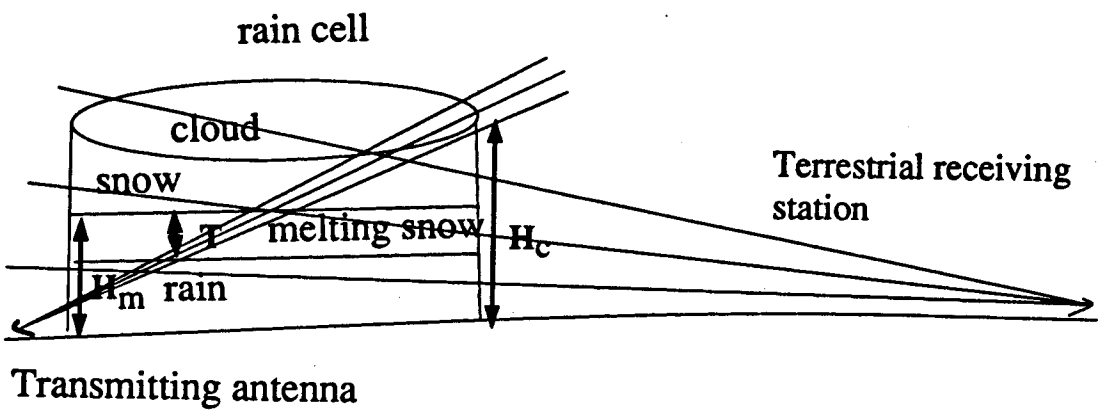

Figure 4.2.1 Interference from up-link to terrestrial link geometry in the near forward direction.

% of time	Rain Rate in mm/h	Transmission loss in dB
1.0	1.9	149.2
0.3	4.3	143.7
0.1	8.3	139.7
0.03	15.0	136.6
0.01	26.3	134.6
0.003	42.0	133.4
0.001	62.0	132.5

Table 4.2 Measured transmission loss for the Chilbolton-Baldock path at 11.2 GHz as a function of rain rate and percentage of time

and 2.1 km average rain height (Hm) is given in Table 4.2 as a function of rain rate and percentage of time.

The geometrical parameters in Table 4.1 were converted to the common Cartesian system used in the model-program. The transmitting antenna is chosen as the origin of the system, with the horizontal plane as the *x-y* plane, the *x* axis pointing in the direction of the receiver, and the z axis pointing vertically upward.

We now define an angle δ, subtended at the Earth's centre by the link length, r_{rt}, assuming an effective Earth radius of r_{eff} = 8500 km:

$$\delta = \frac{r_{rt}}{r_{eff}} \qquad rad \qquad 4.3$$

The Cartesian receiver angle is then calculated by:

$$\epsilon_{r1} = 90 - \theta_r = arcsin(cos\epsilon_r sin\delta + sin\epsilon_r cos\delta) \qquad 4.4$$

and the coordinates of the receiving antenna becomes

$$(x_r, y_r, z_r) = \left(r_{rt}, 0, h_r - h_t - r_{rt}\frac{\delta}{2}\right) \qquad 4.5$$

The converted input parameters for the model-program are given in Table 4.3:

4.2.2 Computed results

The results of the computations for this case are plotted in Figures 4.2.2(a,b,c,d,e) and 4.2.3(a,b,c). Figures 4.2.2(a,b,c,d,e) show the transmission loss versus rain rate for Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km, respectively. The transmission loss calculated for the following frequencies, f = 1.0, 5.0, 10.0, 20.0, 30.0 and 40.0 GHz is shown in each one of these figures. Also, we calculated the interference caused by a rain-only cell, and a rain cell with a melting-snow layer with ρ_s = 0.1, 0.2, 0.3 at each frequency.

Scattering	Kharadly scattering model
Attenuation	Kharadly 3rd attenuation model
Profile of the melting layer	S = h/H (linear)
(x_t, y_t, z_t) of the transmitter	(0, 0 , 0) in km
(θ_t, ϕ_t) of the transmitter	(70, 0) degrees
Polarization of the transmitter	0 degrees (vertical)
$\theta_{1/2}$ of the transmitter	0.00314 rad
(x_r, y_r, z_r) of the receiver	(131, 0, -1.0435) km
(θ_r, ϕ_r) of the receiver	(88.117, 180) degrees
$(\alpha_1, \alpha_2, \mathrm{K})$ of the receiver	(1.6, 4.5, -15)
rain cell height (H_c)	10.0 km
Gain of the transmitter	794328
Gain of the receiver	11220
(x_c, y_c, z_c) of the rain cell	(7.912,0,0) km
Frequency	1, 5, 10, 20, 30, 40 GHz
Rain rate	0.5-150 mm/h.
Hm	2.0, 2.5, 3.0, 3.5, 4.0 km
ρ_s	0.1, 0.2, 0.3

Table 4.3 The converted input parameters for the model-program

The centre of the common volume in this geometry is at 3 km from the ground level (Hm = 3.0 km). We notice that it is when the rain height is in the common volume that we get the maximum effect of the melting-snow layer. The layer increases the interference at the lower frequencies and decreases it for the higher frequencies.

At optimum rain height (Hm = 3 km) and at a frequency of f=1.0 GHz (Figure 4.2.2(c)), the interference enhancement caused by the melting layer for ρ_s = 0.1 is 2.0, 4.2, 7.0, 10.5 dB for rain rate of 1.0, 3.0, 10.0, 30.0 mm/h, respectively. The interference level decreases for ρ_s = 0.2 and ρ_s = 0.3. Nonetheless the enhancement remains significant at 1.5, 3.0, 5.0, 8.0 dB for ρ_s = 0.2 and 1.0, 2.0, 4.0, 6.5 dB for ρ_s = 0.3.

As the frequency is increased, we note that the effect of the melting-snow layer on the transmission loss decreases. The melting-snow layer enhancement decreases to 2.0, 4.0, 6.1, 7.5 dB, and 1.8, 3.0, 3.0, 0.0 dB for f = 5.0 and 10 GHz respectively. An interesting observation occurs when the frequency is increased further. The melting layer starts to degrade, instead of enhance, the interfering signal. For f = 20 GHz, the melting-snow layer causes a drop in the interfering signal by −2.0 and −7.5 dB for rain rate of 10.0 and 30.0 mm/h, respectively. This degradation becomes more pronounced at still higher frequencies. For ρ_s = 0.1, the degradation becomes 0.0, −0.8, −4.0, −12.0 dB for f = 30.0 GHz and −0.5, −1.9, −6.0, −18.0 dB for f = 40.0 GHz. Higher values of ρ_s tends decrease this gap but not by much. For ρ_s = 0.2, the gap becomes −0.5, −1.2, −4.8, −16.0 dB and for ρ_s = 0.3, the gap reduces to −0.5, −1.1, −4.0, −12.0 dB.

As the rain height moves out of the centre of the common volume, the enhancement due to the melting-snow layer declines considerably. At Hm = 2.5 or 3.5 km (Figure 4.2.2(b) and Figure 4.2.2(d), respectively), the effect of the melting layer is still considerable at 1.5, 2.75, 5.0, 7.5 dB for f = 1 and 1.2, 2.5, 4.5, 6.0 dB for f = 5 GHz and Hm =

3.5 km. The enhancement is slightly greater for Hm = 2.5 km. For Hm = 2.0 and 4.0 km (Figure 4.2.2(a) and Figure 4.2.2(e), respectively), the enhancement becomes very small. For Hm = 4.0 km, the enhancement becomes 0.8, 1.2, 2.2, 2.5 for f = 1.0 GHz and 0.5, 1.0, 2.0, 2.5 for f = 5 GHz. For Hm = 2.5 km, the enhancement is slightly greater.

Figures 4.2.3(a,b,c) shows the transmission loss versus rain rate for f = 1.0, 5.0, 10.0, 20.0, 30.0, 40.0 GHz and Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km for a rain-only cell. We observe that for f = 1.0, 5.0, 10.0 GHz, the interference increases with Hm. This is due to the higher reflectivity of rain compared to that in the ice/snow region. For f = 20 GHz, the interference starts to decrease as Hm is increased, in the high rain rate region. For higher frequencies this phenomenon becomes more severe and the interference at Hm = 2.0 is 68.5 dB higher than the interference at Hm = 4.0 for rain rate of 100 mm/h and f = 40.0 GHz (Figure 4.2.3(c)). This leads us to conclude that at higher frequencies and rain rates, the effect of the ice/snow region in the rain cell is more significant than that of rain despite its lower reflectivity.

Even though an exact comparison between the measured transmission loss (Table 4.2) and our calculations is not possible because of frequency difference and because, in reality, Hm acts as a random variable rather than the deterministic values we assume, we observe that the experimental transmission loss adjusted for atmospheric attenuation (discrete data in Figure 4.2.2(a)) agrees well with our calculations for f = 10.0 GHz (Figure 4.2.2(a)).

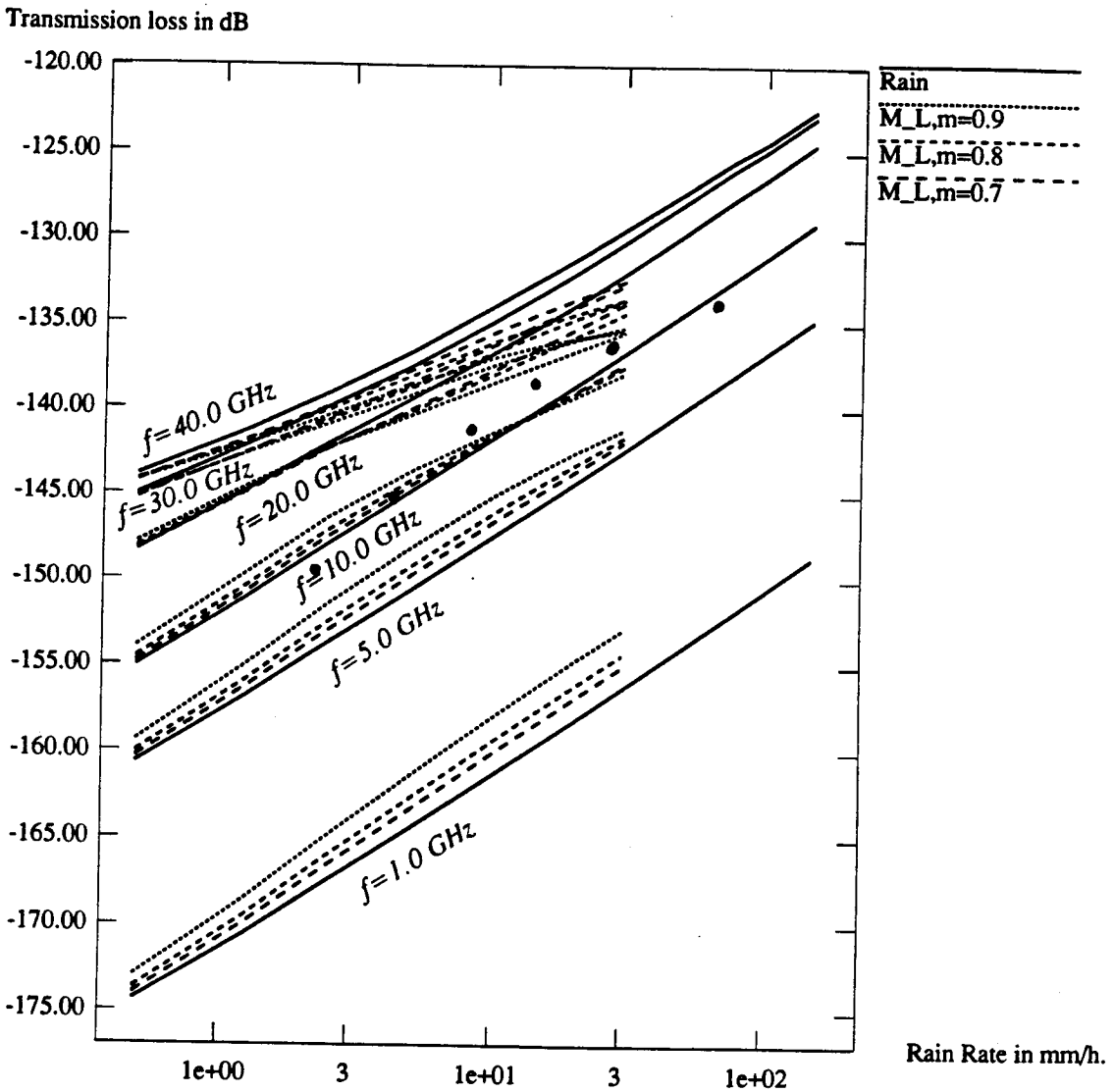

Figure 4.2.2(a) Interference versus rain rate for various frequencies (f in GHz), ρ_s (m = $1-\rho_s$), and for Hm = 2.0 km.

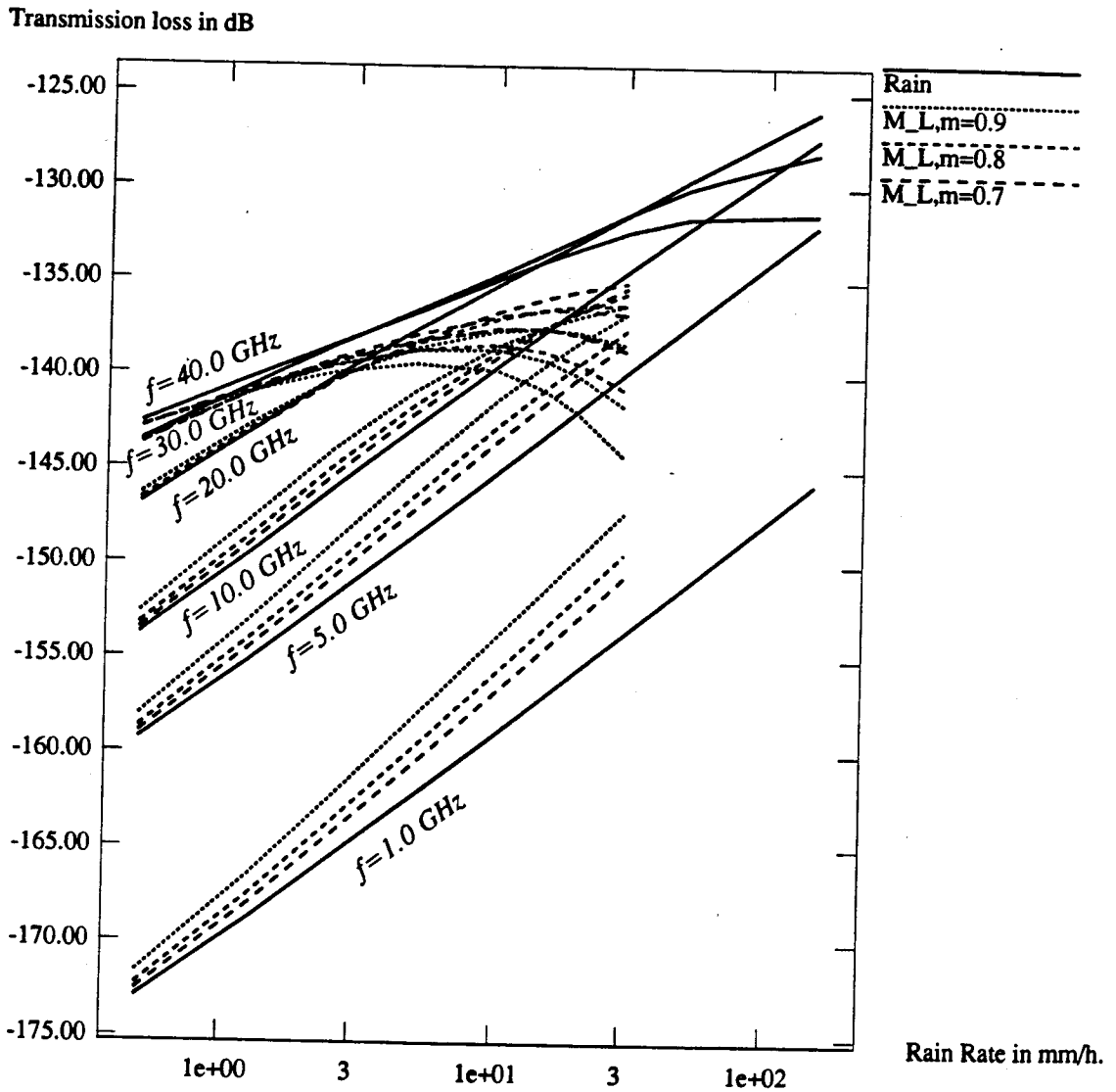

Figure 4.2.2(b) Same as Figure 4.2.2(a), with Hm = 2.5 km.

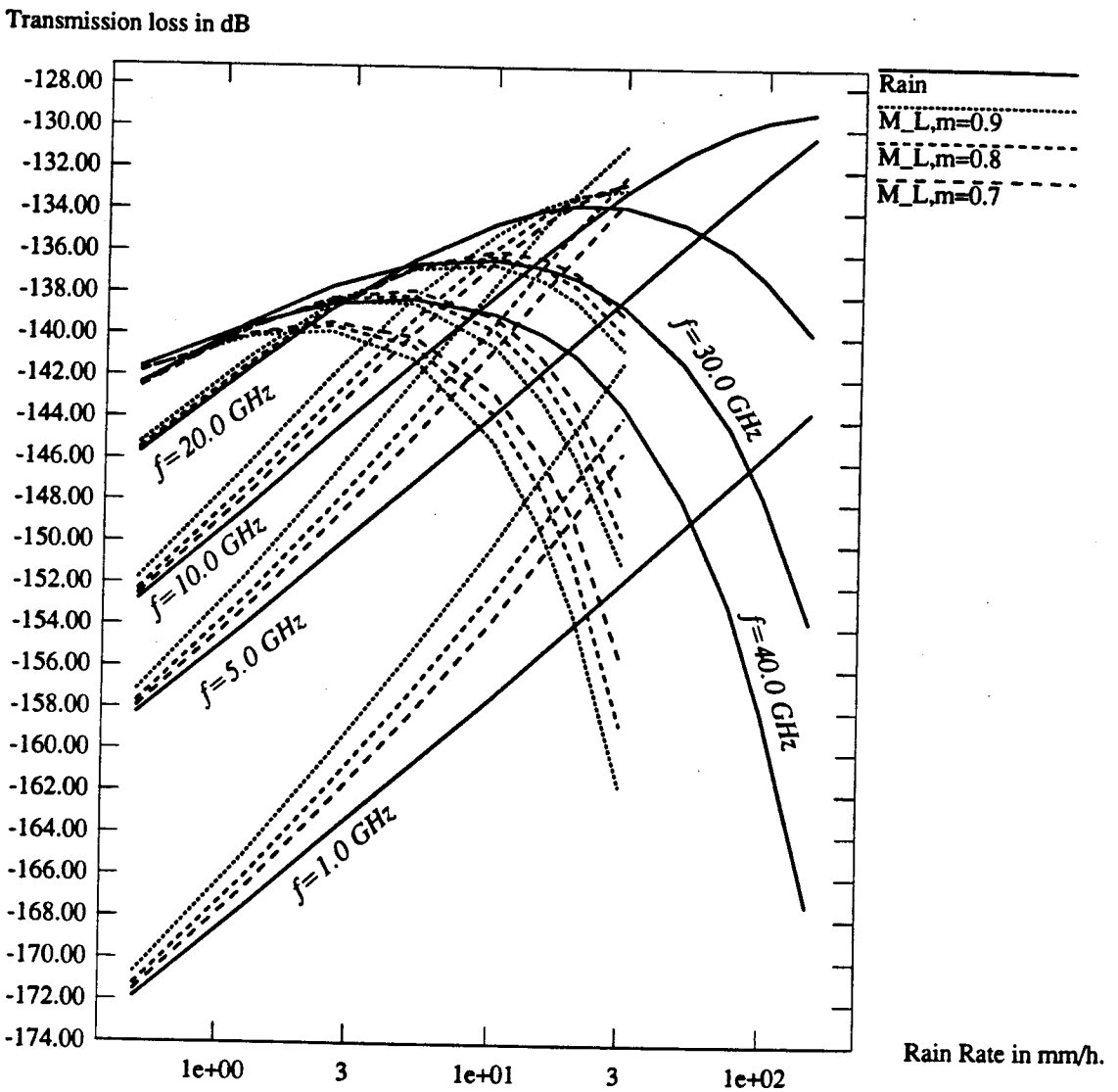

Figure 4.2.2(c) Same as Figure 4.2.2(a), with Hm = 3.0 km.

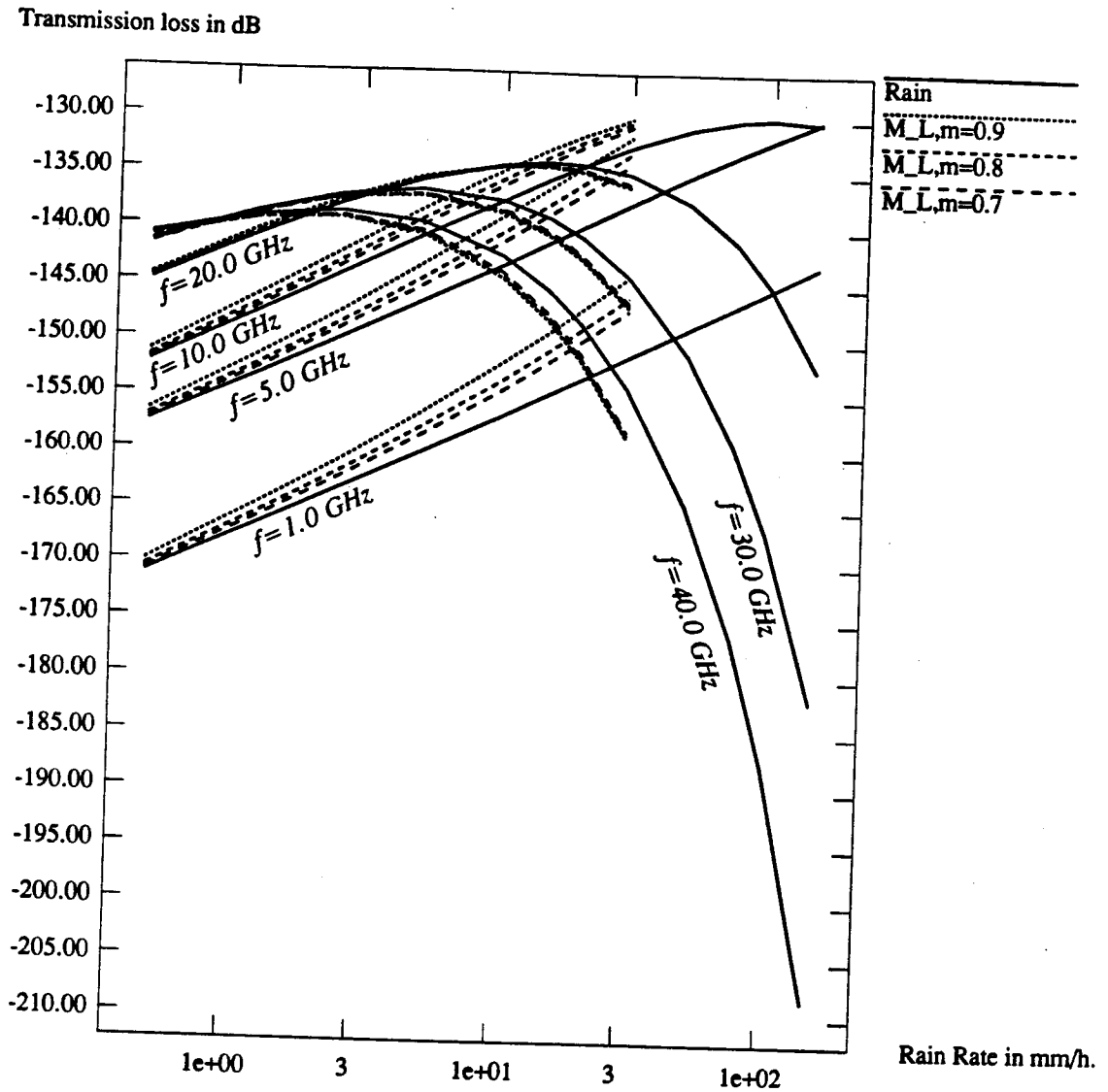

Figure 4.2.2(d) Same as Figure 4.2.2(a), with Hm = 3.5 km.

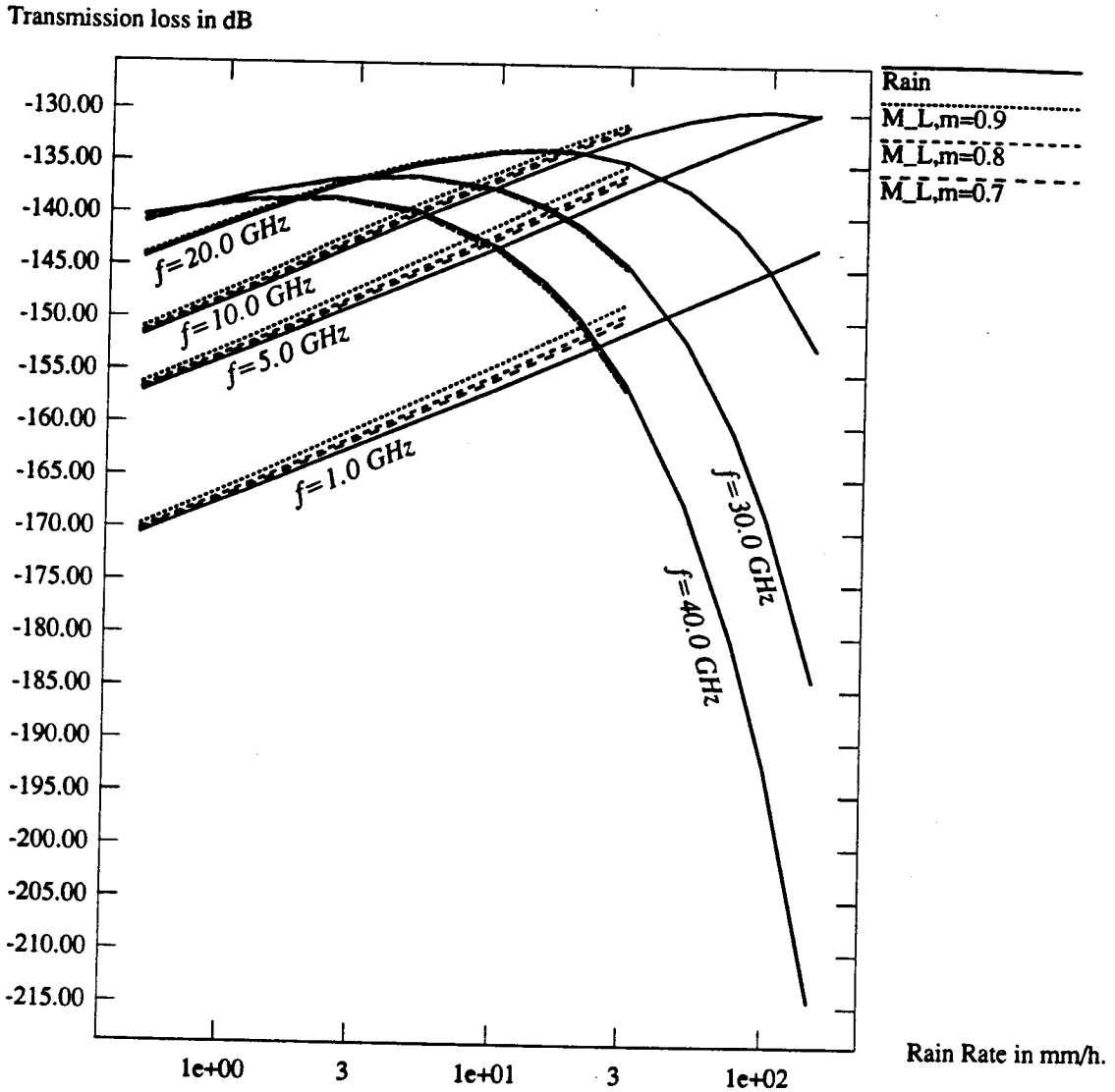

Figure 4.2.2(e) Same as Figure 4.2.2(a), with Hm = 4.0 km.

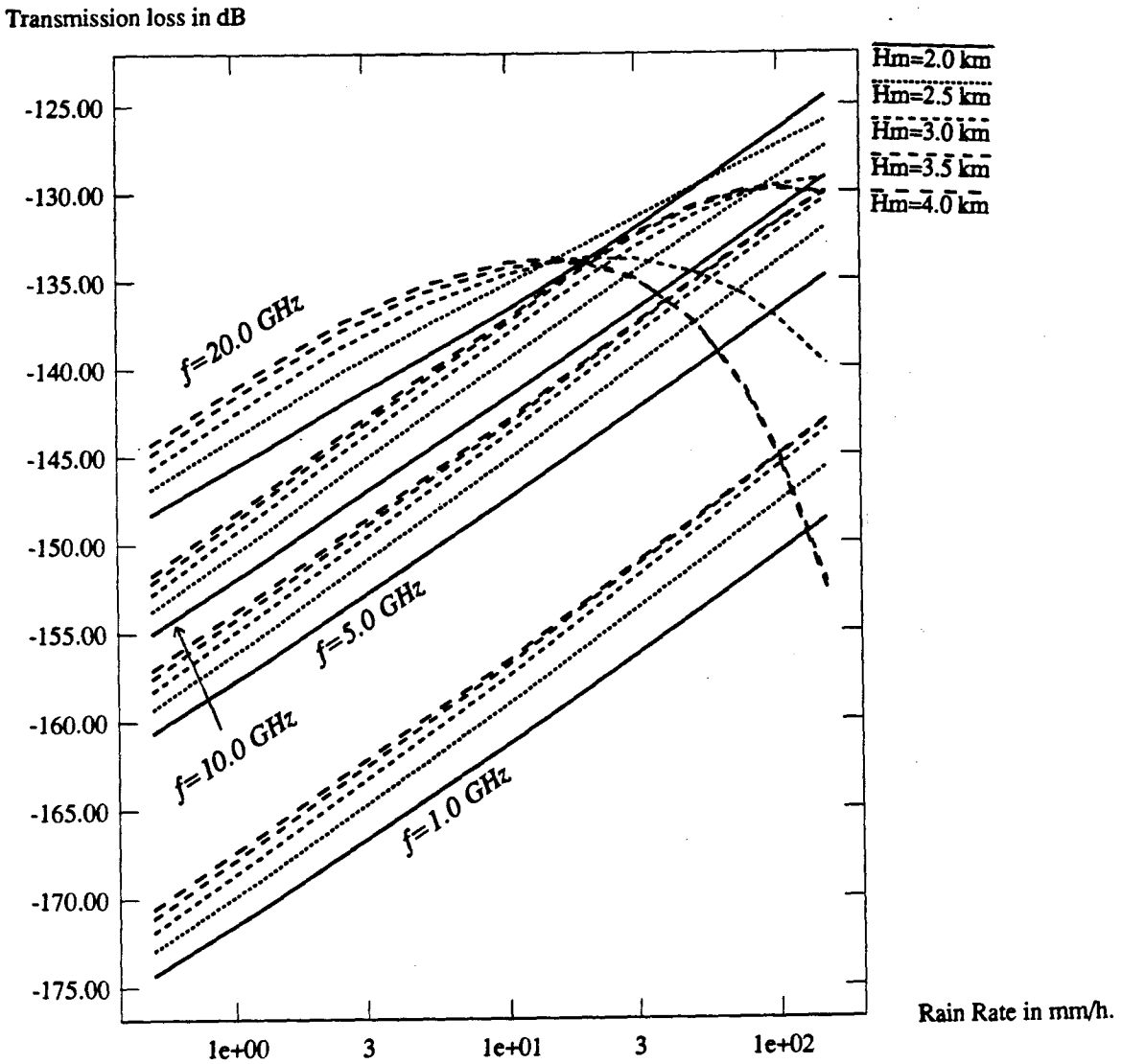

Figure 4.2.3(a) Interference versus rain rate for various rain heights (Hm), and for f (frequency) = 1, 5, 10, 20GHz.

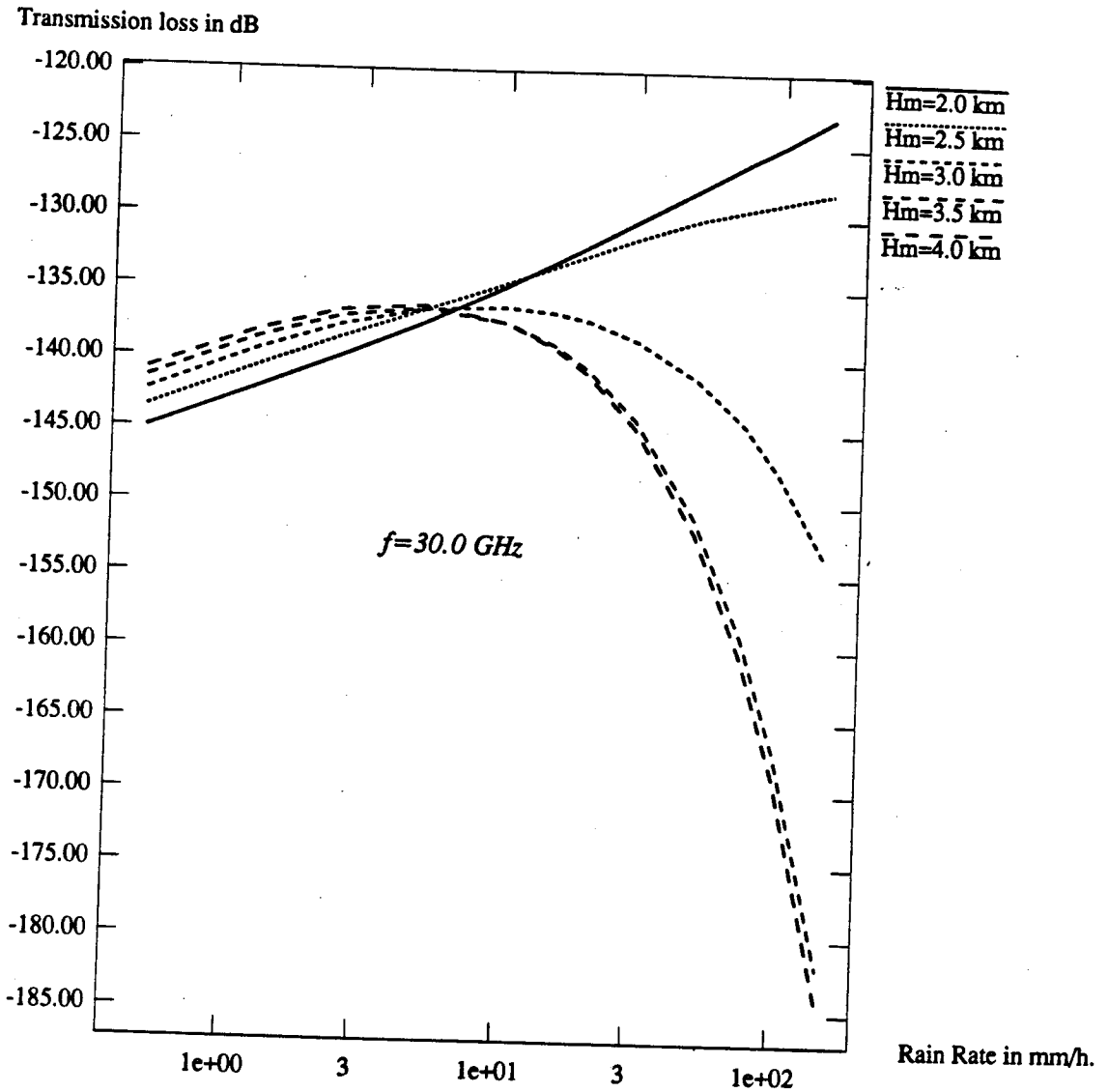

Figure 4.2.3(b) Same as Figure 4.2.3(a), with f = 30 GHz.

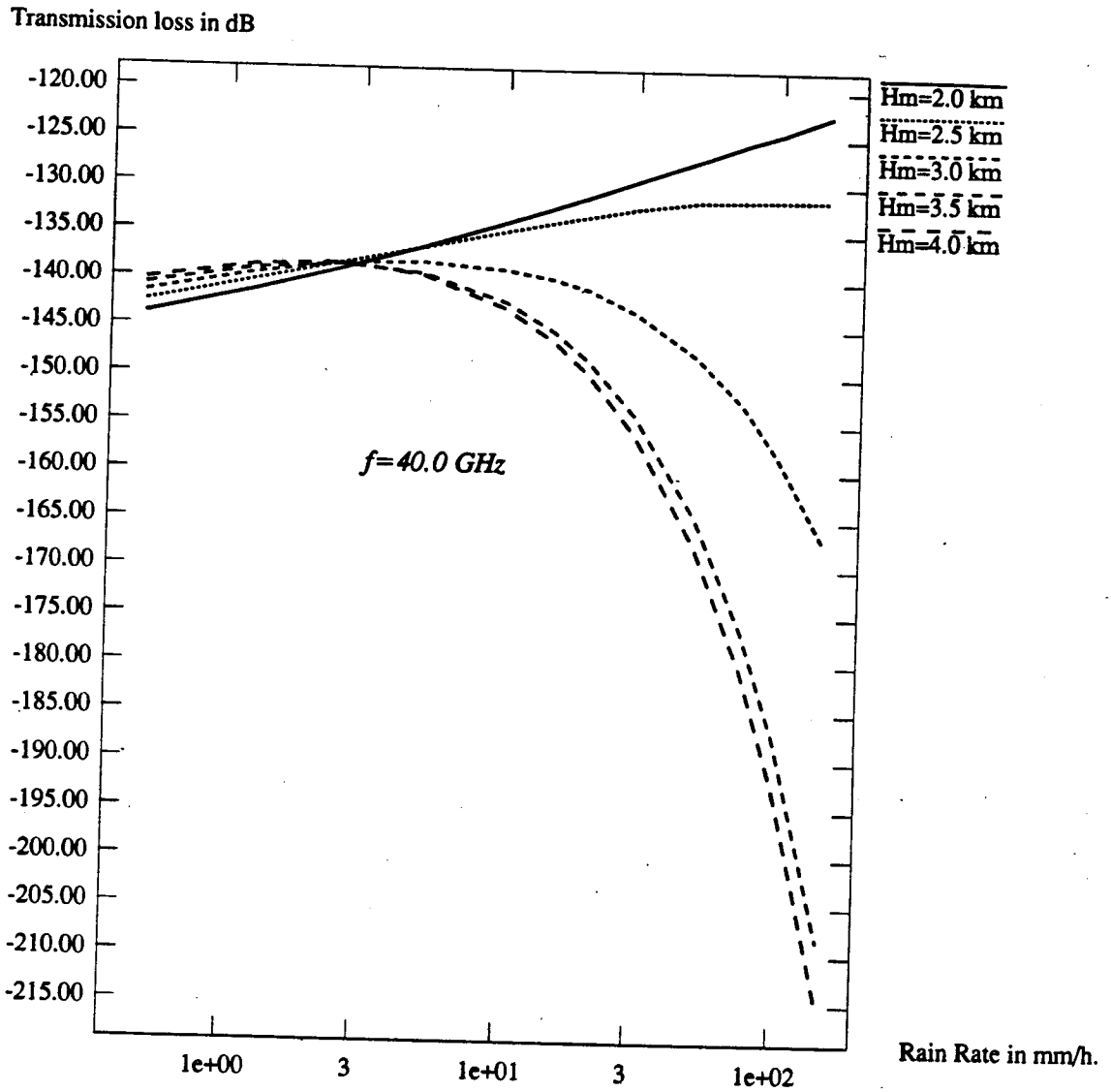

Figure 4.2.3(c) Same as Figure 4.2.3(a), with f = 40 GHz.

4.3 Interference from up-link to terrestrial links in the near-backward direction

4.3.1 Description

The geometry of the interference is close to that of the near-forward scattering (Figure 4.3.1). The only difference is that the receiving antenna is 180 degrees from the previous case but maintaining the same distance to the common volume. The common volume remains 3km high.

4.3.2 Computed results

The results of the computations in this example are given in figures 4.4.2(a,b,c,d,e) and 4.4.3(a,b,c). Figures 4.4.2(a,b,c,d,e) show the transmission loss versus rain rate for Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km, respectively. The transmission loss calculated for the following frequencies, f = 1.0, 5.0, 10.0, 20.0, 30.0 and 40.0 GHz is shown in each of these figures. Also, we calculated the interference caused by a rain-only cell, and a rain cell with a melting-snow layer with ρ_s = 0.1, 0.2, 0.3 at each frequency.

The maximum effect of the melting snow layer occurs when Hm = 3.0 km (Figure 4.3.2(c)). For f = 1.0 GHz, the interference enhancement caused by the melting snow layer for ρ_s = 0.1 is 1.8, 3.0, 6.0, 9.0 dB for rain rate of 1.0, 3.0, 10.0, 30.0 mm/h, respectively. This interference decreases for ρ_s = 0.2 and ρ_s = 0.3. Nonetheless the enhancement remains considerable. The values of the interference enhancement calculated in this case are slightly lower than those calculated in the near-forward direction.

As we increase the frequency, the melting layer enhancement decreases to 1.5, 2.5, 5.25, 6.0 dB and 1.1, 2.1, 2.5, 0.8 dB for f = 5.0 and f = 10 GHz respectively. At higher frequencies (f = 20.0, 30.0, 40.0 GHz) the melting snow layer degrades the interference signal. For ρ_s = 0.1, the degradation becomes −0.4, −1.0, −2.5, −4.0 for f = 30 GHz

(Graph not to scale)

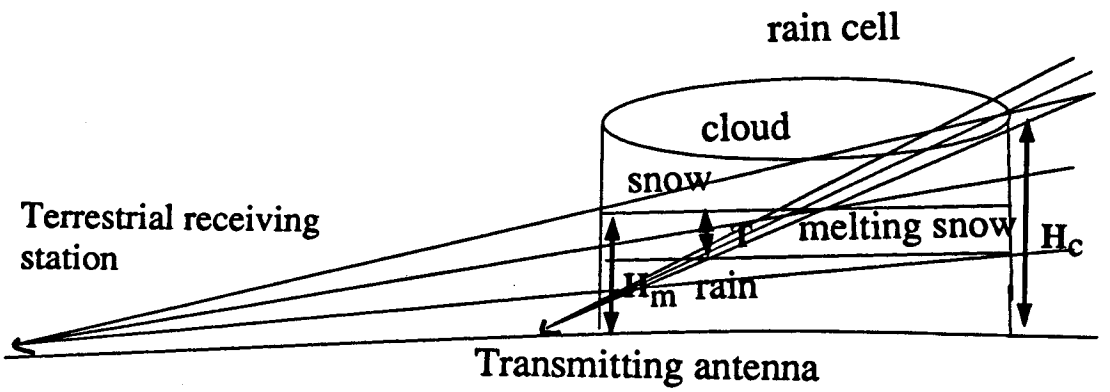

Figure 4.3.1 Interference from up-link to terrestrial link geometry in the near backward direction.

and−0.5, −1.5, −2.5, −1.75 for f = 40.0 GHz. Higher ρ_s values help reduce the gap. This reduction is significantly lower than the one experienced in the previous example.

As Hm moves away from the centre of the common volume, the effect of the melting-snow layer decreases. At Hm = 3.5 km (Figure 4.3.2(d)), the effect of the melting layer is still considerable at 1.2, 2.5, 4.0, 6.25 dB for f = 1.0 and 1.0, 2.0, 3.0, 3.7 dB for f = 5 GHz. The enhancement is slightly greater for Hm = 2.5 km (Figure 4.3.2(b)). This greater enhancement is due to the closer proximity of the melting snow layer to the centre of the common volume. Again the interference enhancement is slightly less than the previous example. For Hm = 2.0, and Hm = 4.0 the interference enhancement decreases significantly. For Hm = 4.0 km, the enhancement becomes 0.8, 1.4, 2.0, 2.5 dB for f = 1.0 GHz and 0.5, 1.0, 1.3, 1.5 dB for f = 5.0 GHz. For Hm = 2.0 km, the enhancement is slightly greater.

Figures 4.3.3(a,b,c) show the transmission loss versus rain rate for f = 1.0, 5.0, 10.0, 30.0, 40.0 GHz and Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km for a rain-only cell. We observe that for f = 1.0, 5.0, 10.0 GHz, the interference increases with Hm at the lower frequencies. This is also true for the higher frequencies coupled with low rain rate. However, the interference drops considerably with high rain rates as Hm increases. For rain rate of 100 mm/h and f = 40 GHz (Figure 4.3.3(c)), the interference for Hm = 2 km is 14.5 dB higher than that for Hm = 4.0 km. We also observe that the reduction of the interference signal is much less than in the previous example.

Comparing the current results with those in the near-forward case, we observe that the two are comparable for lower frequencies and rain rates. For a combination of higher frequency and high rain rate, the difference between the two is very large to be accounted for by scattering properties alone. This difference can only be due to different attenuation paths for the transmitted and scattered waves between both cases.

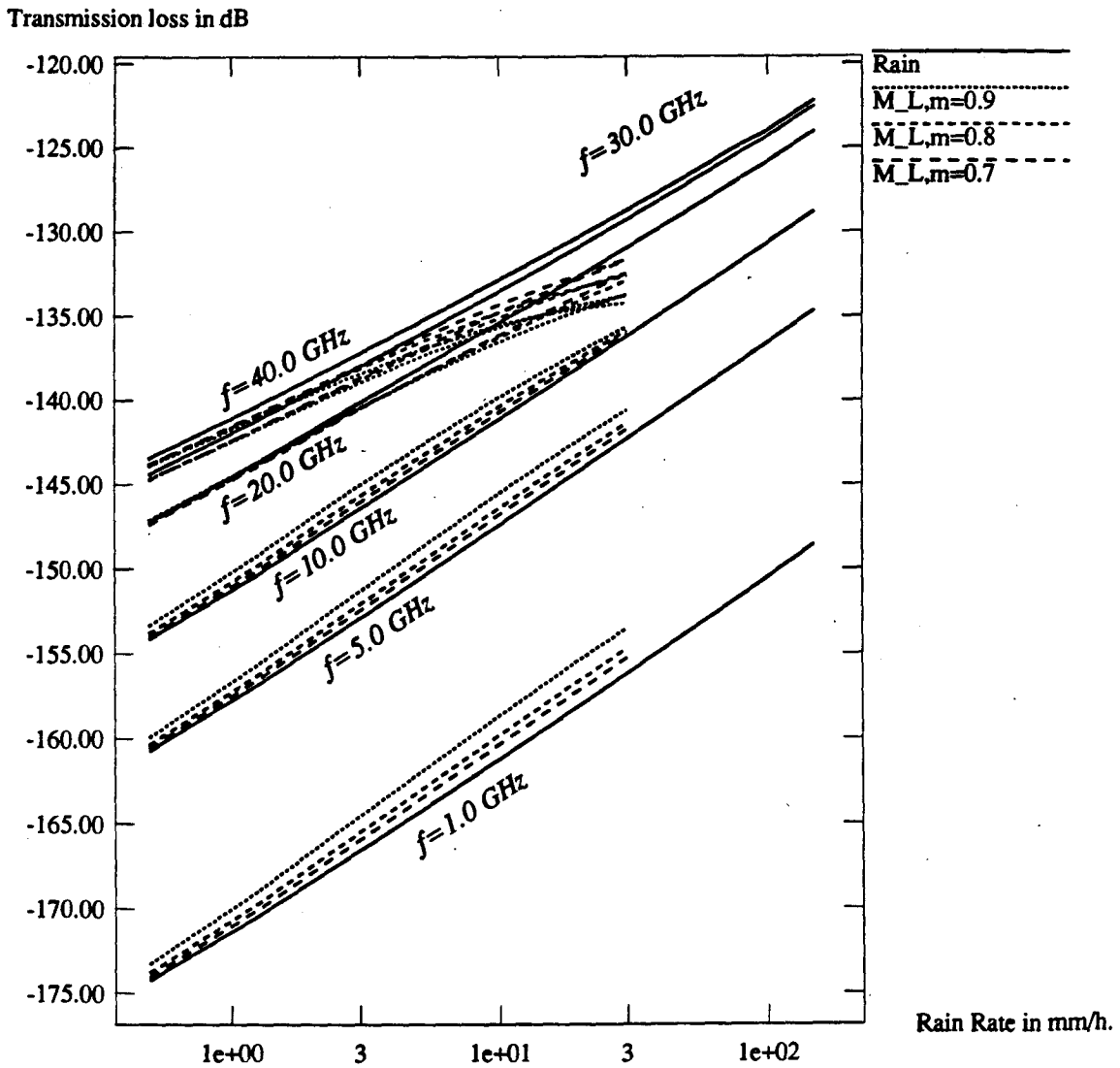

Figure 4.3.2(a) Interference versus rain rate for various frequencies (f in GHz), ρ_s (m = $1-\rho_s$), and for Hm = 2.0 km.

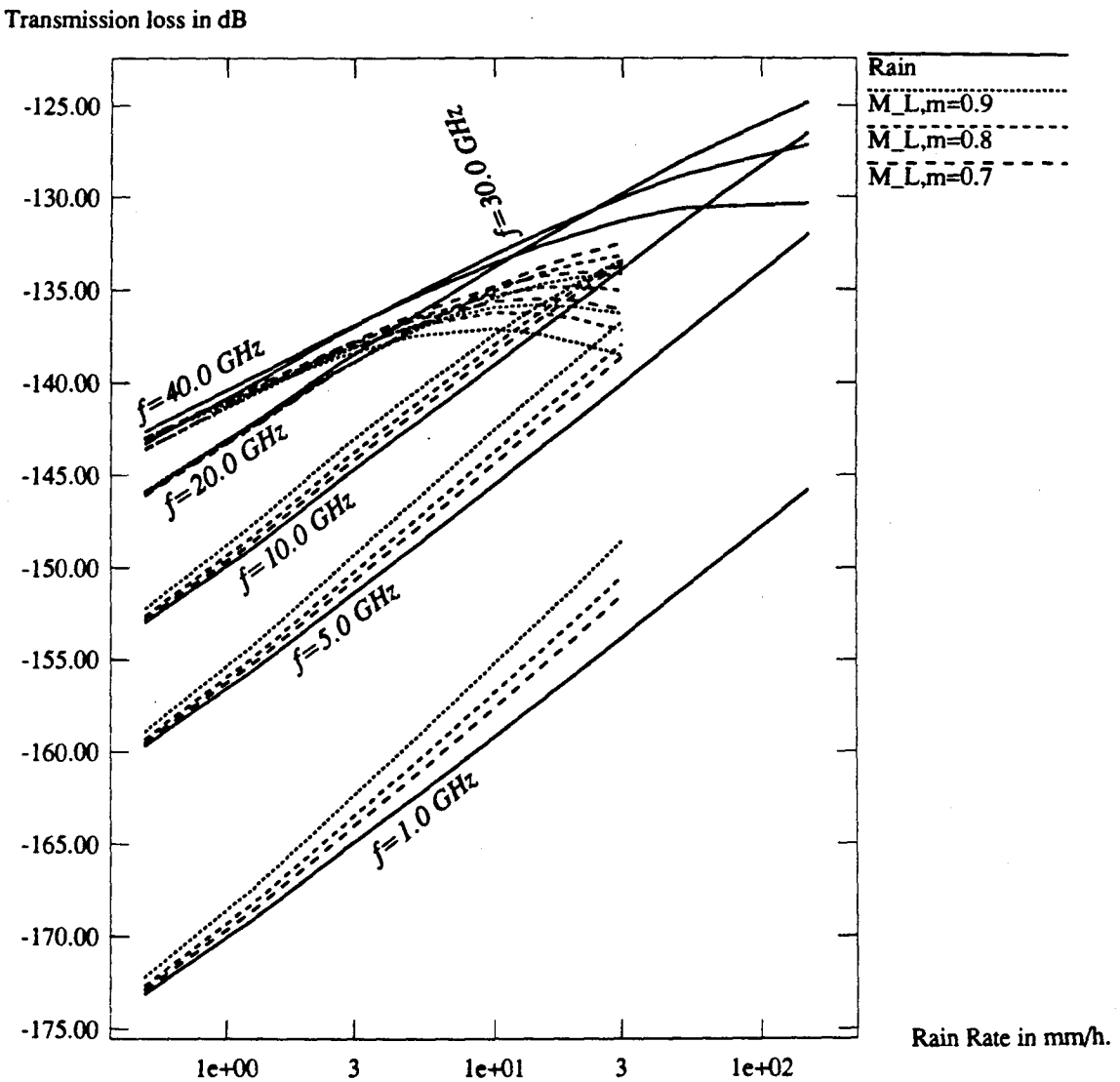

Figure 4.3.2(b) Same as Figure 4.3.2(a), with Hm = 2.5 km.

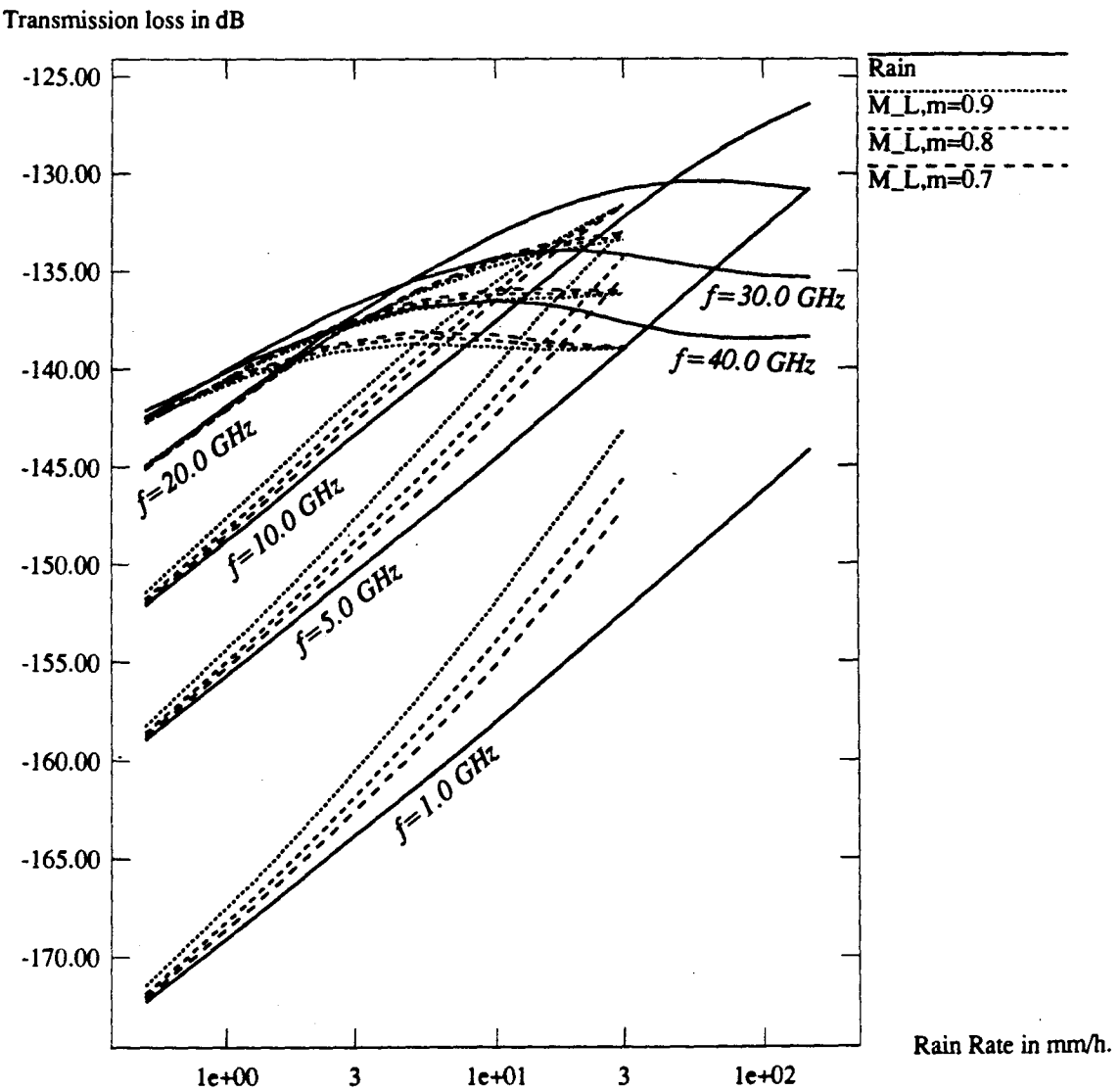

Figure 4.3.2(c) Same as Figure 4.3.2(a), with Hm = 3.0 km.

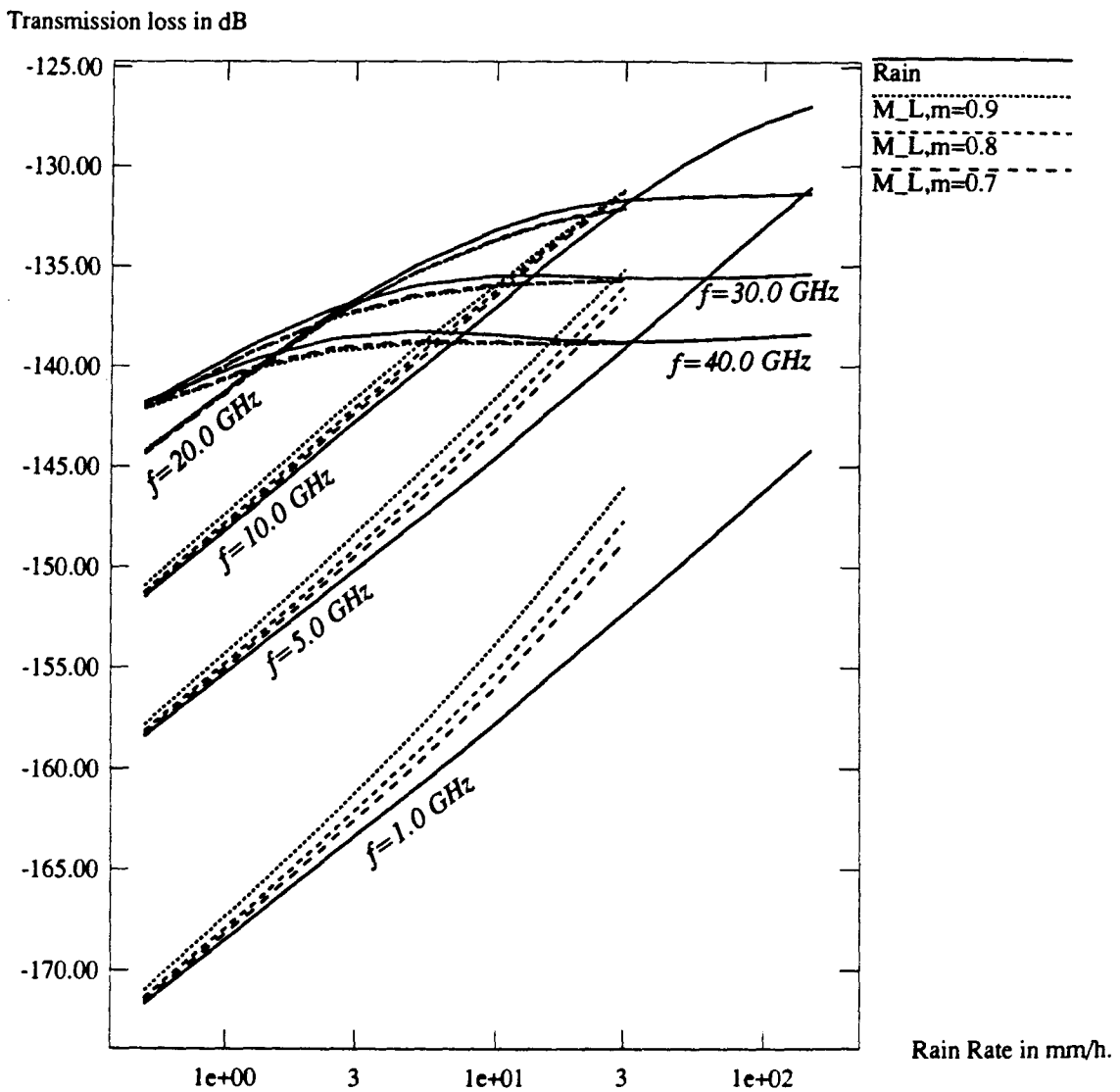

Figure 4.3.2(d) Same as Figure 4.3.2(a), with Hm = 3.5 km.

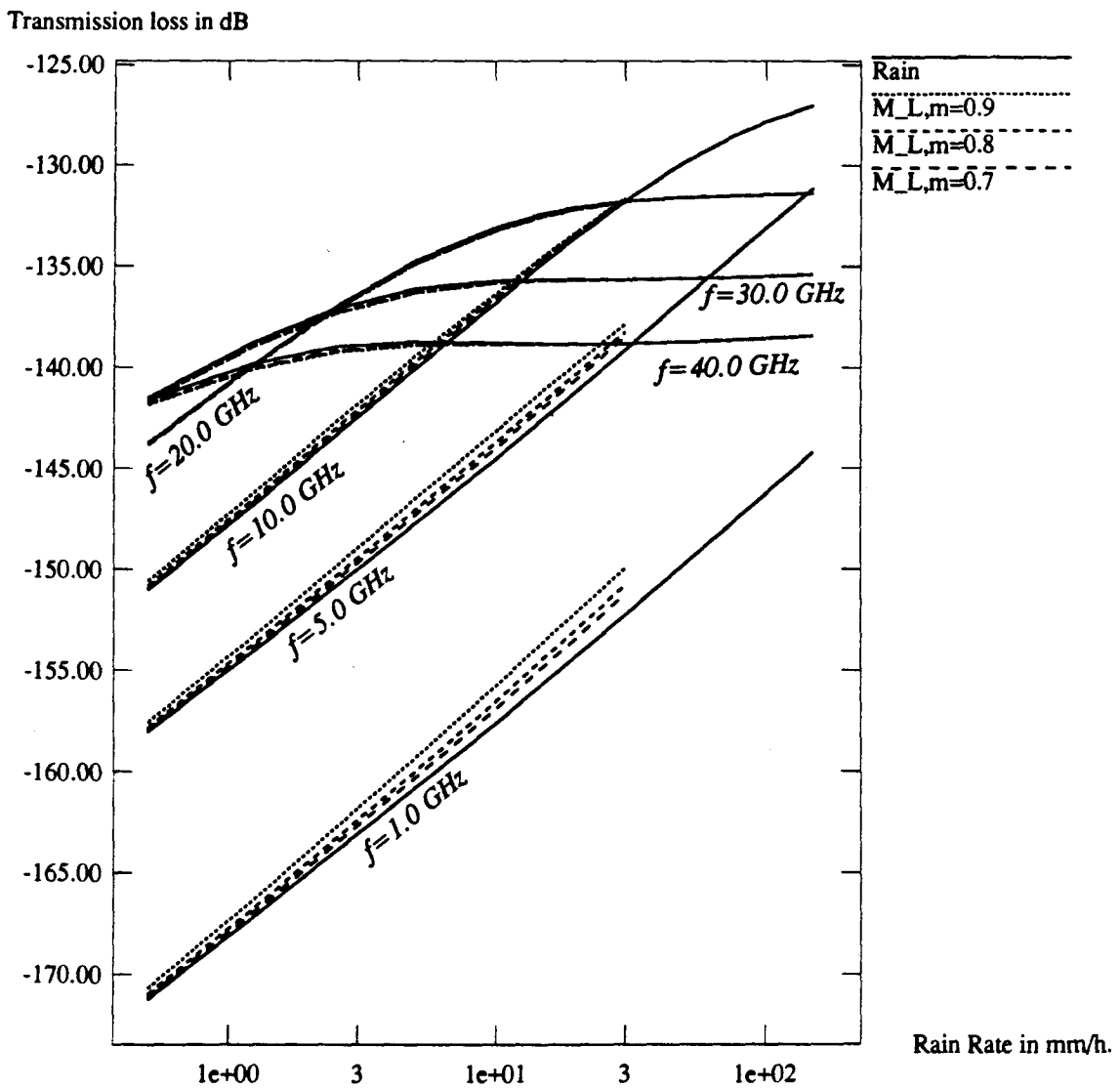

Figure 4.3.2(e) Same as Figure 4.3.2(a), with Hm = 4.0 km.

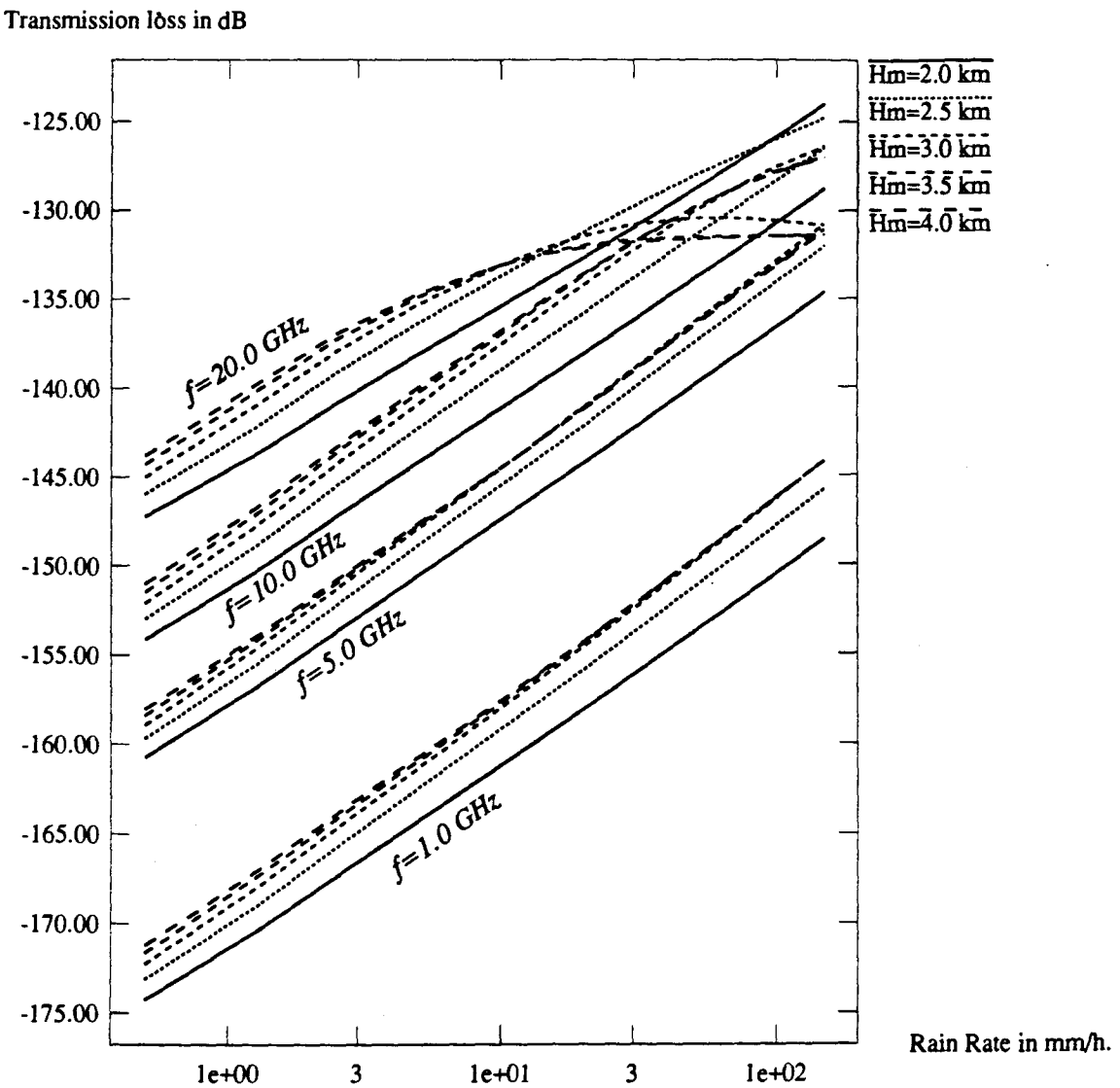

Figure 4.3.3(a) Interference versus rain rate for various rain heights (Hm), and for f (frequency) = 1, 5, 10, 20GHz.

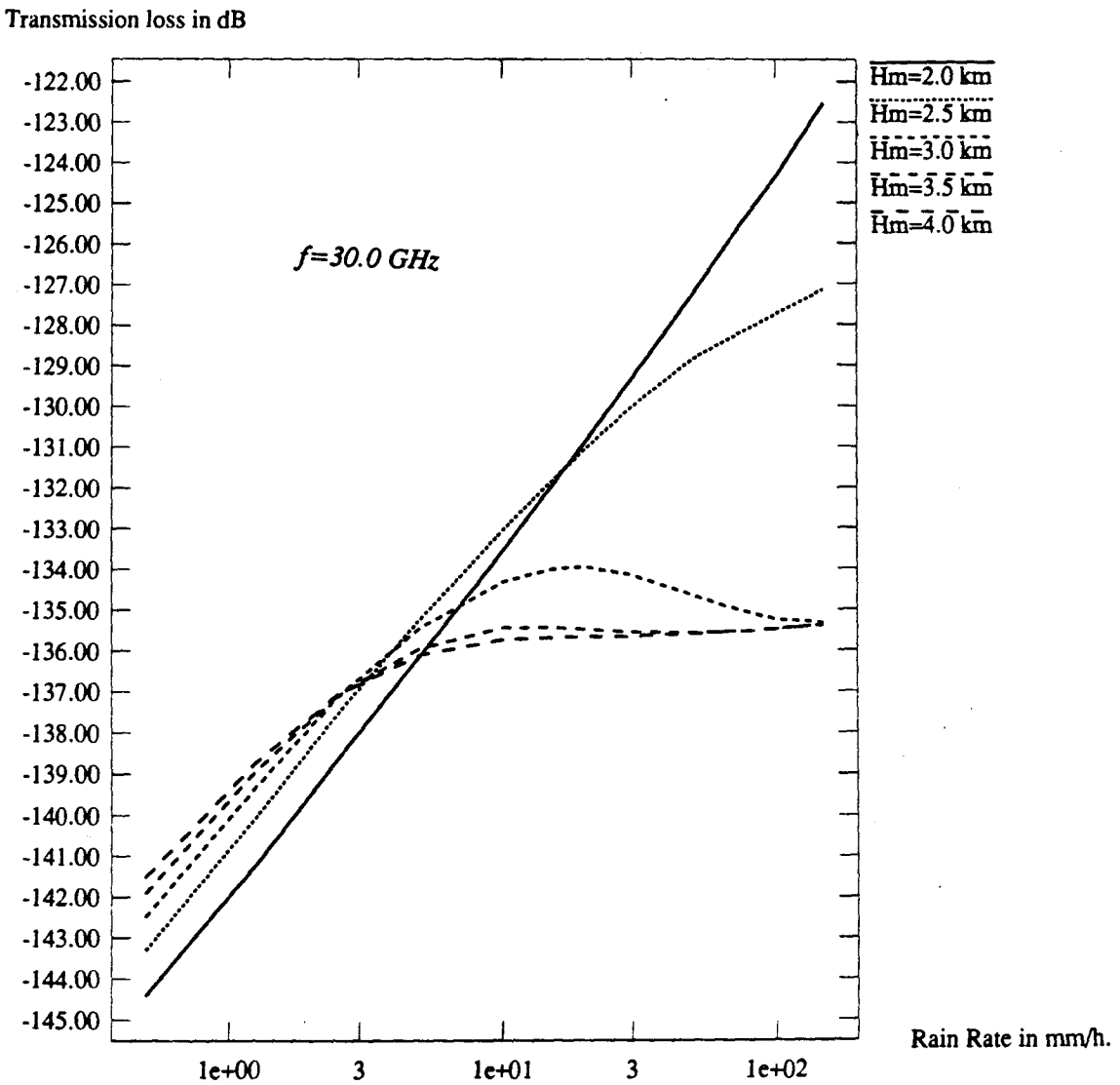

Figure 4.3.3(b) Same as Figure 4.3.3(a), with f = 30 GHz.

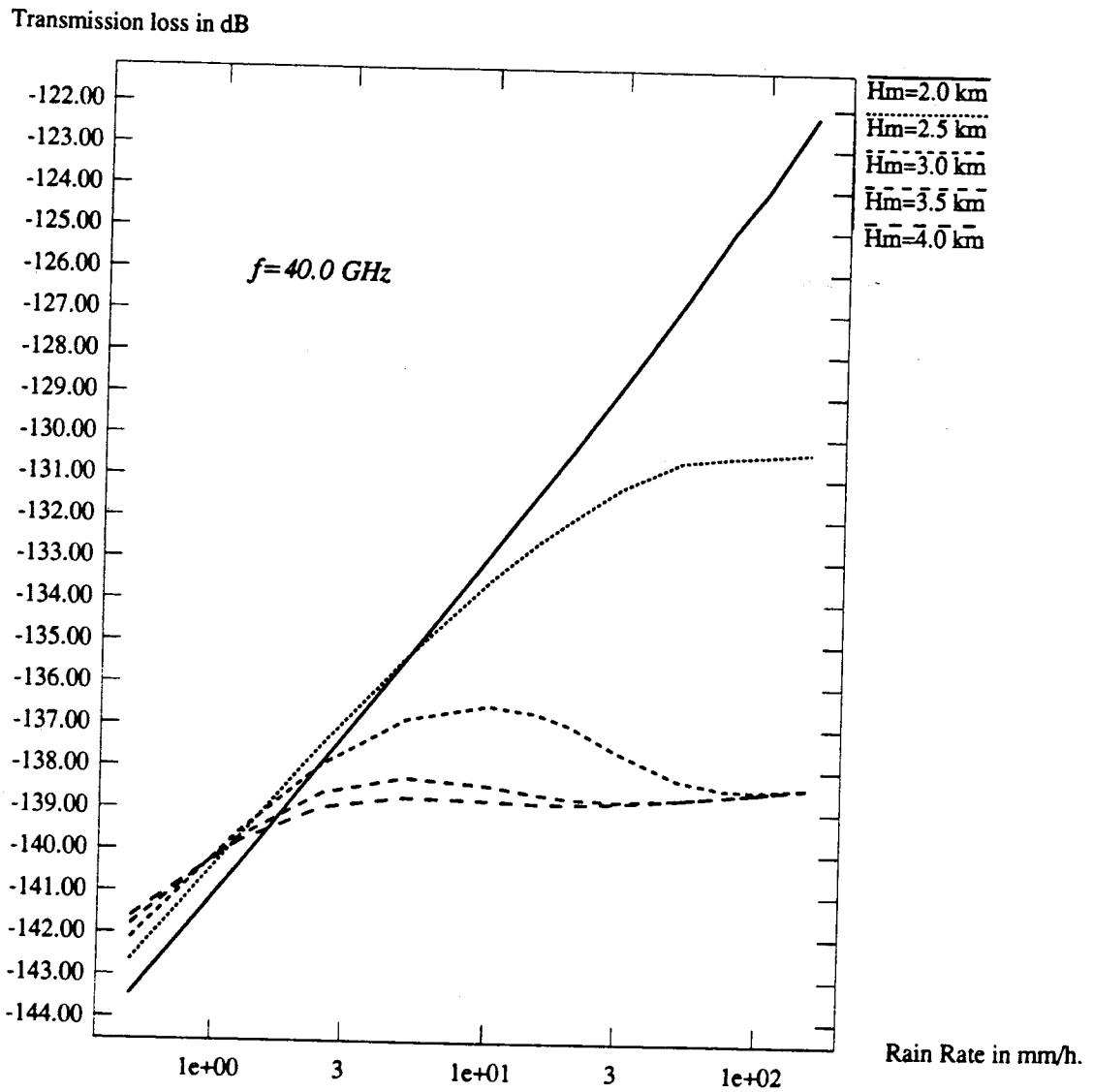

Figure 4.3.3(c) Same as Figure 4.3.3(a), with f = 40 GHz.

4.4 Interference from up-link to satellite in the forward direction

4.4.1 Description

The geometry of the interference is shown in Figure 4.4.1. A radio-wave transmitted by an up-link toward a satellite is scattered by rainfall. The scattered electromagnetic wave interferes with another nearby satellite operating at the same frequency.

The parameter used in these calculations are listed in Table 4.4. The geometrical parameters are given in Cartesian coordinates .

Scattering	Kharadly's scattering model
Attenuation	Kharadly 3rd attenuation model
Profile of the melting layer	S = h/H (linear)
(x_t, y_t, z_t) of the transmitter	(0, 0 , 0) in km
(θ_t, ϕ_t) of the transmitter	(70, 0) degrees
Polarization of the transmitter	0 degrees (vertical)
$\theta_{1/2}$ of the transmitter	0.00314 rad
(x_r, y_r, z_r) of the receiver	(3291, 0, 1900) km
(θ_r, ϕ_r) of the receiver	(110, 180) degrees
$(\alpha_1, \alpha_2, \mathrm{K})$ of the receiver	(3.0, 7.5, -10)
rain cell height (H_c)	10.0 km
Gain of the transmitter	794328
Gain of the receiver	5011.87
(x_c, y_c, z_c) of the rain cell	(7.912,0,0) km
Frequency	1, 5, 10, 20, 30, 40 GHz
Rain rate	0.5-150 mm/h.
Hm	2.0, 2.5, 3.0, 3.5, 4.0 km
m $(m = 1 - \rho_s)$	0.9, 0.8, 0.7

Table 4.4 Parameters used for the interference calculations from up-link to satellite

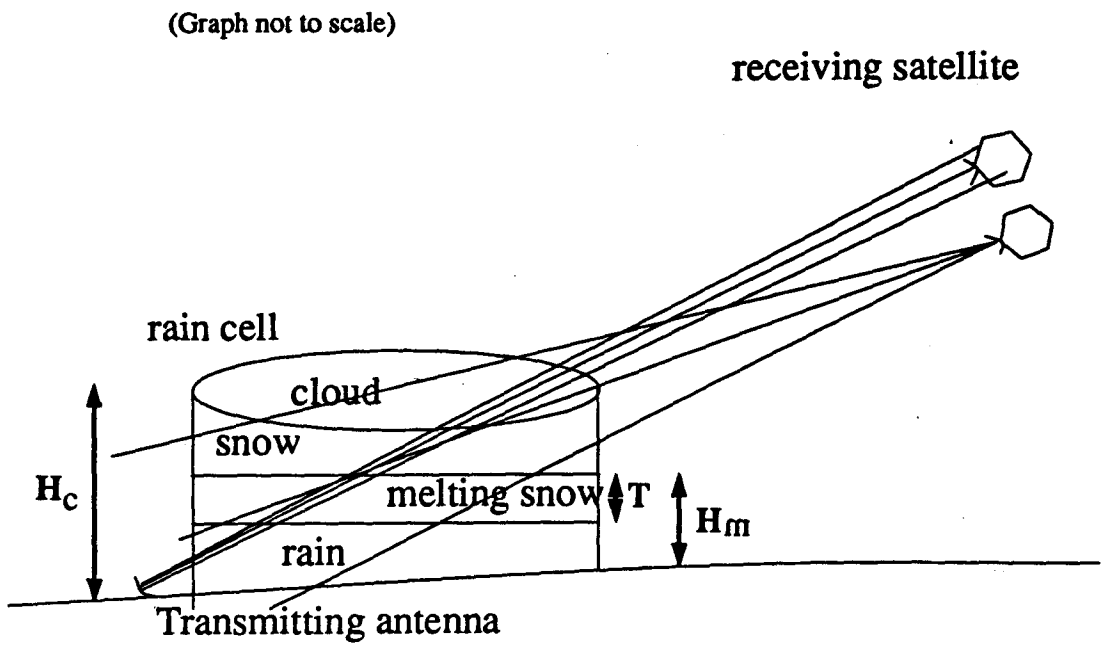

Figure 4.4.1 Interference from up-link to satellite geometry in the forward direction.

4.4.2 Computation results

The results of the computations in this example are given in figures 4.4.2(a,b,c,d,e) and 4.4.3(a,b,c). Figures 4.4.2(a,b,c,d,e) show the transmission loss versus rain rate for Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km respectively. The transmission loss calculated for the following frequencies, f = 1.0, 5.0, 10.0, 20.0, 30.0 and 40.0 GHz is shown in each one of these figures. Also, we calculated the interference caused by a rain-only cell, and a rain cell with a melting snow layer with ρ_s = 0.1, 0.2, 0.3 at each frequency.

In this case, it is noticed that for f = 1, 5, 10 GHz, the enhancement caused by the melting layer is not only significant but it remains strong for a wide range of Hm. With a rain rate of 30 mm/h and frequency of 5.0 GHz the enhancement is 4.0, 6.0, 8.8, 8.0, 3.75 dB for Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km, respectively (Figures 4.4.2(a), (b), (c), (d) and (e), respectively). The interference level is also significant at 10.0 GHz where, for 30 mm/h, the enhancement becomes 3.0 ,4.0 ,5.0 ,3.7, 1.2 dB. At higher frequencies, we observe that the melting layer tends to reduce the interference signal for higher rain rates. This reduction increases with frequency, rain rate and Hm. For a rain rate of 30.0 mm/h and a frequency of 40.0 GHz, the interference signal is reduced by 4.0, 6.0, 6.2, 7.5, 8.0 dB for Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km, respectively. We again observe that ρ_s plays an important role in enhancing or reducing the interference level.

Figures 4.4.3(a,b,c) show the transmission loss versus rain rate for f = 1.0, 5.0, 10.0, 20.0, 30.0, 40.0 GHz and Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km for a rain-only cell. It is observed that at the lower frequencies (f = 1, 5, 10 GHz), the interference increases with higher Hm. At the higher frequencies, the same is true for low rain rates, but for high rain rates, the interference decreases sharply for higher values of Hm. For a rain rate of 100 mm/h and a frequency of 40.0 GHz, the interference for Hm = 2.0 km is 36 dB

higher than that for Hm = 4.0 km (Figure 4.4.3(c)).

4.5 Summary

The above three examples show that the melting-snow layer significantly affects the transmission loss. The maximum effect occurs when the melting-snow layer exists in the common volume. But even outside the common volume, we noticed that the melting layer did exert considerable influence. We observed also that the melting layer tends to increase the interference level at the lower frequencies and decrease it for higher frequencies.

We also observed that the ice/snow region significantly contributes to the interference level at the higher frequencies. The attenuation by rain and melting-snow at high frequencies degrades the scattered signal, thus considerably reducing the interference level from rain and melting-snow. The scattered wave from the ice/snow region does not suffer from attenuation (except if the scattered wave intersects the melting layer or rain. This is limited to the lower parts of the ice/snow region) and thus contributes significantly to the interference level.

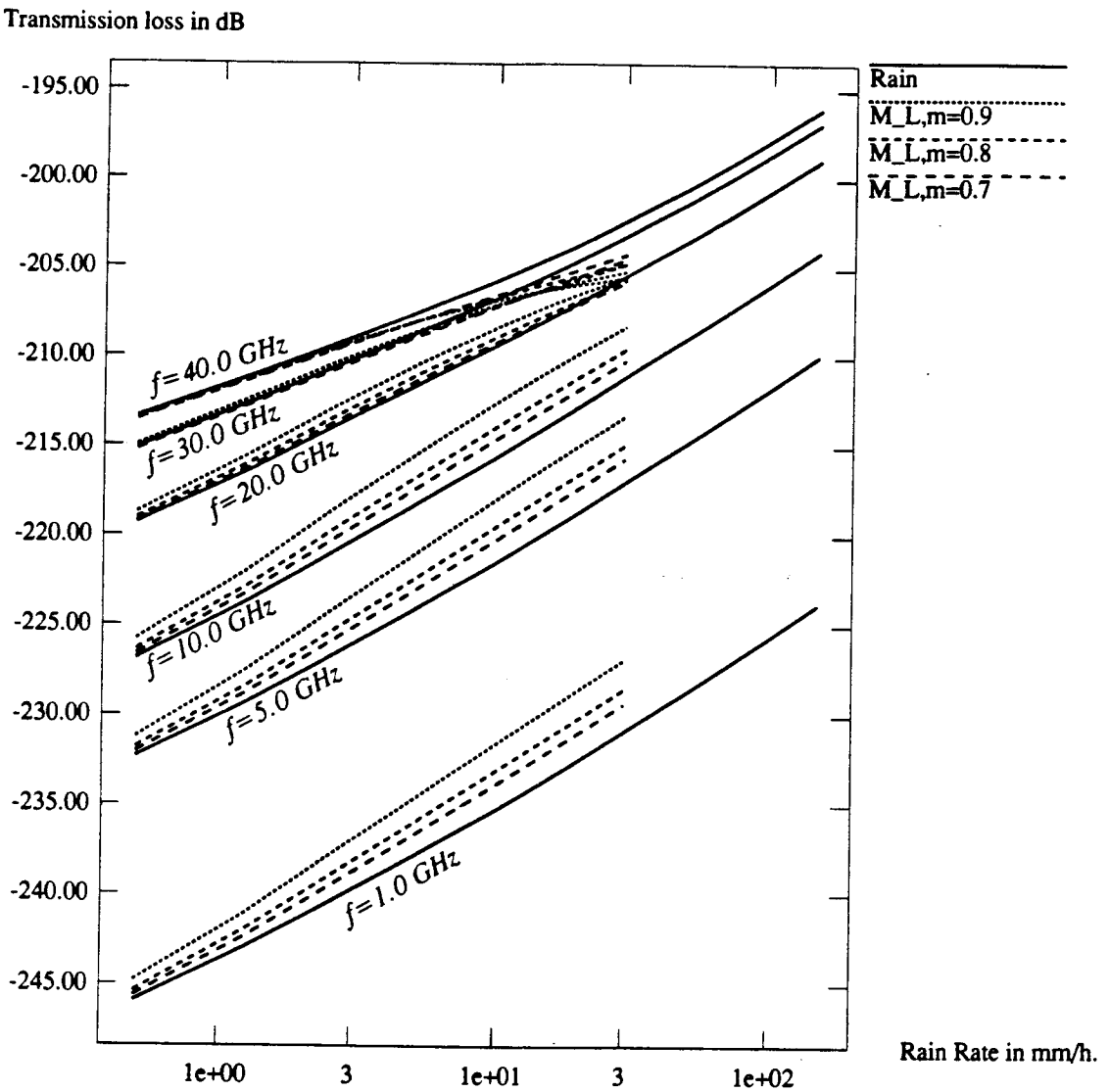

Figure 4.4.2(a) Interference versus rain rate for various frequencies (f in GHz), ρ_s (m = $1-\rho_s$), and for Hm = 2.0 km.

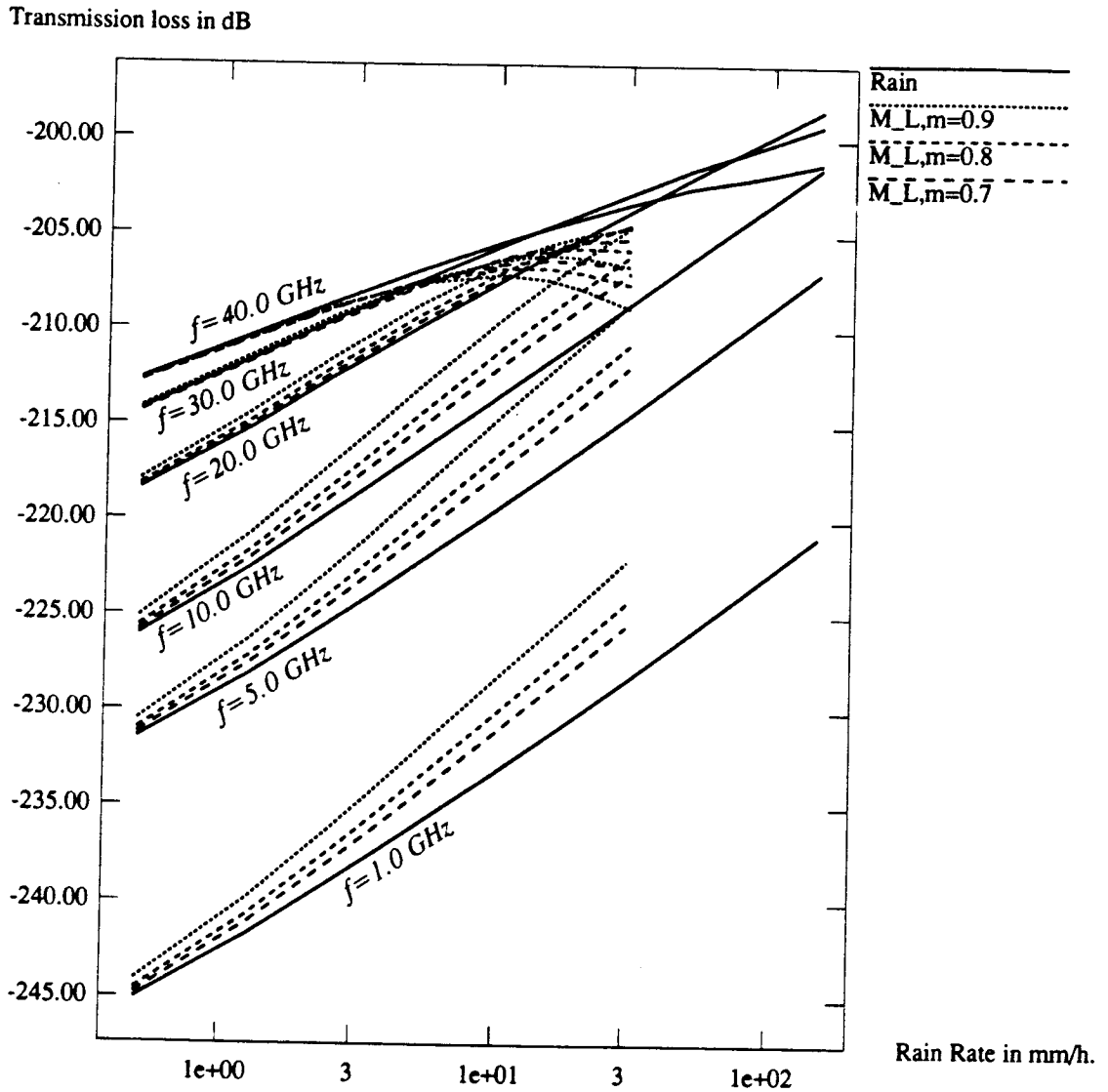

Figure 4.4.2(b) Same as Figure 4.4.2(a), with Hm = 2.5 km.

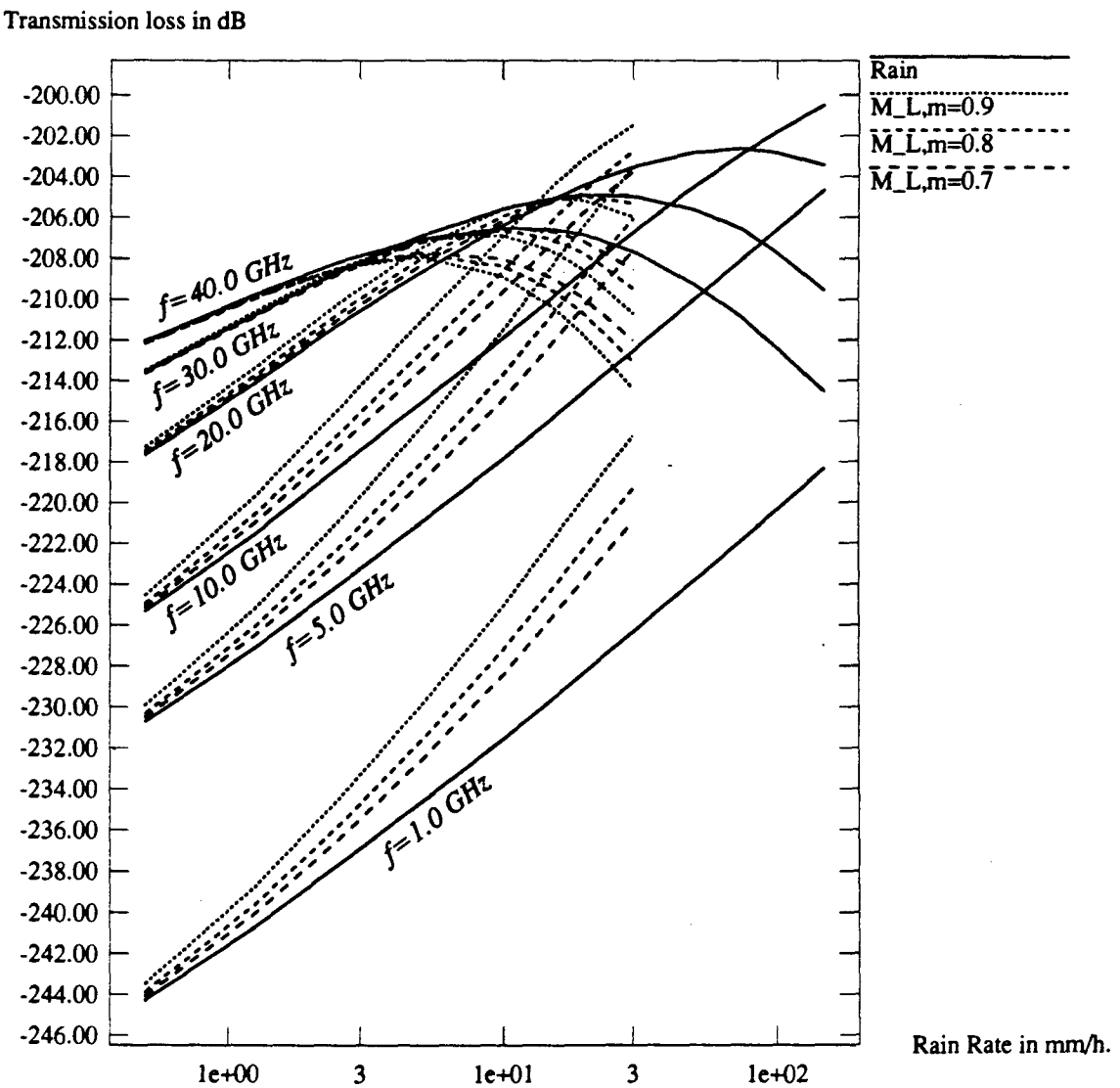

Figure 4.4.2(c) Same as Figure 4.4.2(a), with Hm = 3.0 km.

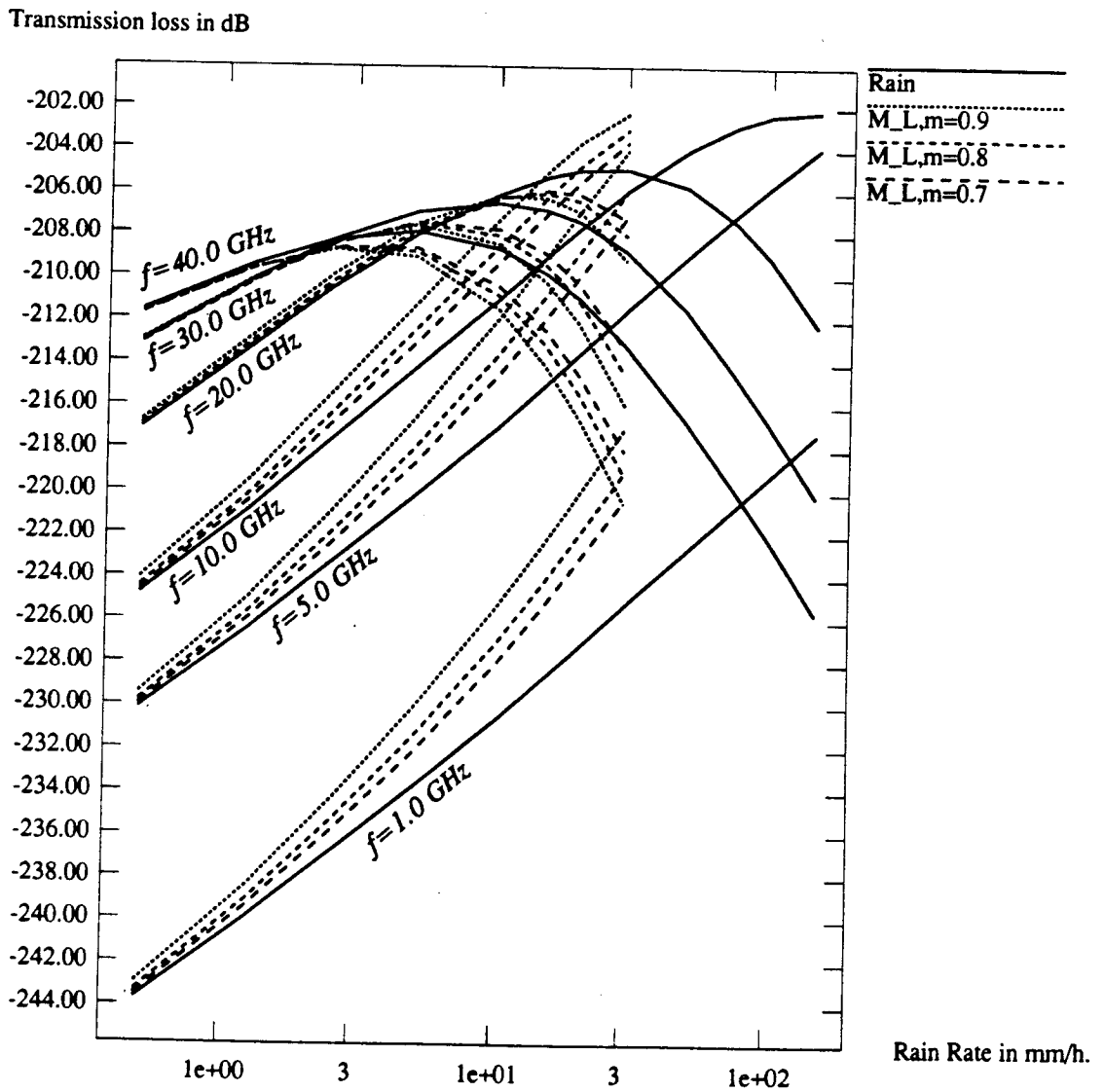

Figure 4.4.2(d) Same as Figure 4.4.2(a), with Hm = 3.5 km.

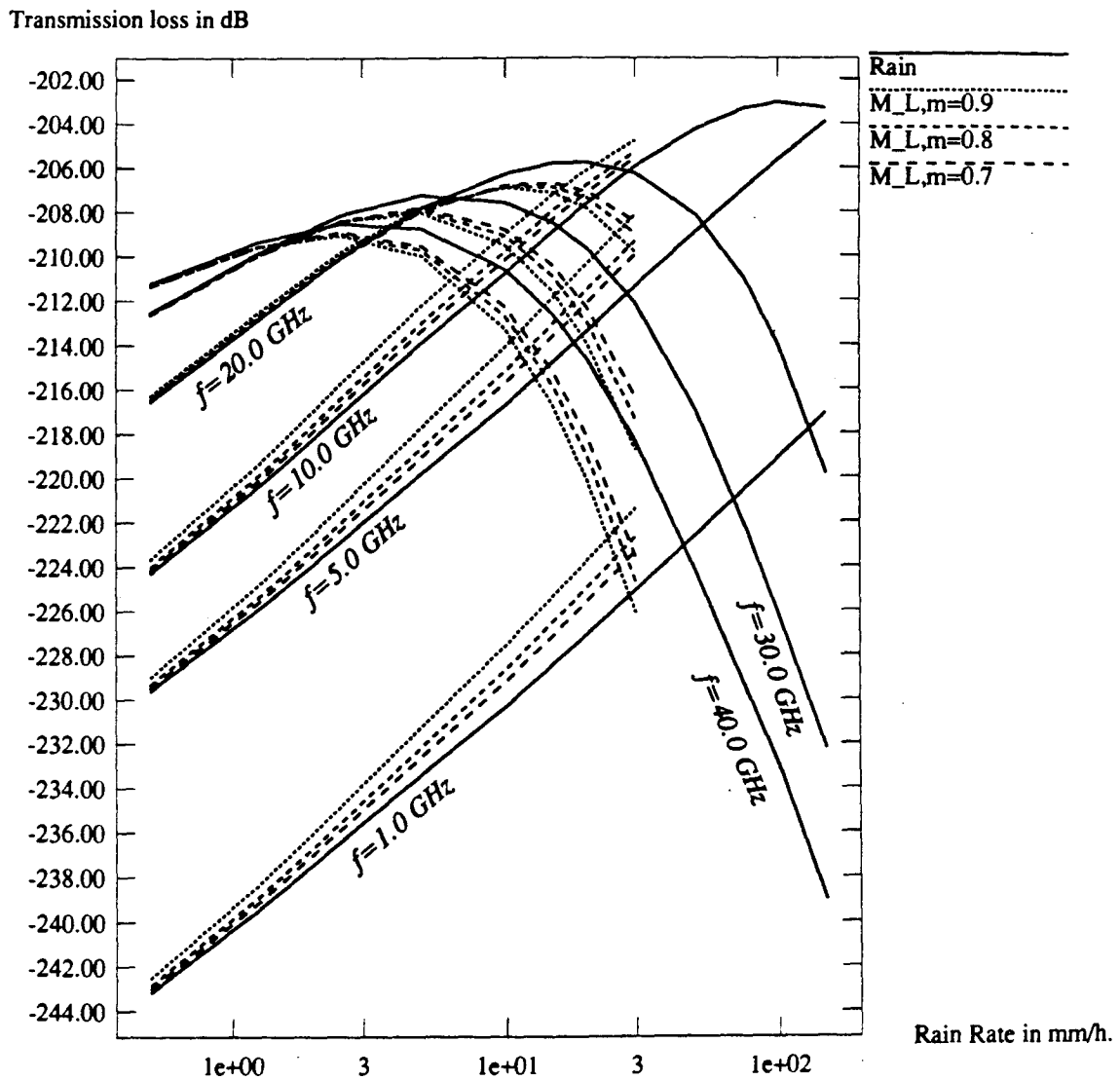

Figure 4.4.2(e) Same as Figure 4.4.2(a), with Hm = 4.0 km.

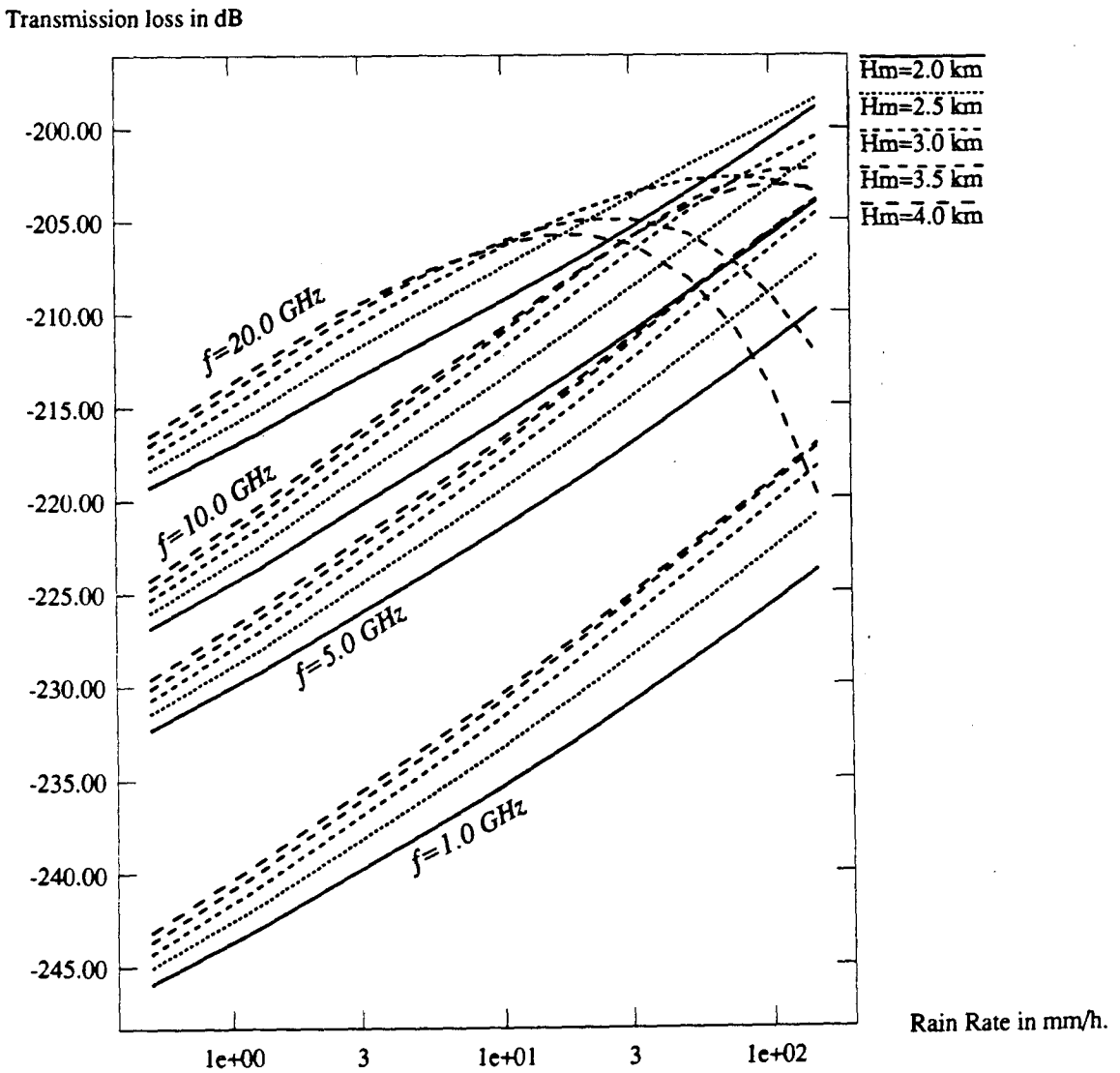

Figure 4.4.3(a) Interference versus rain rate for various rain heights (Hm), and for f (frequency) = 1, 5, 10, 20GHz.

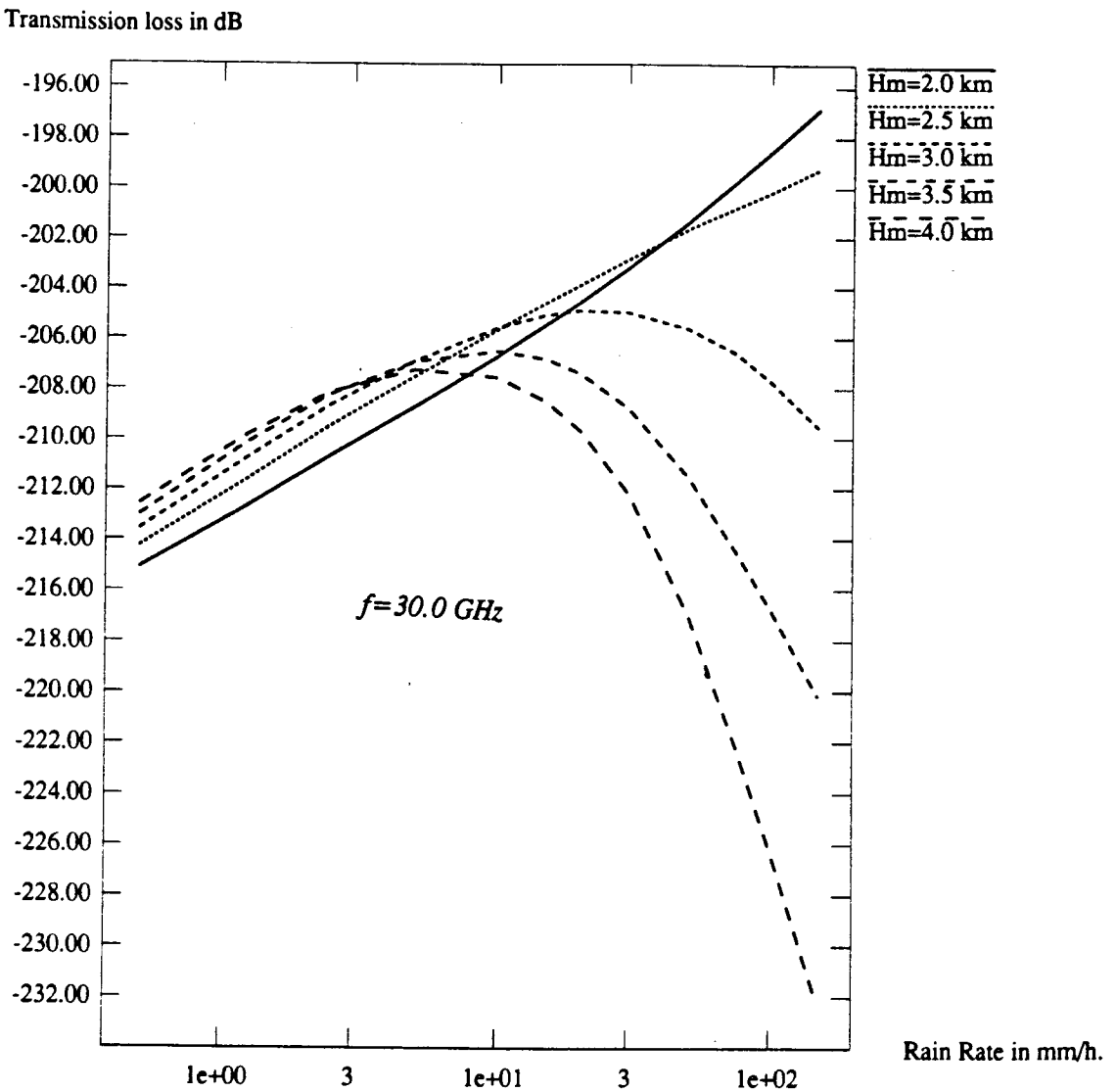

Figure 4.4.3(b) Same as Figure 4.4.3(a), with f = 30 GHz.

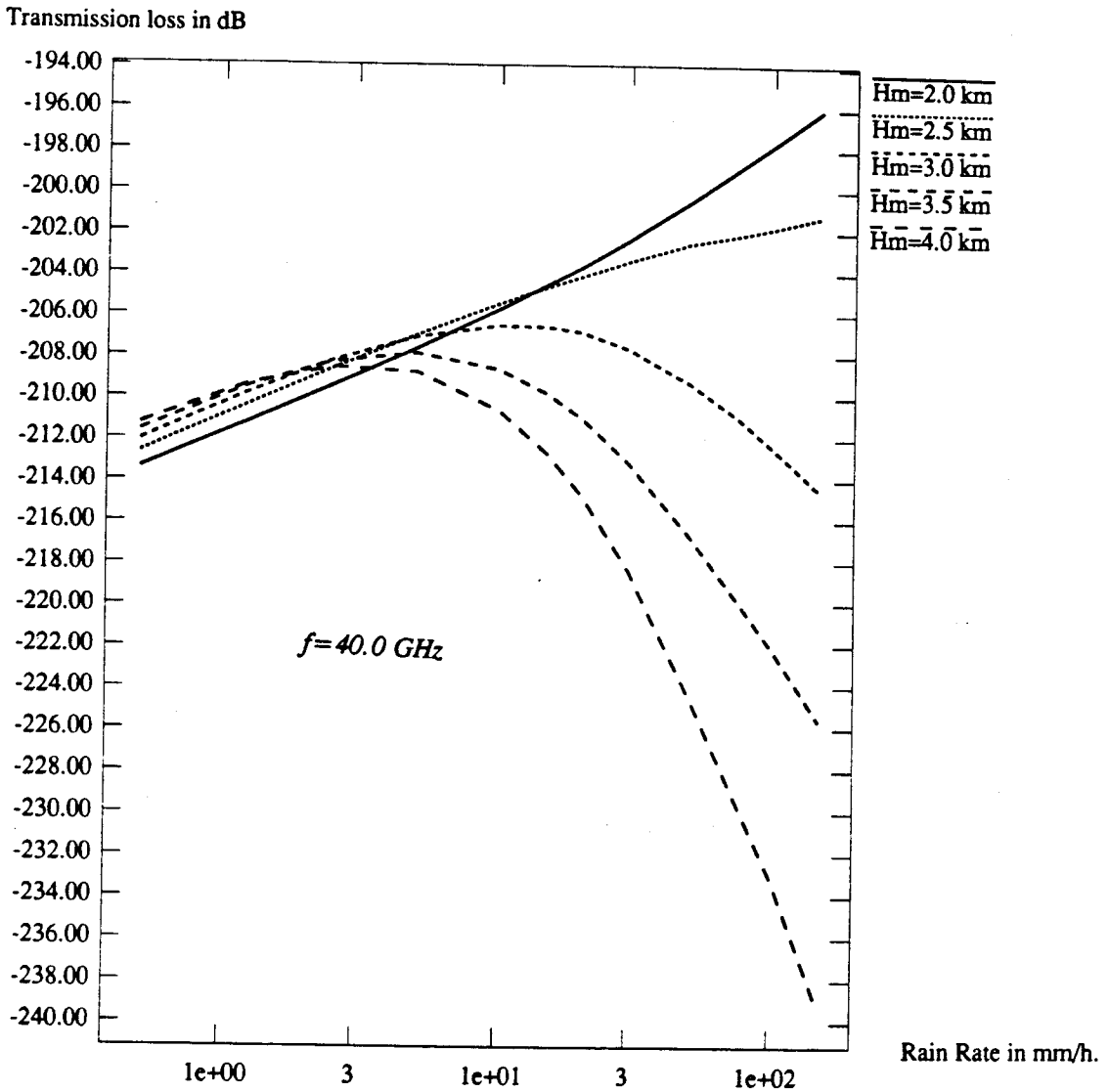

Figure 4.4.3(c) Same as Figure 4.4.3(a), with f = 40 GHz.

Chapter 5 COST 210 rain-cell model

5.1 Introduction

The CCIR working party 5C has recently adopted the COST 210 model [7] as a basis for predicting transmission loss [5]. An accompanying document was presented by Canada [4] which showed that, using the COST 210 rain cell model, the introduction of a melting snow layer in an optimum position significantly affects the transmission loss up to 11 GHz. It also concluded that the melting layer should be taken into consideration while calculating the interference level, since the interference level introduced by the presence of the melting layer is larger than that introduced in changing from one composite climate to another. This is an attempt to expand on the original study and to compare the COST 210 rain model with Capsoni's model and to see if the COST 210 rain cell is able to model the effect of the melting snow layer for a wide range of rain heights and frequencies. Readers should be reminded that it is only the COST 210 rain cell geometry that is implemented and not their interference calculation methodology. To calculate the interference, the method outlined in Chapter 3 was applied with provisions to account for the attenuation outside the rain cell (refer below). This method yielded results similar to those calculated by the COST 210 program for the Chilbolton-Baldock path [7].

5.2 COST 210 rain cell model [7]

The rain cell centre is assumed to be at the intersection of the main beam antenna axes (i.e. centre of the common volume). Scattering is assumed to occur within one fixed, cylindrical rain cell of circular cross-section. The diameter of the cell depends on

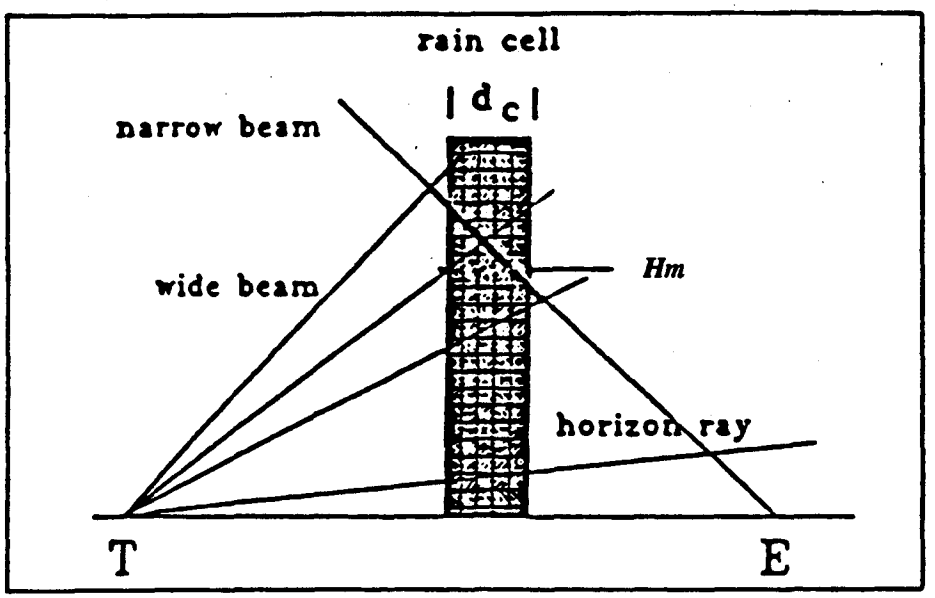

Figure 5.1 COST 210 rain-cell model

the rainfall rate as:

$$d_c = 3.3R^{-0.08} \qquad 5.1$$

On the other hand, attenuation occurs inside and outside the rain cell. Inside the rain cell, the empirical formula for attenuation is used. Outside the rain cell, the attenuation Γ_R, between the edge of the rain cell and a point at distance d is given by the following exponential function:

$$\Gamma_R = A_p r_m \frac{1 - e^{-d/r_m}}{cos\epsilon} \qquad dB/km \qquad 5.2$$

where r_m, the scale length for rain attenuation, is given by:

$$r_m = 600R^{-0.5}10^{-(R+1)^{0.19}} \qquad km \qquad 5.3$$

ϵ = elevation angle, and A_p is the specific attenuation for rain, calculated from the attenuation empirical formula, in dB/km.

Equation 5.2 is valid if the whole path is below the rain height Hm. If only part of the path — let us say between distances d_1 and d_2 from the edge of the rain cell — is below the rain height:

$$\Gamma_R = A_p r_m \frac{\left(e^{-d_1/r_m} - e^{-d_2/r_m}\right)}{cos\epsilon} \qquad dB/km \qquad 5.4$$

For those portions of the propagation path that are above Hm, zero attenuation is assumed.

The diameter of the melting layer cell is assumed to be the same as that of the rain below it. The melting layer attenuation is assumed to reduce at the same exponential rate as the rain attenuation outside the core cell. Since the specific attenuation varies with the height within the melting-snow layer, a numerical integration is carried out in the vertical direction:

$$\Gamma_R = \frac{r_m}{cos\epsilon} \sum_{i=1}^{n} A_{pi}\left(e^{-d_i/r_m} - e^{-d_{i+1}/r_m}\right) \qquad 5.5$$

where A_{pi} is the average specific attenuation in the region between d_i and d_{i+1} in the melting-snow layer. n is the number of integration steps. Despite this addition to the rain cell, we will continue to refer to it as the COST 210 rain cell.

5.3 Results for sample interference geometries

The calculations are done for the geometry described in section 4.2 of Chapter 4. Figures 5.2(a,b,c,d)-5.6(a,b,c,d) show the transmission loss at f = 1.0, 5.0, 10.0, 20.0, 30.0, 40.0 GHz and Hm = 2.0, 2.5, 3.0, 3.5, 4.0 km for both the Capsoni rain cell model and the COST 210 rain cell model. The scattering model used in both cells is that of Dr. Kharadly. The Empirical model is used for attenuation. This is somewhat different from the COST 210 model where they use modified Rayleigh scattering for rain and a different attenuation model. Neither COST 210 attenuation nor scattering models account for the melting-snow region.

For the rain-only cells, we observe that both models predict similar transmission losses for all Hm and rain rates at lower frequencies (f = 1.0, 5.0, 10.0 GHz). However, the two models' results differ considerably at higher frequencies and especially for the lower rain rates. For Hm = 3.0 km and f = 40 GHz (Figure 5.4 (d)), the Capsoni model interference level is 15.0, 16.0, 13.5, 4.2, 1.5 dB higher than the interference level calculated using COST 210 rain cell for R = 1.0, 3.0, 10.0, 30.0 mm/h, respectively. As Hm increases, the two models' interference curves seems to produce better agreement.

For Hm = 3.0 km (Figures 5.4 (a),(b),(c),(d)), which is the optimum position of the melting layer in the common volume, the COST 210 rain cell models the effect of the melting snow layer very nicely. For Hm = 3.5 km (Figures 5.5 (a),(b),(c),(d)), the COST 210 cell tends to overestimate the enhancement caused by the melting snow

layer. This is in contrast to Hm = 2.5 km (Figures 5.3 (a),(b),(c),(d)), where the COST 210 model underestimates its effect considerably. For Hm = 2.0, and 4.0 km (Figures 5.2 (a),(b),(c),(d) and Figures 5.5 (a),(b),(c),(d), respectively), the melting layer does not enter into consideration since it is out of the path of the transmitting beam. We observe from the Capsoni model that for Hm = 2.0 and 4.0 km, the melting layer does play a role (albeit reduced) in the interference problem. The reason that the COST 210 cell does not account for the melting layer is the small radius of the COST 210 cell.

5.4 Conclusion

The computation time for the COST 210 model is much less than that of the Capsoni rain model. This is directly related to the radius of the core rain cell of COST 210. For rain rates of 0.5, 2.5, 5.0, 12.5, 25.0, 50.0, 100.0, 150.0 mm/h, the radius of the Capsoni rain cell is 10.45, 9.40, 8.95. 8.35, 7.90, 7.45, 7.00, 6.74 km respectively. On the other hand the radius of the COST 210 rain cell is 1.74, 1.53, 1.45, 1.35, 1.28, 1.21, 1.14, 1.11 km. We can see readily that the COST 210 rain cell, which is about 6 times smaller than the Capsoni model, will save a considerable amount of computer time.

For lower frequencies, we notice that the Capsoni and COST 210 rain models yield similar results for all Hm values. For higher frequencies, we see that there is a large difference between the two models. The COST 210 model interference level is much lower than that of the Capsoni cell for lower rain rate. For a high rain rate and lower frequencies, the COST 210 model yields the higher interference level. Since the Capsoni rain cell is the more realistic, it is safe to assume that the COST 210 model will underestimate the interference at higher frequencies (and large station separation) and rain rate.

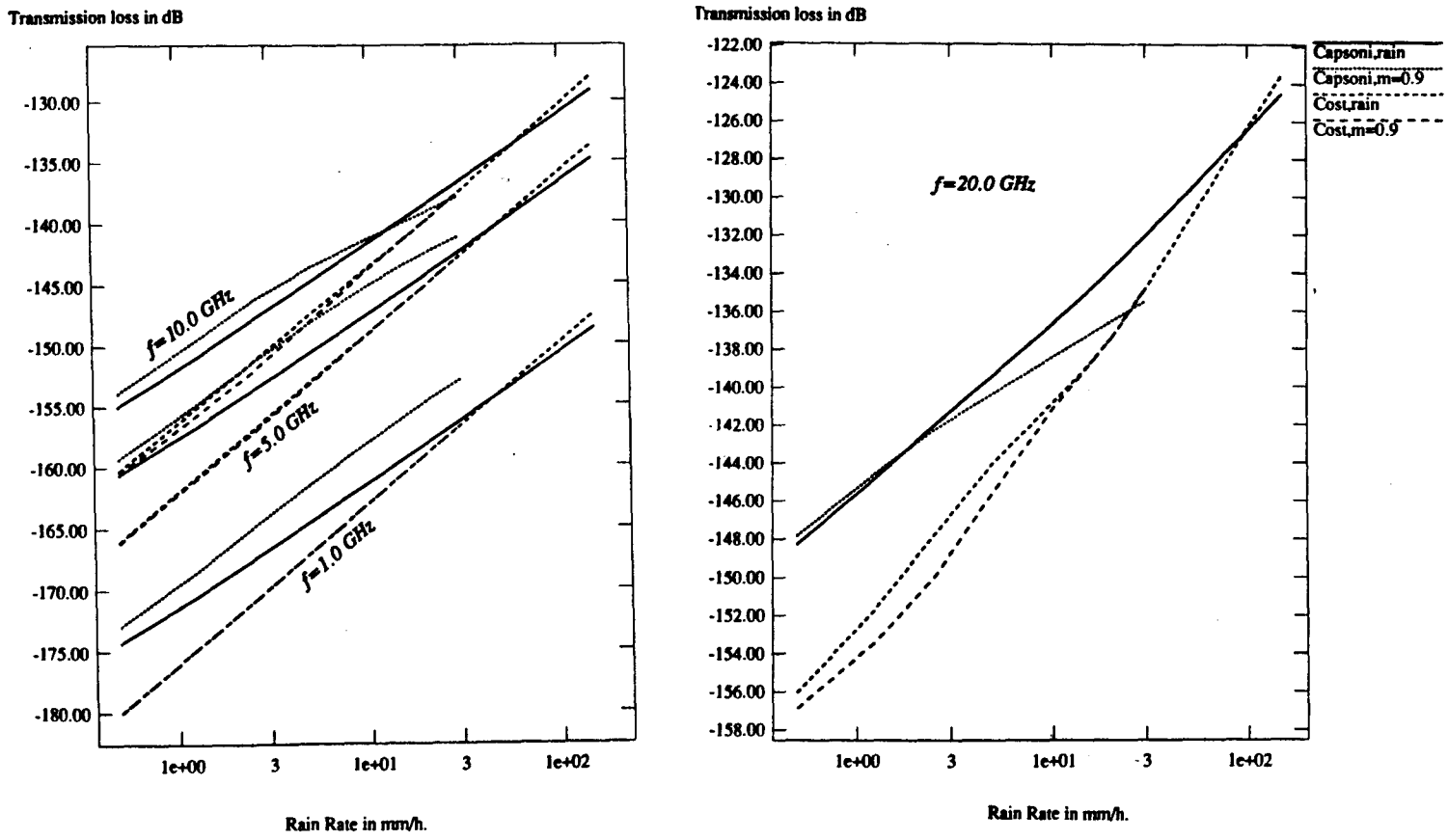

Figure 5.2(a,b) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 2.0 km, and: (a) f (frequency) = 1, 5, 10 GHz, (b) f = 20 GHz.

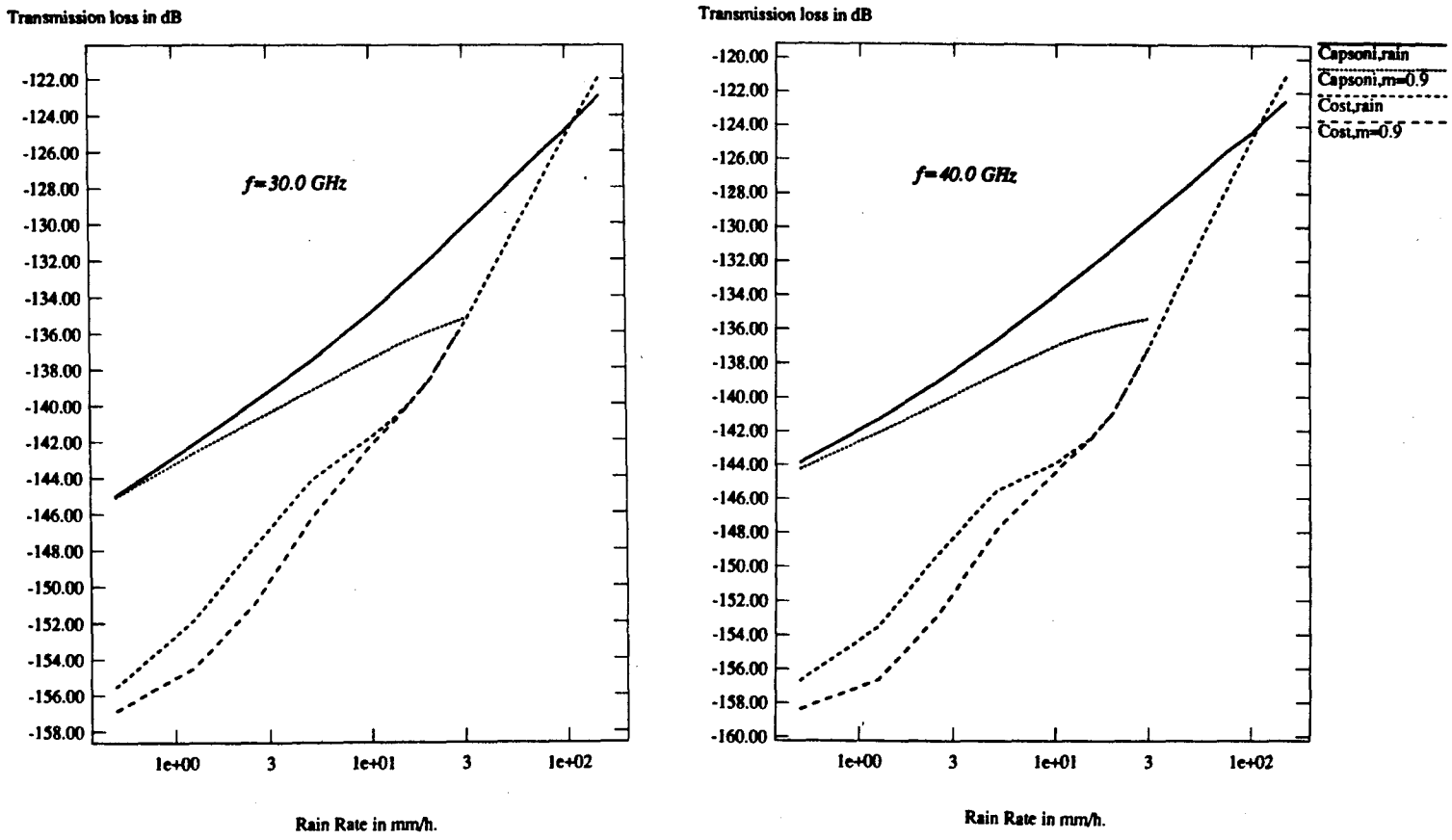

Figure 5.2(c,d) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 2.0 km, and: (c) f (frequency) = 30 GHz, (d) f = 40 GHz.

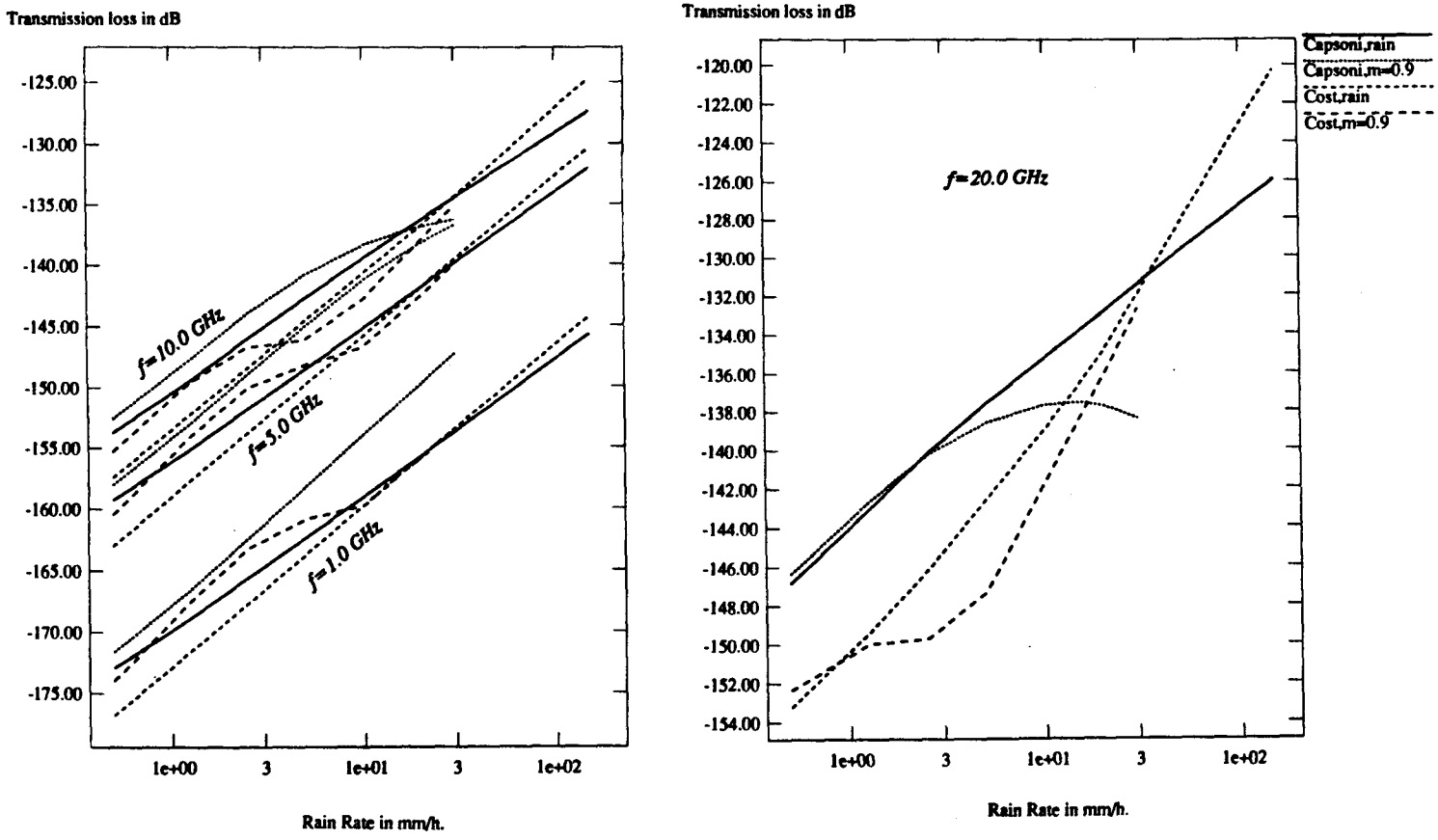

Figure 5.3(a,b) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 2.5 km, and: (a) f (frequency) = 1, 5, 10 GHz, (b) f = 20 GHz.

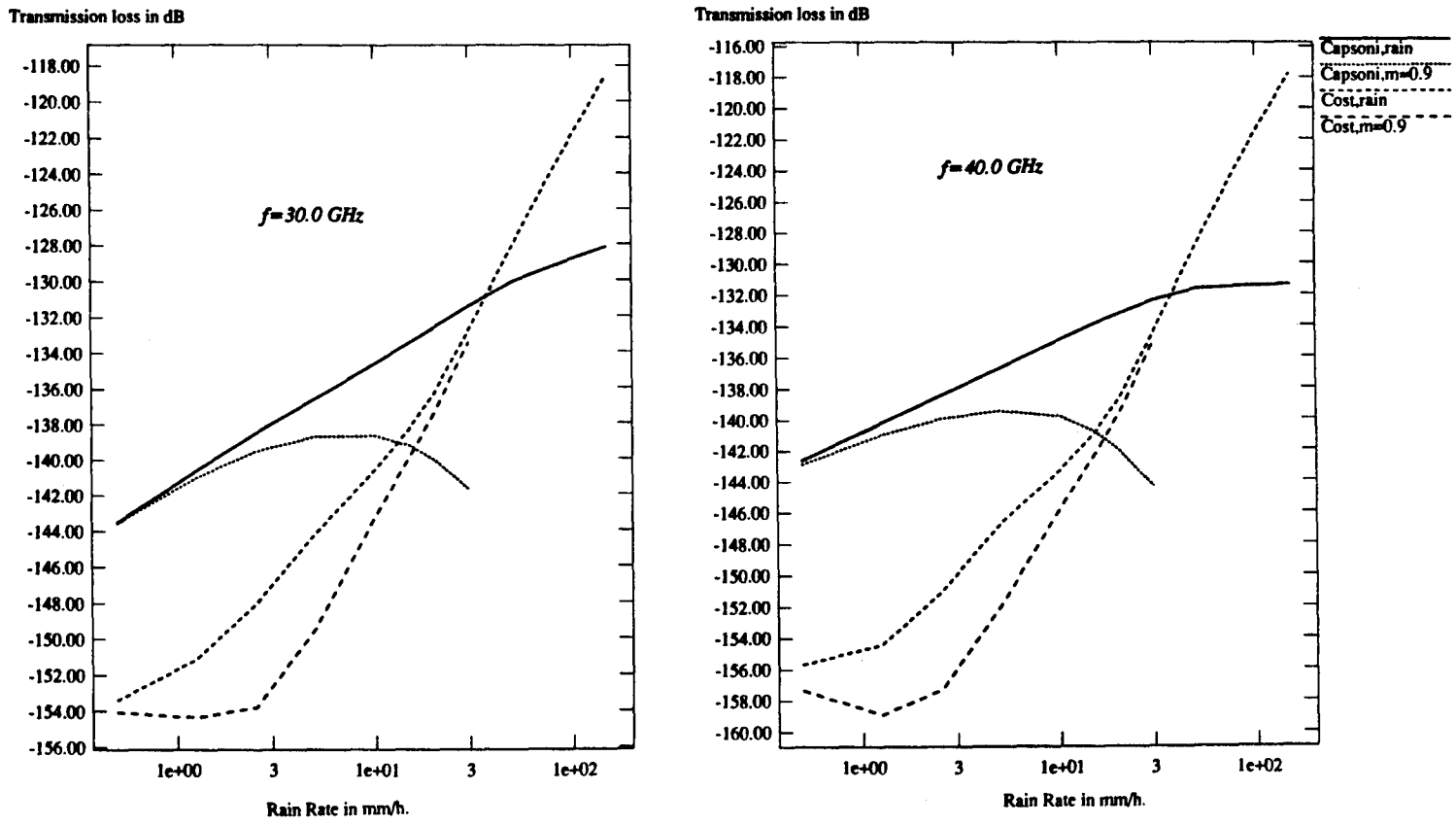

Figure 5.3(c,d) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 2.5 km, and: (c) f (frequency) = 30 GHz, (d) f = 40 GHz.

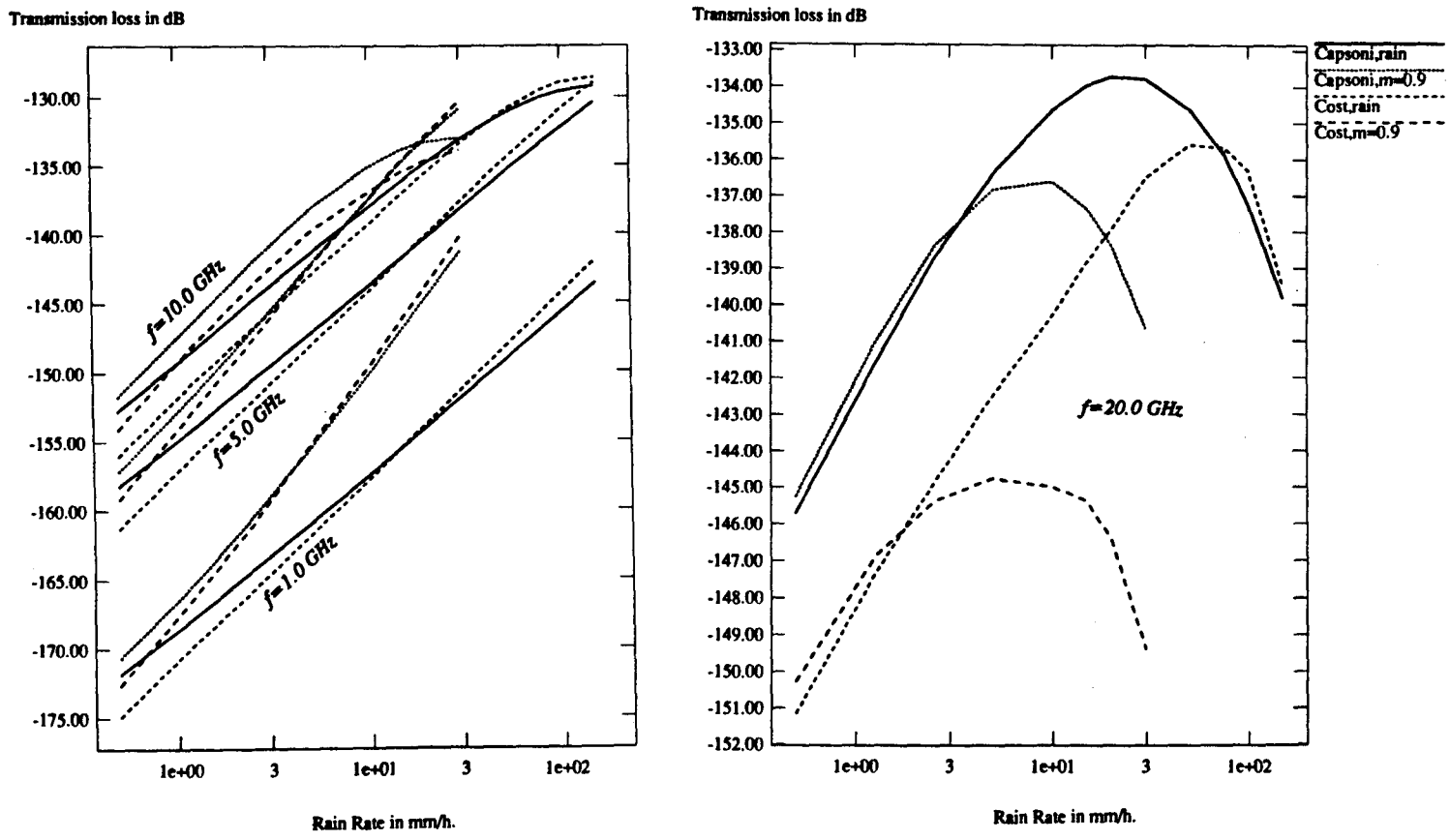

Figure 5.4(a,b) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 3.0 km, and: (a) f (frequency) = 1, 5, 10 GHz, (b) f = 20 GHz.

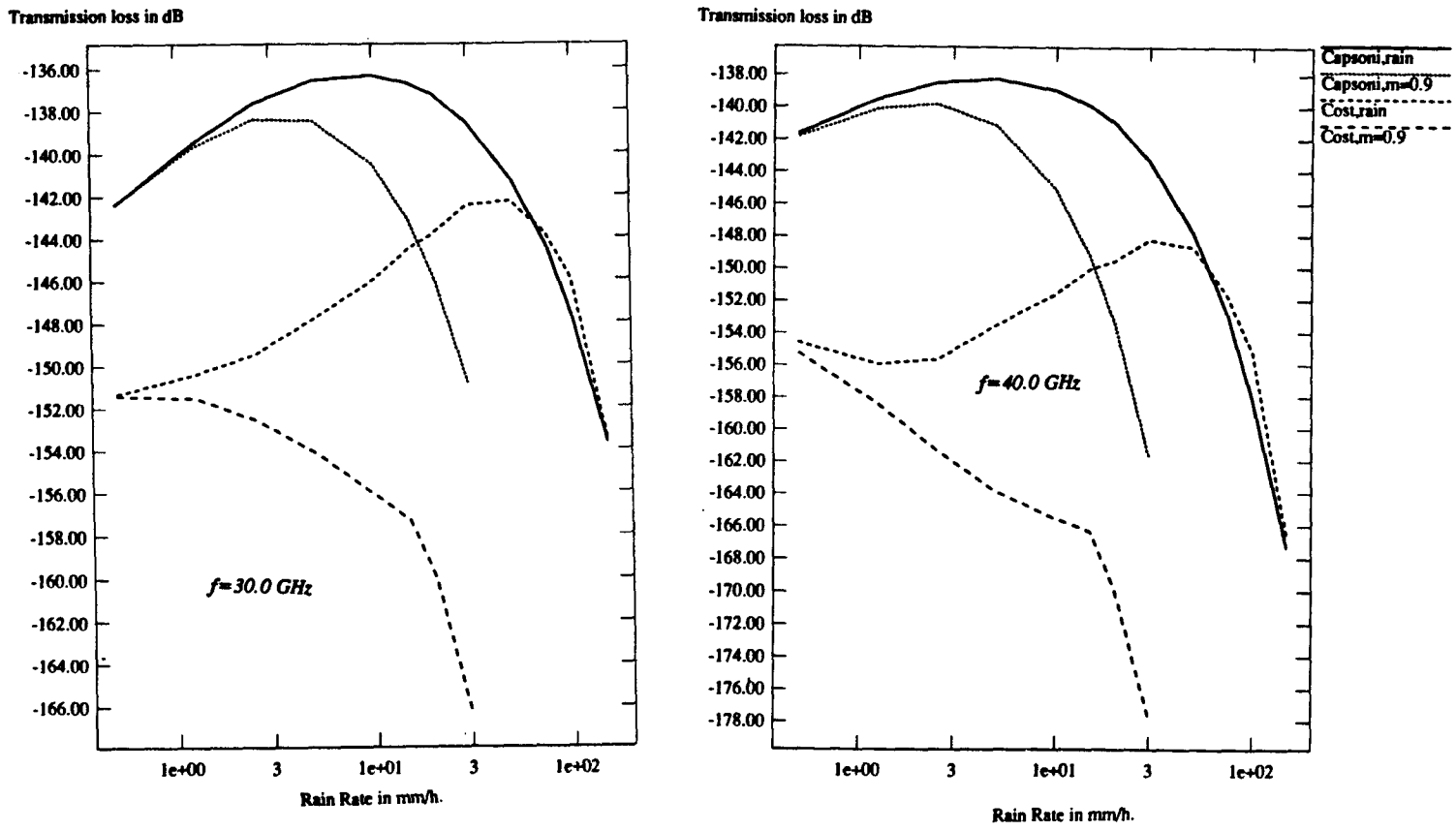

Figure 5.4(c,d) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 3.0 km, and: (c) f (frequency) = 30 GHz, (d) f = 40 GHz.

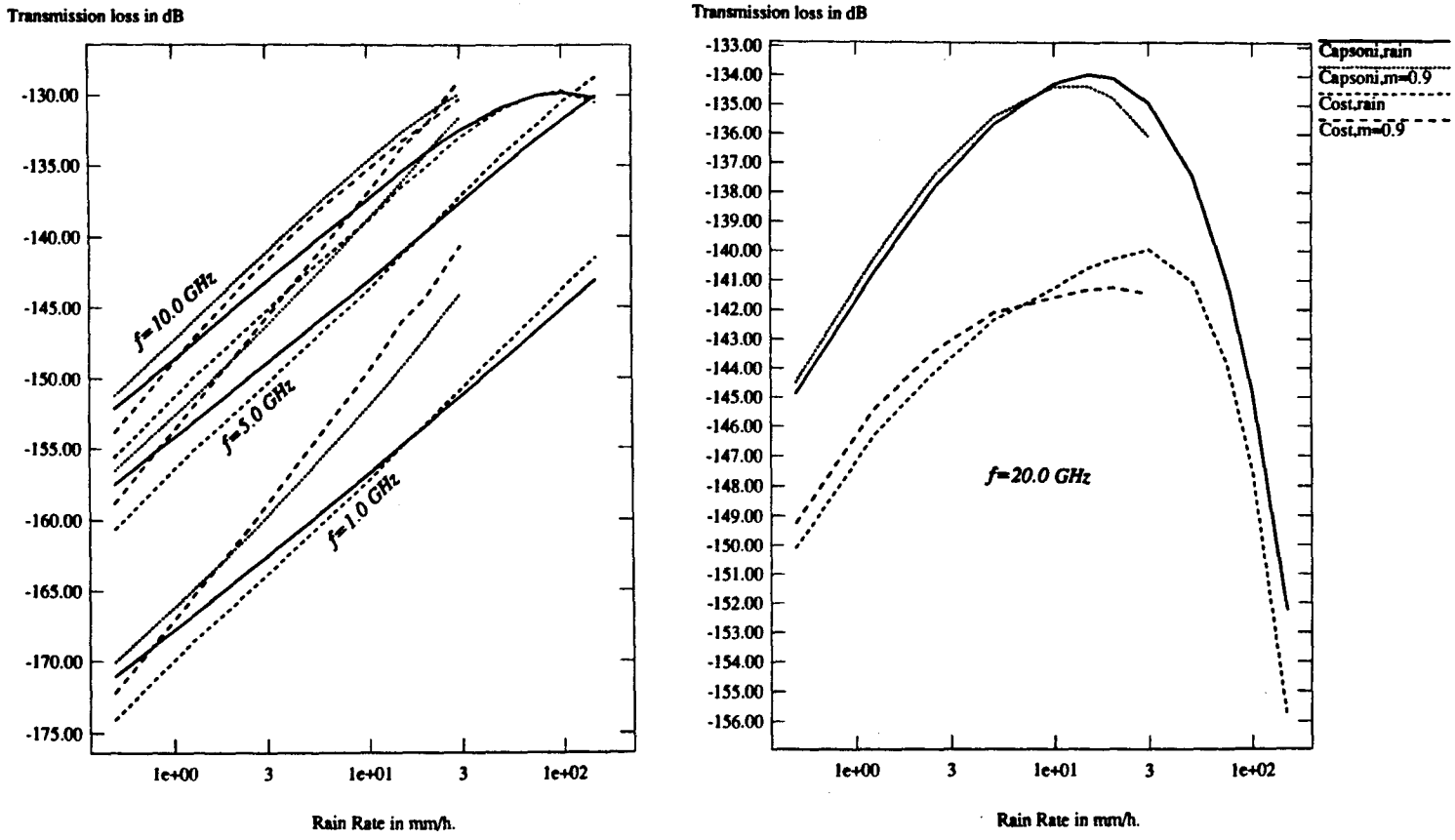

Figure 5.5(a,b) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 3.5 km, and: (a) f (frequency) = 1, 5, 10 GHz, (b) f = 20 GHz.

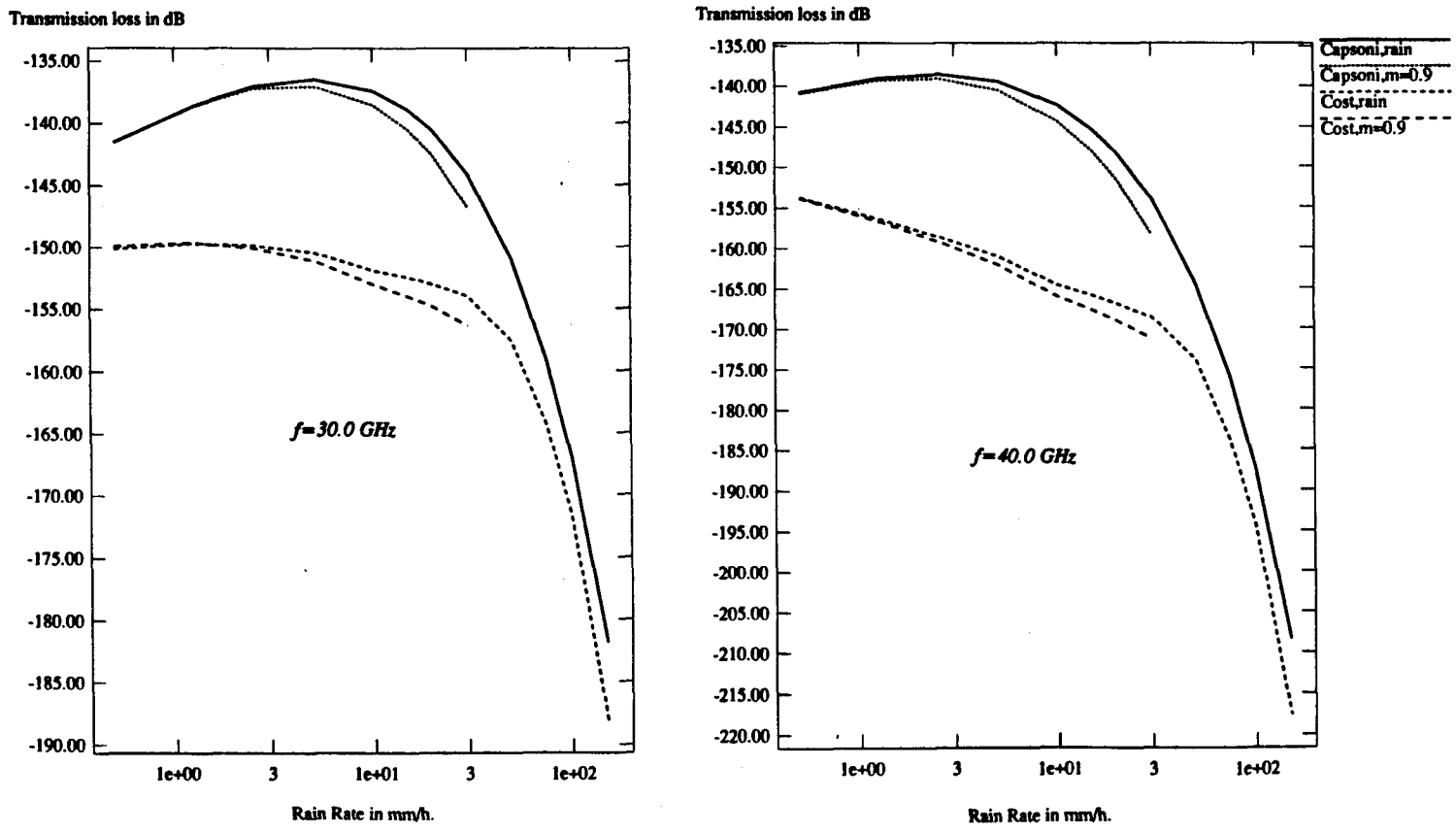

Figure 5.3(c,d) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 3.5 km, and: (c) f (frequency) = 30 GHz, (d) f = 40 GHz.

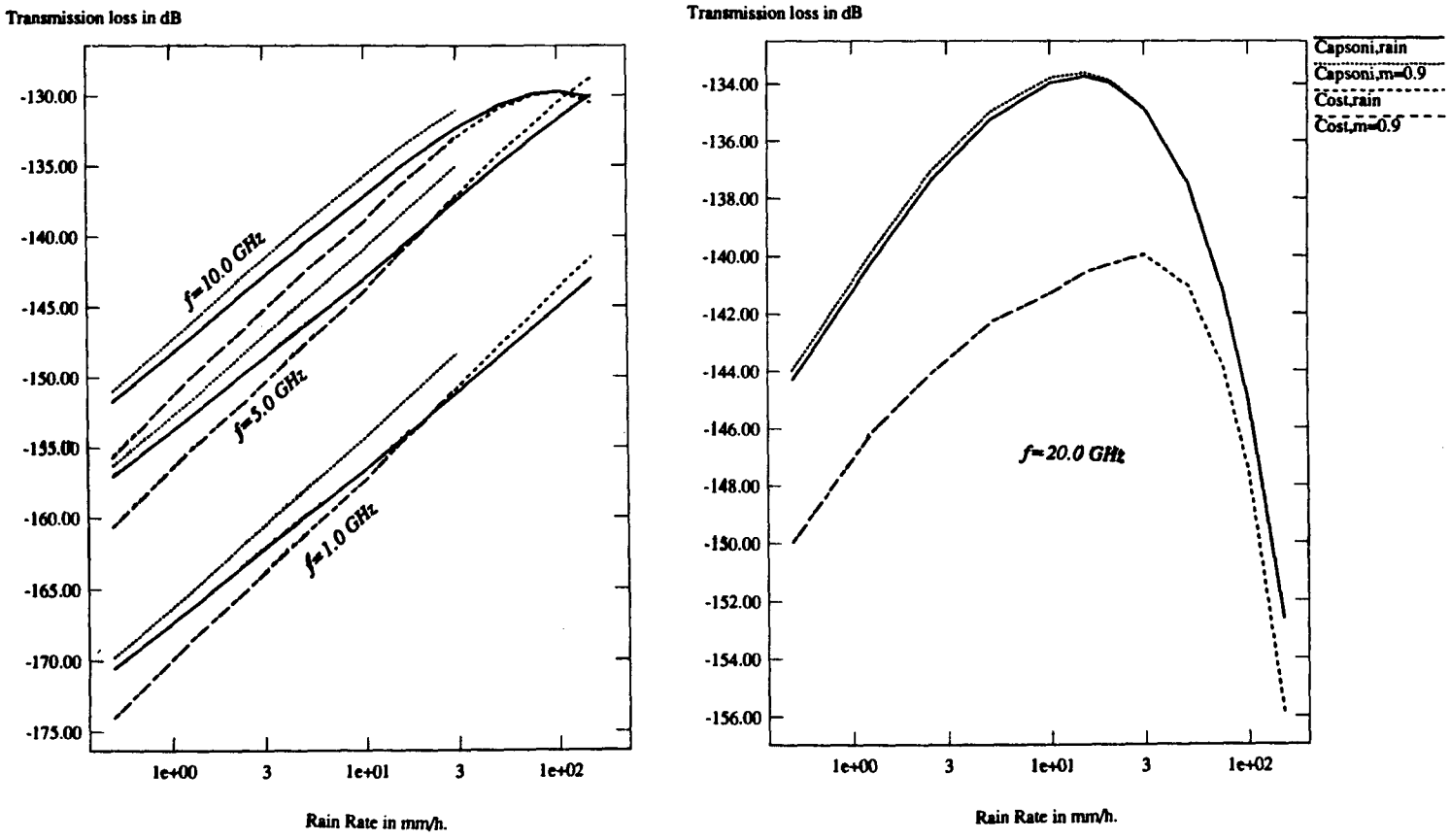

Figure 5.6(a,b) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 4.0 km, and: (a) f (frequency) = 1, 5, 10 GHz, (b) f = 20 GHz.

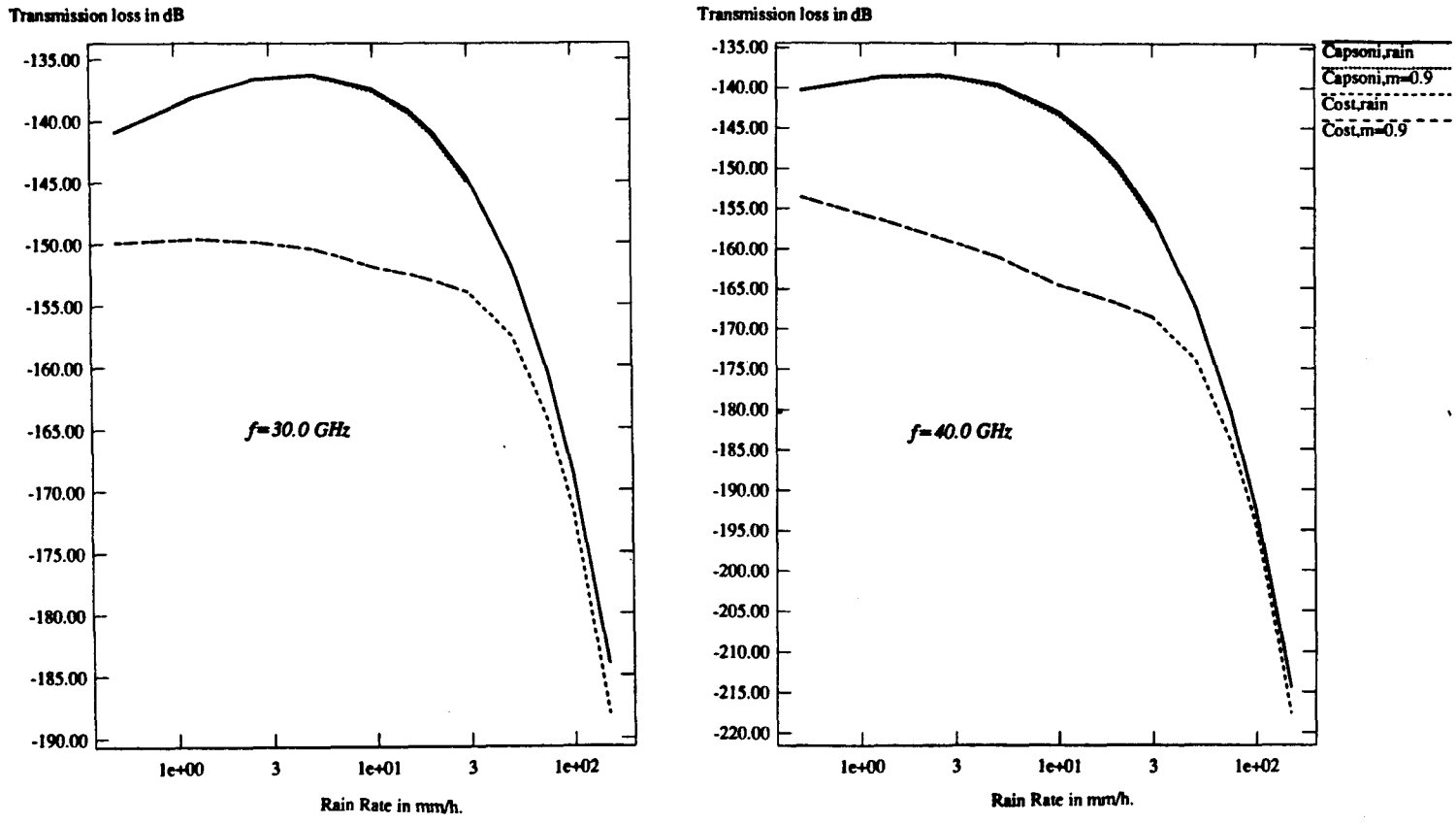

Figure 5.6(c,d) A comparison between Capsoni and COST 210 rain cell models with and without a melting snow layer for Hm = 4.0 km, and: (c) f (frequency) = 30 GHz, (d) f = 40 GHz.

Also, there are inherent weaknesses in the COST 210 rain model. The model is not a physical one where it accurately describes an actual rain cell.As we stated before, the major advantage of the COST 210 rain cell is its small radius. This advantage turns into a disadvantage when modeling the melting snow layer. As we observed, the COST 210 rain cell models the effect of the melting layer quite nicely when that region is near the center of the common volume. On the other hand, if the melting layer height (which is a random variable) moves upward or downward, the model will not be able to account for its effect beyond a relatively short distance.

In general, the COST 210 model seems to be acceptable for modeling the interference for terrestrial stations. It would be quite interesting to extend the model to find out if it can reasonably estimate interference on receiving satellites.

To better judge the COST 210 rain cell, a comparison of the statistical transmission loss is in order. This is currently beyond the scope of this thesis, but should be dealt with at a future date.

Chapter 6 Discussion and Conclusions

6.1 Effect of melting-snow layer

The results introduced in Chapter 4 show that the melting-snow layer plays an important role in the transmission loss in the 1–40 GHz frequency spectrum. This role is by no means uniform. At lower frequencies (f = 1–10 GHz), the melting-snow layer plays a significant role in increasing the interference level. This enhancement is much higher for the f = 1 and 5 GHz than for f = 10 GHz. This is the region where most of today's radio communications is handled. The congestion of the frequency spectrum is pushing for the use of the higher frequencies. Because of the high attenuation associated with these frequencies in the melting-snow layer, outages will become more frequent. These outages will become more important to system engineers than signal interference. On the other hand, stations might increase their transmission power to avoid outages. This will generate a stronger scattered signal and thus a higher interference potential.

Because of increased attenuation, the melting-snow layer decreases the effect of the ice/snow region. This is especially true for higher frequencies. However, the effect of this attenuation is limited to the lower part of the ice/snow region because of the small elevation angle of the scattered wave. Because of the importance of the ice/snow region at higher frequencies, more research is needed to model the scattering more accurately.

At low frequencies, the attenuation is small enough that it will not offset the increase in reflectivity of the melting-snow layer. At high frequencies, the attenuation by the melting-snow layer becomes great enough to smother any increase in the scattering of the melting-snow layer.

It is also observed that for a high directivity antenna, the melting-snow layer interference can increase or decrease depending on the position of the main lobe axis of the receiver relative to the melting-snow layer. If the main lobe axis of the high directivity antenna intersects or is near the melting-snow layer, its effect will be greater.

Also we notice that the density of the core of the melting-snow particles plays an effect — albeit not great — in the calculations. We see that the higher the density is, the smaller is the effect of the melting layer. This can be attributed to the reduction of the particle sizes resulting from higher average density.

The melting layer has been assumed to have a linear melting ratio (S=h/H; where h is the distance down from the top of the melting layer, H is the thickness of the melting layer, S is the ratio of the melted volume to the total volume). This profile provides for a narrow region in the melting layer where attenuation and scattering peaks (around S = 0.1). Kharadly [1992] suggests that this profile underestimates the effect of the melting layer and that different profiles might have to be used.

6.2 Effect of rain height, Hm

The effect of increasing rain height in the rain cell is quite interesting. We can see that for lower frequencies, the higher Hm causes a higher interference level meanwhile at higher frequencies, the interference decreases with a higher Hm.

The reason for this phenomenon is the ice/snow region above the rain region. In this region we have scattering but no attenuation and since scattering increases but with no attenuation to offset it, the interference increases. This leads us to the conclusion that considerable interference for high frequency can be achieved if a high directivity antenna intersects the ice/snow region.

6.3 Effect of rain rate

It is very hard to talk about the effect of rain rate without mentioning frequency. For lower frequencies, interference increases with rain rate, since higher rain rates translates into higher scattering cross section. For higher frequencies, higher rain rates translate into very high attenuation levels and thus lower interference.

6.4 Effect of frequency

For lower frequencies, rain and melting-snow attenuation is negligible and interference can present problems for radio systems operating at the same frequencies.

For higher frequencies, the interference problem seems to disappear since the high attenuation will smother any potential interference wave. Outages, due to the high attenuation level, seems to be a much more serious problem for higher frequency systems. Yet because of this high attenuation level, systems will be forced to increase their transmitting power during these periods and thus increasing the scattered power and thus the interference.

6.5 Reminder

A model-program has been developed to calculate the interference caused by hydrometeors. This model-program is — unlike the COST 210 model — capable of calculating the interference for any given geometry.

Also a study was conducted about the effect of the melting layer on interference. It was found that the melting layer significantly enhances the interference for lower frequencies and should not be ignored. This is especially true in the case of satellite interference.

Chapter 7 Suggestions for future research

There is much work — both theoretical and experimental — that needs to be done on the subject in the future. Some suggestions for future work are:

1. There should be further work on the program to make it more efficient. This can be done by utilizing more efficient routines or by fitting some of the parameters used in Kharadly models into equations. These parameters include the radius of the representative particle and the number of particles per unit volume. The equations will be a function of rain rate and the melting ratio (S). This will make it unnecessary to interpolate them from Table A.1 every time we need to calculate the attenuation.
2. More work needs to be done on the program to make it user-friendly.
3. Introduce the statistics of rain to the model. To do that, more study is required on the statistics of the melting layer, its thickness and height and if any relation exists between them. Currently, there is considerable work being done in this field by the Alberta Research Council [9]
4. Include real earth and space coordinates into program (longitude, latitude).
5. Use the program to study more diverse geometries and a wider range of parameters.
6. Include gaseous attenuation into the calculations since for f = 50 GHz the attenuation is 15 dB/km. Fog attenuation might also be significant over long distances. Fog attenuation is 0.1 dB/km for f = 50.0 GHz. This will translate into 10.0 dB for a 100.0 km path length.
7. Further research is needed to see if the COST 210 model can be extended to interference on satellites.

8. More work is needed on the interference caused by hydrometeors on low gain systems. This can be useful in cellular communications.
9. Since the Kharadly scattering model does not extend to the snow region, more research should be done to extend it. Also more work should be done to make it more accurate.
10. Develop formulas for scattering and attenuation for higher frequencies. As a first step, it will be useful to extend the scattering formulas to 100.0 GHz since the empirical model for attenuation is valid over that range.
11. More research is needed concerning the structure of the melting-snow region including its profile. The Alberta research [9] can provide valuable information on the subject.
12. More research is needed in the area above the melting snow layer. Again, the Alberta research [9] is bound to shed light on this subject.

Appendix A Precipitation modeling

A.1 Rain medium

The rain medium consists of drops of water drops of different sizes falling at a velocity depending on the size of the drop. For most applications, it is reasonable to assume that these particles are spheres. The size distribution of the spheres and their velocities v are given in Table A.1 [14].

Precipitation rate (mm/h)	0.25	1.25	2.5	5	12.5	25	50	100	150	
Drop size (cm)	Percent of the total volume									v (m/s)
0.05	28.0	10.9	7.3	4.7	2.6	1.7	1.2	1.0	1.0	2.06
0.1	50.1	37.1	27.8	20.3	11.5	7.6	5.4	4.6	4.1	4.03
0.15	18.2	31.3	32.8	31.0	24.5	18.4	12.5	8.8	7.6	5.40
0.2	3.0	13.5	19.0	22.2	25.4	23.9	19.9	13.9	11.7	6.49
0.25	0.7	4.9	7.9	11.8	17.3	19.9	20.9	17.1	13.9	7.41
0.3		1.5	3.3	5.7	10.1	12.8	15.6	18.4	17.7	8.06
0.35		0.6	1.1	2.5	4.3	8.2	10.9	15.0	16.1	8.53
0.4		0.2	0.6	1.0	2.3	3.5	6.7	9.0	11.9	8.83
0.45			0.2	0.5	1.2	2.1	3.3	5.8	7.7	9.00
0.5				0.3	0.6	1.1	1.8	3.0	3.6	9.09
0.55					0.2	0.5	1.1	1.7	2.2	9.13
0.6						0.3	0.5	1.0	1.2	9.14
0.65							0.2	0.7	1.0	9.14
0.7									0.3	9.14

Table A.1 Drop size distribution and their velocities for various precipitation rates [14]

The model can further be simplified by considering the rain medium to be composed of rain drops of a representative radius $\bar{a}$. The rain rate (R) can then be given by:

$$R = 48\pi \times 10^5 \bar{a}^3 vN \qquad \text{A. (30)}$$

where,

$$\bar{a} = \left[1 / \sum_i \frac{p_i}{a_{Ri}^3} \right]^{-1/3} \qquad \text{A. (31)}$$

p_i is the fraction of the volume of rain V_R composed of the rain drops of radius a_{Ri}. The number of representative rain drops in this fictitious rain medium is given by:

$$N = \frac{R}{48\pi \times 10^5 \bar{a}^3 v} \qquad \text{A. (32)}$$

where R is measured in mm/h, $\bar{a}$ in cm, v in m/s, and N in cm^{-3}. The velocity can be found using Table A.1.

A.2 Melting-snow medium

Unlike the rain medium, the melting snow layer is "essentially inhomogeneous". It is the region at the zero isothermal where snow melts into rain. Because of the difference in density between the snow and water, the snow particle starts to decrease in size as it melts with the water forming a layer on the outside of the snow particle. The region between where the melting starts and where the melting ends is called the "melting-snow layer". For our melting-snow layer, we assume the following:

1. The melting layer has a steady thermal structure.
2. A steady supply of snowflakes of prescribed size is maintained at the 0^oC level, at the top of the melting region. The relative distribution of those particles is the same as that in Table A.1.

3. There is no aggregation or breakup of snowflakes in the melting region.
4. Snowflakes have spherical shapes.
5. The melted water forms a coat around the snowflake.
6. Growth by collision and coalescence with cloud drops and by condensation of water vapor is ignored.
7. The melting particle increases in size as we move from the rain medium (S = 1) in the bottom of the melting layer to the top of the melting layer (S = 0). The radius of the representative melting snow layer is given by:

$$\bar{a} = \left[(\rho_s + (1 - \rho_s)S) \sum \frac{p_i v_{Ri}}{a_{Ri}^3 v_{mi}} \right]^{-1/3} \qquad \text{A. (33)}$$

Where

ρ_s	=	density of the snow core of the particle
v_{Ri}	=	fall velocity of the rain drop of radius a_{Ri}
v_{mi}	=	fall velocity of the corresponding melting-snow spheres with a degree of melting S

The velocity of the melting snow particle is given by:

$$v_{mi} = 1.5 + (v_{Ri} - 1.5) \sin\left(\frac{\pi S}{2}\right) \qquad \text{A. (34)}$$

S is the ratio of the melted volume of water to the total volume of the melting snow particle.

Two models have been developed by Kharadly [10, 12] for the melting-snow layer. In [10], the effect of the fall velocity on number density is ignored which led to the violation of the conservation of mass criterion. In [12], the effect of fall velocity is taken into consideration.

Appendix B Kharadly attenuation models

B.1 Artificial dielectric model

The specific attenuation A_p and the phase β are given from the general expression for the propagation characteristic [10]:

$$\gamma = A_p + j\beta = 2\pi f(-\mu_0\epsilon)^{1/2} \qquad \text{B.1}$$

From the above expression the attenuation and phase can be easily approximated by:

$$\begin{aligned} A_p &\simeq 9.1 g_e'' N f \times 10^4 \\ \Delta\beta &\simeq 6 g_e' N f \times 10^5 \end{aligned} \qquad \text{B.2}$$

where the effective value of the polarizability at high frequencies $g_e = g_e' - j g_e''$ is given by:

$$g_e = \frac{g}{1 + j\left(\frac{f}{f_r}\right)^n} \qquad \text{B.3}$$

with,

$$n = \frac{2 + Y\left(\frac{f}{f_r}\right)^m}{1 + (Y+1)\left(\frac{f}{f_r}\right)^m} \qquad \text{B.4}$$

and,

$$f_r = \frac{c\xi}{2\pi\bar{a}}$$

where $m = 2$, $Y = 100$, and $\zeta = 0.81$. The low-frequency value of the polarizability for a two-concentric sphere is given by:

$$g = 4\pi a_2^3 \frac{(\epsilon_2 - 1)(2\epsilon_2 + \epsilon_1) - \left(\frac{a_1}{a_2}\right)^3 (\epsilon_2 - \epsilon_1)(2\epsilon_2 + 1)}{(\epsilon_2 + 2)(2\epsilon_2 + \epsilon_1) - 2\left(\frac{a_1}{a_2}\right)^3 (\epsilon_2 - \epsilon_1)(\epsilon_2 - 1)} \qquad \text{B.5}$$

where a_1, a_2, ϵ_1, ϵ_2 are the radius of the inner sphere, the radius of the outer sphere, the permittivity of the inner sphere, and the permittivity of the outer sphere, respectively. The permittivity of water, ϵ, is given in [18]:

$$\epsilon = \epsilon' - j\epsilon'' \qquad \text{B.6}$$

$$\epsilon' = \epsilon_\infty + \frac{(\epsilon_s - \epsilon_\infty)\left[1 + (\lambda_s/\lambda)^{1-\alpha}\sin(\alpha\pi/2)\right]}{1 + 2(\lambda_s/\lambda)^{1-\alpha}\sin(\alpha\pi/2) + (\lambda_s/\lambda)^{2(1-\alpha)}} \qquad \text{B.7}$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_\infty)(\lambda_s/\lambda)^{1-\alpha}\cos(\alpha\pi/2)}{1 + 2(\lambda_s/\lambda)^{1-\alpha}\sin(\alpha\pi/2) + (\lambda_s/\lambda)^{2(1-\alpha)}} + \frac{\tau\lambda}{18.8496 \times 10^{10}} \qquad \text{B.8}$$

where

$\epsilon_s = 78.54 \times [1.0 - 4.597 \times 10^{-3}(t - 25.0) + 1.19 \times 10^{-5}(t - 25.0)^2 - 2.8 \times 10^{-8}(t - 25.0)^3]$

$\tau = 12.5664 \times 10^8$

$\epsilon_\infty = 5.27137 + 0.0216474t - 0.00131198t^2$

$\alpha = -\frac{-16.8129}{t+273} + 0.0609265$

$\lambda_s = 0.00033836e^{2513.98/(t+273)}$

B.2 Corrected attenuation models

B.2.1 Kharadly 3rd model for attenuation

Because of the deviation of the results of the 1st model from that of the exact values for the melting-snow layer, Kharadly introduced a correction factor that brought the results of the model closely to the exact attenuations calculated using Mie scattering. The correction factor is given by [12]:

$$\text{Factor1} = \left\{\frac{n\left[(2+S)\frac{f}{f_r} + 1\right]}{\frac{f}{f_r} + 2 - S}\right\} \times \left\{\frac{2-S}{2+S}\right\}^{(1-S)} \qquad (2.7)$$

where f is the frequency in GHz, f_r is the resonant frequency of the melting-snow particle, S is the melting degree , defined as the melted to the total volume in the representative melting-snow particle.

B.2.2 Kharadly 4th model for attenuation

Because of the deviation of the results of the 2nd model from that of the exact values for the melting snow layer, Kharadly introduced a correction factor that brought the results of the model closely to the exact attenuations calculated using Mie scattering. The factor is given by:

$$\text{Factor2} = \left[\{n + S(1-n)\}\left\{1 + \frac{n^2\bar{a}(1-S)}{2\delta}\left[1 + \frac{(1-5S)f}{5f_r}\right]\right\}\right]^{(1-S)} \tag{2.8}$$

where $\bar{a}$ is the radius of the representative particle, δ is the skin depth of water = $\frac{100}{Real\left[f \times C_1 \times \sqrt{-\epsilon}\right]}$, with C_1 = 20.958, f is the frequency in GHz and ϵ is the complex permittivity of water.

The range of applicability of Kharadly's formulas is between 1–40 GHz

Appendix C Kharadly scattering model [11]

When an electromagnetic wave is incident on a dielectric sphere, it scatters (Figure C.1) . This scattering can be calculated using Mie scattering. This technique is computer intensive, and thus, not efficient to use. Other approaches have been developed by researchers in the field

One of the simpler techniques to model the scattering from rain has been developed by Kharadly [11]. Kharadly has based his model on two assumptions

1. A rain drop or a melting-snow particle, under the effect of an incident electric field, behaves as a point dipole.
2. The rain medium which has particles of different sizes can be represented with a fictitious medium of particles of the same geometry, but with the same particle size.

After introducing correction factors to deal with some of the inaccuracy introduced as a result of the simplification of the model, Kharadly concluded the following formula for hydrometeor scattering [11]:

$$\sigma(\theta,\phi) = \sigma(\bar{a}) \times \mathrm{F}\left(\mathrm{M}''\right) \times \mathrm{F}(n) \times \mathrm{F}(S) \times \mathrm{N_m} \qquad \textbf{C.1}$$

where,

$$\sigma(\bar{a}) = 4(k_o\bar{a})^{2n}\left|\frac{\epsilon-\epsilon_o}{\epsilon+2\epsilon_o}\right|^2 \frac{\pi\bar{a}^2}{1+\left(\frac{f}{f_r}\right)^{2n}}\mathrm{F}(\theta,\phi) \qquad \textbf{C.1(a)}$$

$$\mathrm{F}(\theta,\phi) = \left[\sin^{\frac{2}{n}}\theta + \frac{\frac{f}{f_r}}{1+\frac{f}{f_r}}\xi^2\left(\sin^3\theta\cos\phi + \frac{1}{2}\cos^4\theta\right)\right]^n \qquad \textbf{C.1(b)}$$

$$\mathrm{F}(\mathrm{M}'') = 1 + \frac{M''}{2.6}\left[1 - \frac{M''}{2.6}\left(1+\frac{R}{600}\right)\right]\sin\theta\cos\phi \qquad \textbf{C.1(c)}$$

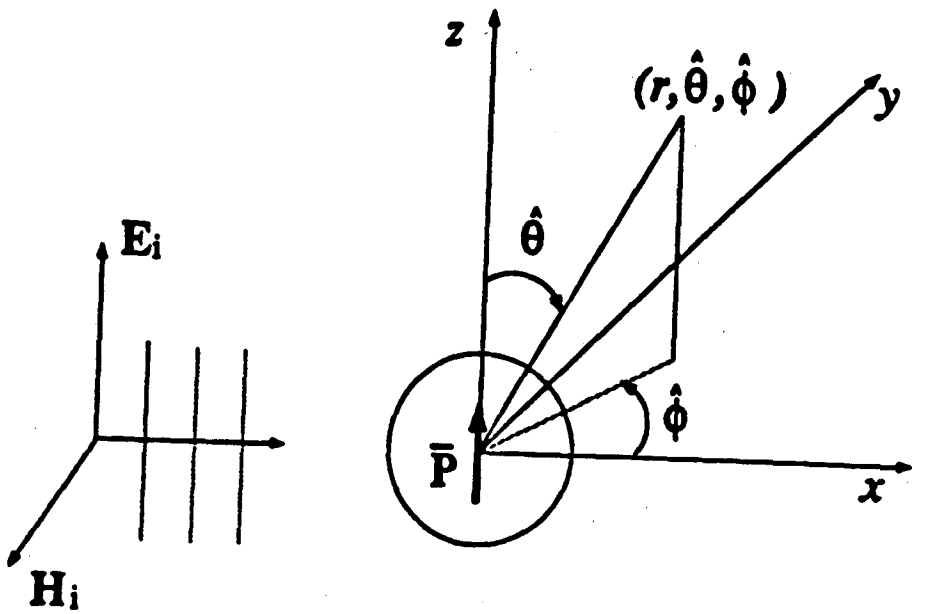

Figure C.1 Scattering geometry of a rain particle due to an incident electromagnetic wave.

$$\mathbf{F}(n) = \frac{(1+n)^2}{2n(2.5n-1)}\left[\frac{n^2+\frac{f}{f_r}}{1+n^2\frac{f}{f_r}}\right]^n\left[\frac{1+\frac{R}{300}}{2}+\frac{\left(\frac{f}{f_r}\right)^2}{1+\left(\frac{f}{f_r}\right)^2}\left(1-\frac{R}{150}\right)\right] \quad \textbf{C.1(d)}$$

$$\mathbf{F}(S) = \{n^2\left[\frac{150}{150+R}\times\frac{25S}{1+\left(\frac{f}{f_r}\right)^2}\right]^{(1-S)^4}\left(\frac{R}{100}\right)^{0.5}\times \left[\frac{R+100}{100}\left(1-0.5\frac{f}{f_r}\sin^2\phi\right)+\frac{1+\left(\frac{f}{f_r}\right)^2}{2n^2}\cos\phi\sin\theta\right]\}^{1-S} \quad \textbf{C.1(e)}$$

where,

$k_o = \frac{2\pi}{\lambda_o}$

$\lambda_0 =$ free-space wavelength

$n = \frac{2+200\left(\frac{f}{f_r}\right)^3}{1+201\left(\frac{f}{f_r}\right)^3}$

$f =$ frequency

$f_r = \frac{c}{\lambda_r}$, where c is the velocity of light in free space

$\lambda_r = \frac{2\pi\bar{a}}{\xi}$

$\bar{a} =$ outer radius of the representative melting-snow sphere

$\xi = 0.866(1+1.5\times10^{-4}f)$, where f is in GHz

$\epsilon_o =$ permittivity of free space

$\epsilon =$ permittivity of water

$M = M' - jM''$, is the refractive index of water ($= \epsilon_r^{1/2}$)

$\theta, \phi =$ polar and azimuthal angles, as in FigA.1

N_m = number of melting-snow particle per unit volume (rain drop density)

S = degree of melting = $\frac{\text{volume of melted snow}}{\text{total volume}}$

The radius of the representative melting snow sphere is given by:

$$\bar{a} = \left[(0.1 + 0.9\mathrm{S}) \sum_{\mathrm{i}} \frac{p_i v_{Ri}}{a_{Ri}^3 v_{mi}} \right]^{-1/3}$$

where

$p_i =$ fraction of rain drop of radius a_{Ri}

$v_{Ri} =$ fall velocity of rain drop of radius a_{Ri}

$v_{mi} =$ fall velocity of corresponding melting-snow spheres with a degree of melting S

$= 1.5 + (v_{Ri} - 1.5) \sin \frac{\pi \mathrm{S}}{2}$

Appendix D Empirical formula for attenuation

The most convenient method for modelling the attenuation of rain is by putting it in the following form [16]:

$$A_p = \alpha_{(f)} R^{\beta_{(f)}} \qquad \text{D.1}$$

where α and β have been found using a program which implements the least square data fitting technique. Given a value of β, the program will find the α that corresponds to the most accurate fit with the original (given) data. α, and β have been calculated for 27 frequencies ranging from 1–100 GHz. The original values of attenuations are the Mie calculations done by Kishk [12]. α, and β have then been fitted in two equations in function of frequency. These two equations are:

$$\beta_{(f)} = [1 \quad \tfrac{1}{f^2} \quad f^2 \quad f^3 \quad f^4 \quad f^2 e^{-f} \quad \tfrac{1}{f}] \begin{bmatrix} +1.16933000000 \\ -0.25154000000 \\ -2.45000 \times 10^{-4} \\ +3.50920 \times 10^{-6} \\ -1.46357 \times 10^{-8} \\ -0.44110000000 \\ +0.14282500000 \end{bmatrix} \qquad \text{D.1(a)}$$

$$\alpha_{(f)} = [f^{2.1} \quad f^6 \quad f^{2.5} \quad f^4 \quad f^8 \quad f^7] \begin{bmatrix} +3.4777654 \times 10^{-05} \\ +3.8866095 \times 10^{-12} \\ +2.9044983 \times 10^{-05} \\ -3.8528788 \times 10^{-08} \\ +2.3261638 \times 10^{-16} \\ -4.8164211 \times 10^{-14} \end{bmatrix} \qquad \text{D.1(b)}$$

The next step was to extend the formula to the melting snow layer. We did that by dividing the values of the attenuations for the different melting degrees (S) by the attenuation for rain. We call the result value of division as the melting snow layer normalized attenuation. A formula is found that gives a good fit for the normalized attenuation:

$$A_{n(R,f,S)} = M_1 S^{a_1-1} e^{-b_1 S^{a_1}} + M_2 S^{a_2-1} e^{-b_2 S^{a_2}} + M_3 e^{-b_3 S} + 1 \qquad \text{D.2}$$

Then,

$$A_p = A_n \times \alpha_{(f)} R^{\beta_{(f)}} \qquad \text{D.3}$$

In order to simplify equation D.2, the following assumptions can be safely made:

b_1 = 18

b_2 = 6.3

a_2 = 1.7

M_3 = —1

b_3 = 230

Equation D.2 then becomes:

$$A_{n(R,f,S)} = M_1 S^{a_1-1} e^{-18 S^{a_1}} + M_2 S^{0.7} e^{-6.3 S^{1.7}} - e^{-230 S} + 1 \qquad \text{D.4}$$

A formula to fit a_1 is found:

$$a_{1(f)} = [1 \quad f \quad \tfrac{1}{f} \quad \tfrac{1}{f^2} \quad f^{2.1}e^{-f} \quad \tfrac{1}{f^3}] \begin{bmatrix} +1.6806 \\ -2.791 \times 10^{-3} \\ -3.41706 \\ +5.0493 \\ +0.4707755 \\ -2.26293 \end{bmatrix} \qquad \text{D4(a)}$$

M_1 and M_2 are found to satisfy the following equations:

$$\begin{aligned} M_{1(R,f)} &= C_{0(f)} + C_{1(f)}R^{c_1} + C_{2(f)}R^{c_2} \\ M_{2(R,f)} &= D_{0(f)} + D_{1(f)}R^{d_1} + D_{2(f)}R^{d_2} \end{aligned} \qquad \text{D.5}$$

where

$c_1 = d_1 = 0.003$

$c_2 = d_2 = 0.0002$

Equation D.5 then becomes:

$$\begin{aligned} M_{1(R,f)} &= C_{0(f)} + C_{1(f)}R^{0.003} + C_{2(f)}R^{0.0002} \\ M_{2(R,f)} &= D_{0(f)} + D_{1(f)}R^{d_1} + D_{2(f)}R^{d_2} \end{aligned} \qquad \text{D.6}$$

Where $C_0(f)$, $C_1(f)$, $C_2(f)$ are given by:

$$C_{n(f)} = \begin{cases} \left[1 \quad f^2e^{-f} \quad f^{.2} \quad f^{.01} \quad f^{.7} \quad e^{-f} \quad \sin\left(\frac{f}{.9}\right)\right][X_{1n}] \\ \qquad for\ 1.0 < f < 12.0\ in\ GHz \\ \left[1 \quad f^{.003} \quad e^{f-100} \quad \frac{1}{\cosh(f-20)} \quad \ln(f) \quad \frac{1}{\cosh(f-40)} \quad \sin\left(\frac{f}{.08}\right)\right][Y_{1n}] \\ \qquad for\ 12.0 < f < 100.0\ in\ GHz \end{cases} \qquad \text{D.6(a)}$$

$$X_{1n} = \begin{bmatrix} n=0 & n=1 & n=2 \\ -4.46871 \times 10^{10} & -3.17499 \times 10^{09} & +4.78623 \times 10^{10} \\ +1.40323 \times 10^{08} & +1.00081 \times 10^{07} & -1.50331 \times 10^{08} \\ -6.96003 \times 10^{08} & -4.93871 \times 10^{07} & +7.45011 \times 10^{08} \\ +4.50656 \times 10^{10} & +3.20179 \times 10^{09} & -4.82676 \times 10^{10} \\ -6.42129 \times 10^{07} & -4.56513 \times 10^{06} & +6.87778 \times 10^{07} \\ +8.73118 \times 10^{08} & +6.21166 \times 10^{07} & -9.35236 \times 10^{08} \\ +1.40150 \times 10^{06} & +9.94801 \times 10^{04} & -1.50098 \times 10^{06} \end{bmatrix}$$

$$Y_{1n} = \begin{bmatrix} n=0 & n=1 & n=2 \\ -6.29528 \times 10^{10} & -4.08460 \times 10^{09} & +6.70282 \times 10^{10} \\ +6.29636 \times 10^{10} & +4.08533 \times 10^{09} & -6.70397 \times 10^{10} \\ +5.96653 \times 10^{05} & +4.25990 \times 10^{04} & -6.39256 \times 10^{05} \\ -3.88357 \times 10^{05} & -2.78377 \times 10^{04} & +4.16678 \times 10^{05} \\ -1.92394 \times 10^{08} & -1.24892 \times 10^{07} & +2.04855 \times 10^{08} \\ -1.82230 \times 10^{05} & -1.28176 \times 10^{04} & +1.95046 \times 10^{05} \\ +8.65689 \times 10^{04} & +6.23398 \times 10^{03} & -9.28018 \times 10^{04} \end{bmatrix}$$

Also, $D_0(f)$, $D_1(f)$, $D_2(f)$ are given by:

$$D_{n(f)} = \begin{cases} [1 \quad f \quad f^2 \quad f^3 \quad fe^{-f} \quad f^2e^{-f} \quad \sin(0.6(f-2.8)) \quad \ln(f)][X_{2n}] \\ \qquad for\ 1.0 < f < 20.0\ in\ GHz \\ [1 \quad f \quad f^2 \quad f^3 \quad fe^{-f} \quad f^2e^{-f} \quad \sin(0.6(f-2.8)) \quad \ln(f)][Y_{2n}] \\ \qquad for\ 20.0 < f < 100.0\ in\ GHz \end{cases}$$

D.6(b)

$$X_{2n} = \begin{bmatrix} n=0 & n=1 & n=2 \\ -2.09914 \times 10^{07} & -1.49368 \times 10^{06} & +2.24852 \times 10^{07} \\ +1.40003 \times 10^{07} & +9.95647 \times 10^{05} & -1.49959 \times 10^{07} \\ -8.88279 \times 10^{05} & -6.31410 \times 10^{04} & +9.51422 \times 10^{05} \\ +1.98926 \times 10^{04} & +1.41351 \times 10^{03} & -2.13062 \times 10^{04} \\ +4.17453 \times 10^{06} & +2.97214 \times 10^{05} & -4.47162 \times 10^{06} \\ +1.59365 \times 10^{07} & +1.13469 \times 10^{06} & -1.70713 \times 10^{07} \\ +7.50124 \times 10^{05} & +5.31790 \times 10^{04} & -8.03303 \times 10^{05} \\ -2.08356 \times 10^{07} & -1.48261 \times 10^{06} & +2.23186 \times 10^{07} \end{bmatrix}$$

$$Y_{2n} = \begin{bmatrix} n=0 & n=1 & n=2 \\ -4.43961 \times 10^{07} & -3.15028 \times 10^{06} & +4.75465 \times 10^{07} \\ -8.94385 \times 10^{05} & -6.33473 \times 10^{04} & +9.57732 \times 10^{05} \\ +6.29234 \times 10^{03} & +4.45502 \times 10^{02} & -6.73784 \times 10^{03} \\ -1.90282 \times 10^{01} & -1.34692 \times 10^{00} & +2.03751 \times 10^{01} \\ -2.52272 \times 10^{15} & -1.80339 \times 10^{14} & +2.70306 \times 10^{15} \\ +1.27660 \times 10^{14} & +9.12578 \times 10^{12} & -1.36786 \times 10^{14} \\ -2.29312 \times 10^{04} & -1.62315 \times 10^{03} & +2.45541 \times 10^{04} \\ +1.95225 \times 10^{07} & +1.38423 \times 10^{06} & -2.09068 \times 10^{07} \end{bmatrix}$$

Figures D.1–4 show that the empirical model agrees with the exact calculations. Although the formulas seems to be huge, their computer running time is quite short. Also, since the frequency remains constant during the integration, we can calculate the variables which are function of frequency at the beginning of the program and then we will be left with a simple formula for attenuation.

Unfortunately, this formula assumes that the density of the core in the melting snow particle to be 0.1. However it should not be very difficult to incorporate the density of the core into the equation without increasing the computer-running time of the formula considerably.

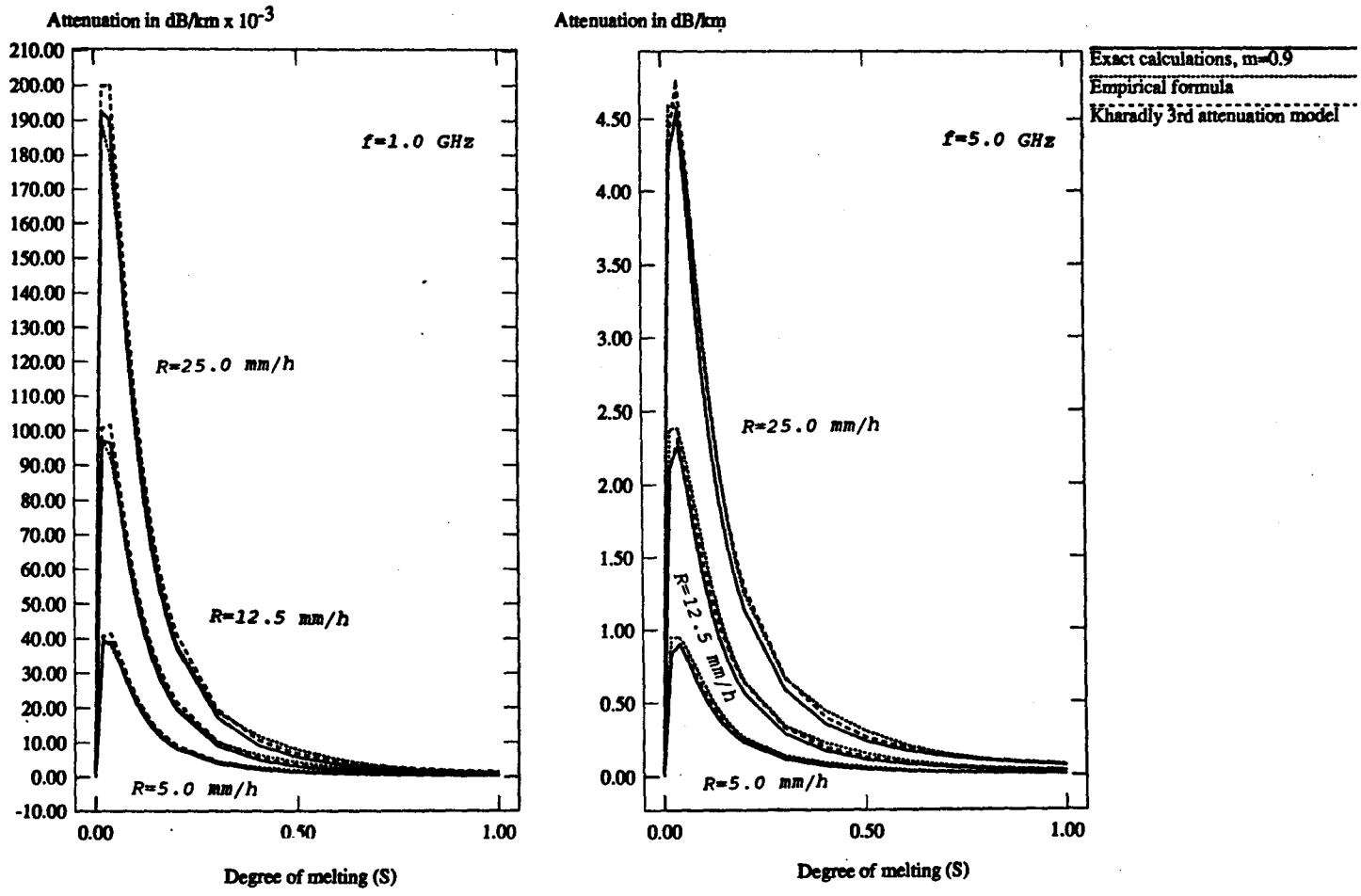

Figure D.1 A comparison of the attenuation profile of the melting layer for Kharadly 3rd attenuation model, Empirical model, and the Exact calculations for f (frequency) = 1.0 and 5.0 GHz (ρ_s = 0.1).

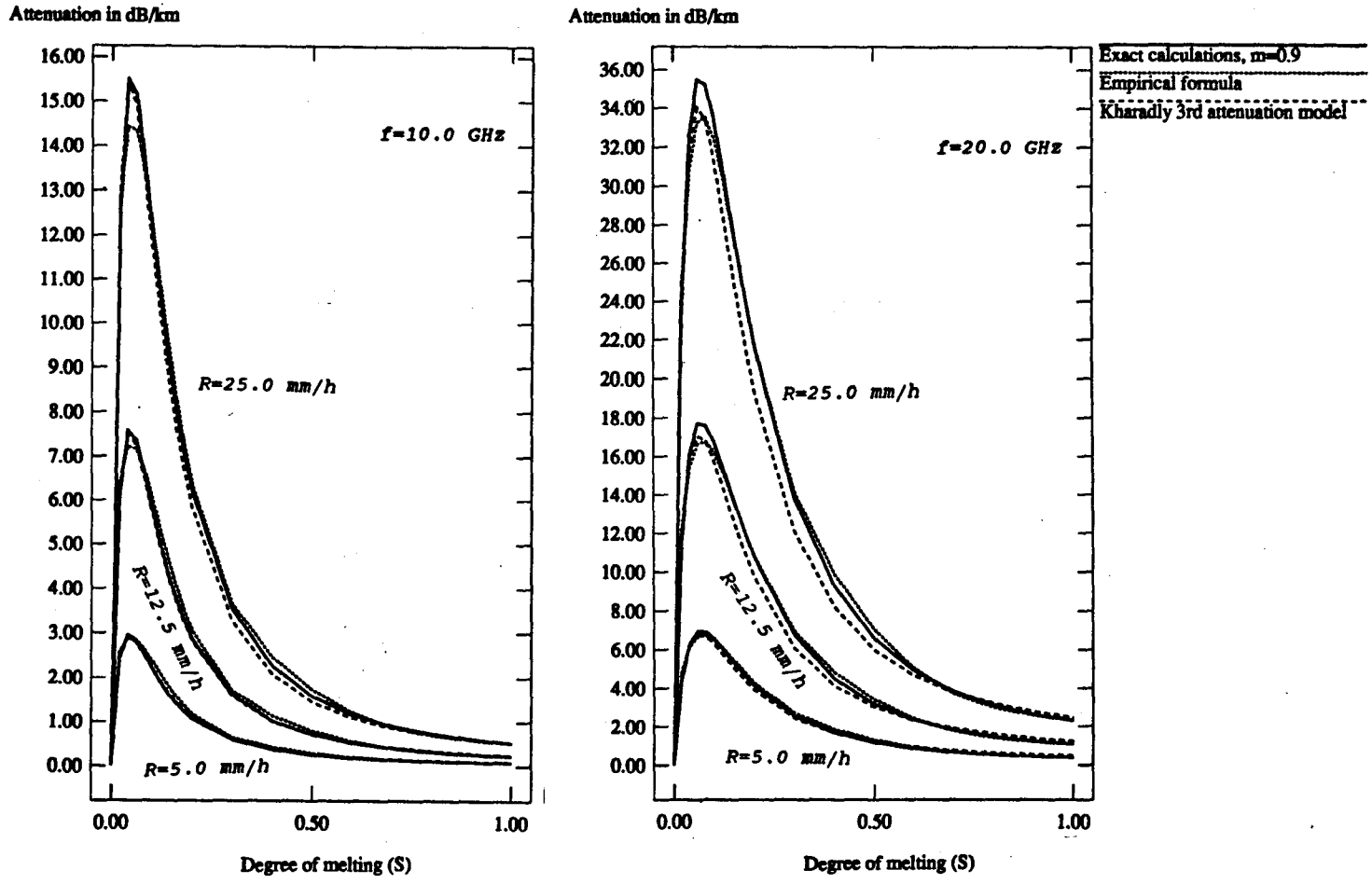

Figure D.2 A comparison of the attenuation profile of the melting layer between Kharadly 3rd attenuation model, Empirical model, and the Exact calculations for f (frequency) = 10.0 and 20.0 GHz (ρ_s = 0.1).

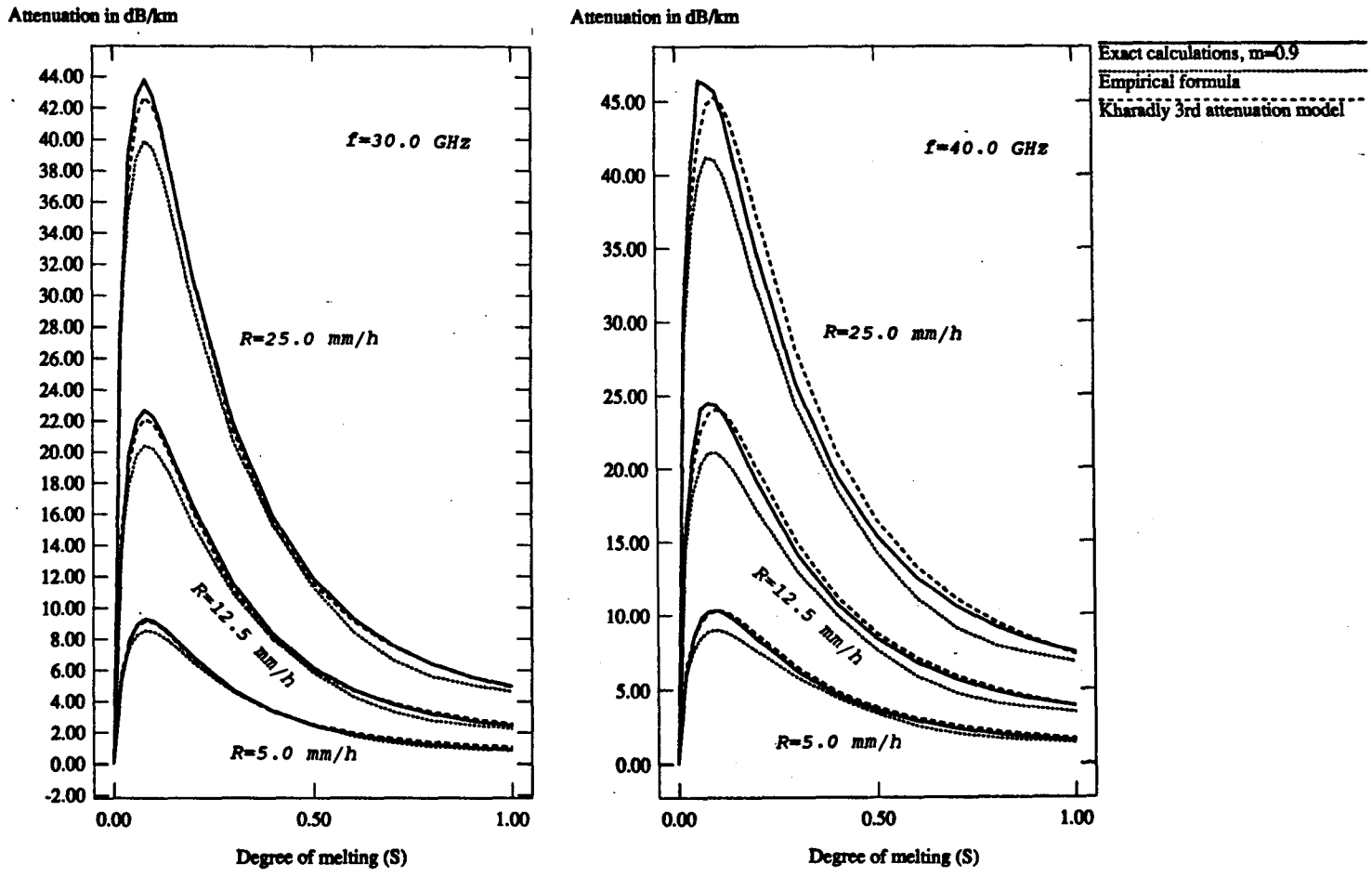

Figure D.3 A comparison of the attenuation profile of the melting layer between Kharadly 3rd attenuation model, Empirical model, and the Exact calculations for f (frequency) = 30.0 and 40.0 GHz (ρ_s = 0.1).

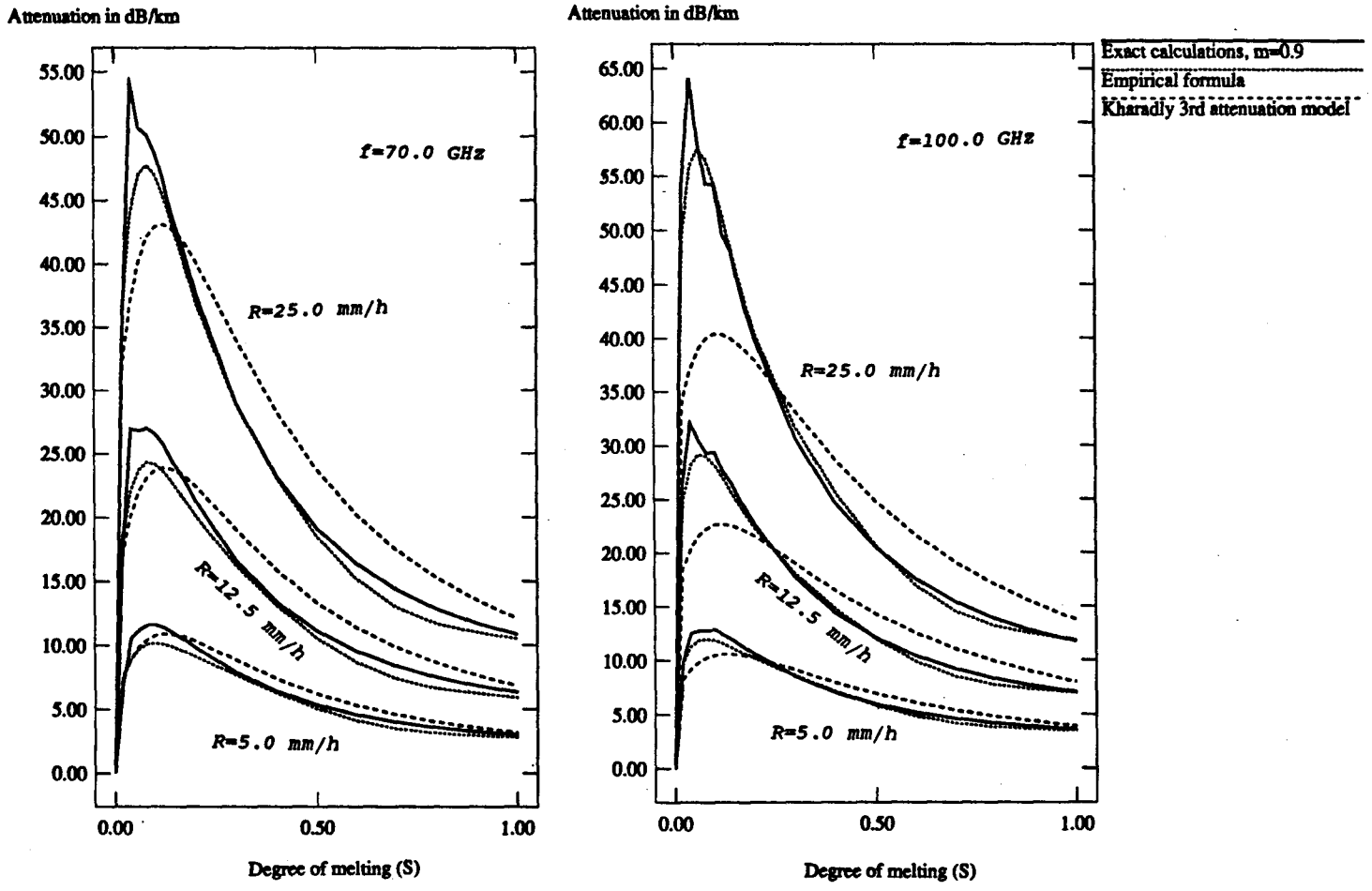

Figure D.4 A comparison of the attenuation profile of the melting layer between Kharadly 3rd attenuation model, Empirical model, and the Exact calculations for f (frequency) = 70.0 and 100.0 GHz (ρ_s = 0.1).

Appendix E The program for the "Universal Model"

The following is a listing of the program used in the calculations of the interference for the modified Capsoni rain model:

```
*
      DOUBLE PRECISION FREQ,T,QUANTITY,THETA,PHI,
     &     XH,YH,ZH,XTHE_T,XPHI_T,
     &     XR,YR,ZR,XXXXXX,YYYYYY,
     &     TR_ALPHA,TR_HALF_THETA,RE_ALPHA,RE_HALF_THETA,
     &     H_MELT,H_THICKNESS,H_RAIN,RAD,RMAX,FREQ,QUANTITY,T,
     &     D_RHO,G1,G2,HBW1,HBW2,K,MINT
      INTEGER TASKNUMBER1,TASKNUMBER2,SENTINAL
      CHARACTER*2 DECISION
*
      CALL AT_SC_MENU(TASKNUMBER1,TASKNUMBER2)
      CALL POSITIONINPUT(XH,YH,ZH,XTHE_T,XPHI_T,
     &     XR,YR,ZR,XXXXXX,YYYYYY)
*
      CALL GEO_INPUT(TR_ALPHA,TR_HALF_THETA,RE_ALPHA,
     &     RE_HALF_THETA,DECISION,H_MELT,H_THICKNESS,H_RAIN,RAD,
     &     R0,RMAX,FREQ,QUANTITY,T,D_RHO,G1,G2,HBW1,HBW2,K,MINT)
*
      CALL GEOMETRIC_MODEL(XH,YH,ZH,XTHE_T,XPHI_T,
     &     XR,YR,ZR,XXXXXX,YYYYYY,TR_ALPHA,T,QUANTITY,
     &     TR_HALF_THETA,RE_ALPHA,RE_HALF_THETA,DECISION,
     &     H_MELT,H_THICKNESS,H_RAIN,RAD,R0,RMAX,FREQ,D_RHO,G1,G2,
     &     THETA,PHI,TASKNUMBER1,TASKNUMBER2,HBW1,HBW2,K,MINT)
*
      STOP
      END
*******************************************************************************
*************** AT_SC_MENU ****************************************************
*******************************************************************************
*
      SUBROUTINE AT_SC_MENU(TASKNUMBER1,TASKNUMBER2)
*
      INTEGER TASKNUMBER1, TASKNUMBER2
*
      READ*,TASKNUMBER1
      READ*,TASKNUMBER2
*
      RETURN
      END
*******************************************************************************
**************** SUBROUTINE GEO_INPUT *****************************************
*******************************************************************************
*
      SUBROUTINE GEO_INPUT(TR_ALPHA,TR_HALF_THETA,RE_ALPHA,
     &     RE_HALF_THETA,DECISION,H_MELT,H_THICKNESS,H_RAIN,RAD,R0,
     &     RMAX,FREQ,QUANTITY,T,D_RHO,G1,G2,HBW1,HBW2,K,MINT)
*
      DOUBLE PRECISION TR_ALPHA,TR_HALF_THETA,RE_ALPHA,
     &     RE_HALF_THETA,H_MELT,H_THICKNESS,H_RAIN,RAD,R0,RMAX,
```

```
     &     FREQ,QUANTITY,T,D_RHO,G1,G2,HBW1,HBW2,K,MINT
      CHARACTER*2,DECISION
*
      READ*,TR_ALPHA
      READ*,TR_HALF_THETA
      READ*,RE_ALPHA
      READ*,RE_HALF_THETA
      READ*,DECISION
      IF (DECISION.eq.'Y')THEN
         READ*,H_MELT
         READ*,H_THICKNESS
      ENDIF
      READ*,H_RAIN
      READ*,RAD
      READ*,R0
      READ*,RMAX
      READ*,FREQ
      READ*,T
      READ*,QUANTITY
      READ*,D_RHO
      READ*,G1
      READ*,G2
      READ*,HBW1
      READ*,HBW2
      READ*,K
      READ*,MINT
*
      RETURN
      END
*******************************************************************************
*************** SUBROUTINE GEOMETRIC_MODEL ************************************
*******************************************************************************
*
*     XH,YH,ZH       - COORDINATES OF RAIN CELL (BOTTOM CENTER)
*     XTHE_T,XPHI_T    - DIRECTION OF MAIN BEAM ON TRANSMITTER
*     XR,YR,ZR       - COORDINATES OF RECEIVER
*     XXXXXX,YYYYYY    - DIRECTION OF MAIN BEAM ON RECEIVER
*     TR_ALPHA       - ANGLE OF ALPHA ON TRANSMITTER
*     TR_HALF_THETA  - THETA (HALF) FOR THE TRANSMITTER
*     RE_HALF_THETA  - THETA (HALF) FOR THE RECEIVER
*     DECISION       - 'Y' THERE IS A MELTING LAYER
*     H_MELT         - HEIGHT WHERE MELTING LAYER STARTS
*     H_THICKNESS    - THICKNESS OF MELTING LAYER
*     H_RAIN         - HEIGHT OF RAIN CELL
*     RAD            - RADIUS OF RAIN CELL
*     R0             - RAIN RATE DISTRIBUTION VARIABLE
*     RMAX           - MAXIMUM RAIN RATE
*     FREQ           - FREQUENCY
*     D_RHO          - INCREMENT FOR POSITION OF MAIN BEAM
*     G1             - GAIN OF TRANSMITTER
*     G2             - GAIN OF RECEIVER
*     T_X,T_Y,T_Z    - DIRECTION OF TRANSMITTER MAIN LOBE
*     R_X,R_Y,R_Z    - DIRECTION OF RECEIVER MAIN LOBE
*     X1,Y1,Z1       - 1ST INTERSECTION OF RAIN CELL AND LOBE OF TRANSMITTER
*     X2,Y2,Z2       - 2ND INTERSECTION OF RAIN CELL AND LOBE OF TRANSMITTER
*     X,Y,Z          - INTERSECTION OF RAIN CELL AND TRANSMITTED BEAM
*     X1P,Y1P,Z1P    - 1ST INTERSECTION OF RAIN CELL AND LOBE OF RECEIVER
*     X2P,Y2P,Z2P    - 2ND INTERSECTION OF RAIN CELL AND LOBE OF RECEIVER
*     X11,Y11,Z11    - CLOSEST INTERSECTION OF RAIN CELL AND LOBE OF RECEIVER
*     XPR,YPR,ZPR    - LOCATION OF RECEIVER RELATIVE TO NEW AXIS (X',Y',Z')
*     XDPR,YDPR,ZDPR- NEW POSITION OF RECEIVER AFTER TRANSLATION OF TRANSMITTER
*                      TO RAIN CELL
*     DPRHO,DPTHETA,
*     DPPHI          - SPHERICAL COORDINATES OF RECEIVER WHEN ORIGINAL
*                      COORDINATE SYSTEM HAS BEEN ROTATED AND TRANSLATED
```

```
*     T               - TEMPERATURE
*     QUANTITY        - THE MASS VALUE OF THE RAIN, SNOW LAYER
*     S               - THE PARAMETER A/B OF THE MELTING SNOW LAYER
*     HMIN            - BOTTOM HEIGHT OF RAIN CELL MEASURED FROM TRANSMITTER
*     HMAX            - TOTAL HEIGHT OF RAIN CELL MEASURED FROM TRANSMITTER
*     HFR             - HEIGHT OF FREEZING LAYER MEASURED FROM TRANSMITTER
*     HM              - HM HEIGHT OF MELTING LAYER MEASURED FROM TRANSMITTER
*     HEIGHT          - HEIGHT OF BEAM IN RAIN CELL
*     RATE            - RAIN RATE
*     ATTEN,ATTE2     - ATTENUATION DB/KM AND FROM GAMMA RESPECTIVELY
*     THETA           - THETA DIRECTION OF SCATTERTING
*     PHI             - PHI DIRECTION OF SCATTERING
*     XN,YN,ZN        - COORDINATES OF X,Y,Z WHEN AXIS TRANSLATED TO (XR,YR,ZR)
*     YYYYYY           - ANGLE BETWEEN SCATTERED BEAM BEING RECEIVED AND
*                        DIRECTION OF RECEIVING ANTENNA
*     AG,AH           - ATTENUATION DUE TO GAS AND HUMIDITY RESPECTIVELY
*     RT              - 3X3 MATRIX TO ROTATE AXIS
*     TASKNUMBER1     - ATTENUATION TASKNUMBER
*     TASKNUMBER2     - SCATTEING TASKNUMBER
*     HBW1            - HALF POWER BEAM WIDTH FOR RECEIVING ANTENNA MAIN LOBE
*     HBW2            - HALF POWER BEAM WIDTH FOR RECEIVE ANTENNA SECONDARY LOBE
*     K               - GAIN OF SECONDARY LOBE RELATIVE TO MAIN LOBE
*     A_X,A_Y,A_Z     - COORDINATE OF ALPHA TRANSMITTER
*
*******************************************************************************
*
      SUBROUTINE GEOMETRIC_MODEL(XH,YH,ZH,XTHE_T,XPHI_T,
     &     XR,YR,ZR,XXXXXX,YYYYYY,TR_ALPHA,T,QUANTITY,
     &     TR_HALF_THETA,RE_ALPHA,RE_HALF_THETA,DECISION,
     &     H_MELT,H_THICKNESS,H_RAIN,RAD,R0,RMAX,FREQ,D_RHO,G1,G2,
     &     THETA,PHI,TASKNUMBER1,TASKNUMBER2,HBW1,HBW2,K,MINT)
*
      DOUBLE PRECISION XH,YH,ZH,XTHE_T,XPHI_T,S,T,QUANTITY,
     &     XR,YR,ZR,XXXXXX,YYYYYY,TR_ALPHA,RATE,ATTEN,HMIN,
     &     TR_HALF_THETA,RE_ALPHA,RE_HALF_THETA,HMAX1,HFR,HM,HEIGHT,
     &     H_MELT,H_THICKNESS,H_RAIN,RAD,R0,RMAX,FREQ,D_RHO,G1,G2,GT,
     &     A_X,A_Y,A_Z,RHO,T_X,T_Y,T_Z,X1,Y1,Z1,X2,Y2,Z2,
     &     R1,R2,R,R_X,R_Y,R_Z,RT(3,3),X,Y,Z,X0,Y0,Z0,H1T,
     &     R1P,R2P,X1P,Y1P,Z1P,X2P,Y2P,Z2P,X11,Y11,Z11,XPR,YPR,ZPR,
     &     XTRAN,YTRAN,ZTRAN,XDPR,YDPR,ZDPR,DPRHO,DPTHETA,DPPHI,
     &     THETA,PHI,RTATT,XN,YN,ZN,YYYYYY,AG,AH,VAR,F,VARDUM,
     &     HBW1,HBW2,K,XI1,YI1,ZI1,XYZ,RI,G,GE,ANGI,TEML,MINT,
     &     NARR(2,3),ANUM,BNUM,A1NUM,RADAR_CONST
*
      INTEGER FLAG,TASKNUMBER1,TASKNUMBER2
      CHARACTER*2 DECISION
*
      VAR=0.D0
      T=0.D0
      R=1.D0
*
      CALL SPHERE2RECT(T_X,T_Y,T_Z,XTHE_T,XPHI_T,R)
*
      X0=0
      Y0=0
      Z0=0
      CALL LINE_CYLINDER_INTERSECT(X0,Y0,Z0,XH,YH,ZH,RAD,MINT,
     &     X1,Y1,Z1,X2,Y2,Z2,T_X,T_Y,T_Z,FLAG)
      IF (FLAG.LE.0) THEN
         PRINT*, '-99999'
         RETURN
      ENDIF
      IF (TASKNUMBER1. EQ. 5) THEN
         CALL A_B(FREQ,ANUM,BNUM)
         CALL N_CALC(FREQ,NARR)
```

```
         CALL A1_CALC(FREQ,A1NUM)
      ENDIF
      A_X=0
      A_Y=DSIND(TR_ALPHA)
      A_Z=DCOSD(TR_ALPHA)
*
      CALL SPHERE2RECT(R_X,R_Y,R_Z,XXXXXX,YYYYYY,R)
*
      CALL ROT_PARAMETERS(T_X,T_Y,T_Z,A_X,A_Y,A_Z,RT)
*
*     RT IS A 3 X 3 ARRAY WHICH HAS X',Y',Z' IN THE FIRST, SECOND
*     AND THIRD ROWS RESPECTIVELY.
*
      R1=DSQRT(X1**2+Y1**2+Z1**2)
      R2=DSQRT(X2**2+Y2**2+Z2**2)
      IF (R1.GT.R2) THEN
         RHO=R2+D_RHO/2
         RI=R1
         HEIGHT=Z1
      ELSE
         RHO=R1+D_RHO/2
         RI=R2
         HEIGHT=Z2
      ENDIF
*
 600  CALL SPHERE2RECT(X,Y,Z,XTHE_T,XPHI_T,RHO)
      R2=DSQRT((XR-X)**2+(YR-Y)**2+(ZR-Z)**2)
*
      XI1 = X - XR
      YI1 = Y - YR
      ZI1 = Z - ZR
      XYZ  = DSQRT(XI1**2 + YI1**2 + ZI1**2)
      XI1 = XI1/XYZ
      YI1 = YI1/XYZ
      ZI1 = ZI1/XYZ
      CALL LINE_CYLINDER_INTERSECT(XR,YR,ZR,XH,YH,ZH,RAD,MINT,
     &     X1P,Y1P,Z1P,X2P,Y2P,Z2P,XI1,YI1,ZI1,FLAG)
*
      R1P=DSQRT((X1P-XR)**2+(Y1P-YR)**2+(Z1P-ZR)**2)
      R2P=DSQRT((X2P-XR)**2+(Y2P-YR)**2+(Z2P-ZR)**2)
      IF (R1P.GT.R2P)THEN
         X11=X2P
         Y11=Y2P
         Z11=Z2P
      ELSE
         X11=X1P
         Y11=Y1P
         Z11=Z1P
      ENDIF
*
*     FINDING (XR,YR,ZR) RELATIVE TO NEW AXIS (X',Y',Z')-->(X'R,Y'R,Z'R)
*
      XPR=RT(1,1)*XR+RT(1,2)*YR+RT(1,3)*ZR
      YPR=RT(2,1)*XR+RT(2,2)*YR+RT(2,3)*ZR
      ZPR=RT(3,1)*XR+RT(3,2)*YR+RT(3,3)*ZR
*
      CALL TRANSLATION(X0,Y0,Z0,RHO,Y0,Z0,XTRAN,YTRAN,ZTRAN)
      XDPR=XPR-XTRAN
      YDPR=YPR-YTRAN
      ZDPR=ZPR-ZTRAN
      CALL RECT2SPHERE(XDPR,YDPR,ZDPR,DPTHETA,DPPHI,DPRHO)
*
*     FINDING S
*
      HMAX1=H_RAIN+ZH
```

```
      HFR=ZH+H_MELT+H_THICKNESS
      HM=H_MELT+ZH
      HMIN=ZH
      CALL GET_S(HMAX1,HFR,HM,HMIN,Z,S,DECISION)
*
*     CALCULATING RAIN RATE
*
      CALL RAINRATE(XH,YH,X,Y,RMAX,R0,RATE)
*
*     CALCULATE THE SPECIFIC ATTENUATION
*
      CALL ATT_TASK(FREQ,T,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &              NARR,A1NUM,ANUM,BNUM)
      TATT=ATTEN*D_RHO/1000+TATT
*
*     CALCULATE THE SCATTERING CROSS SECTION
*
      CALL SCAT_TASK(F,DPTHETA,DPPHI,S,RATE,FREQ,T,QUANTITY,
     &               TASKNUMBER2,DECISION,H_THICKNESS)
*
      IF (DECISION.EQ.'Y') THEN
         H1T = HFR
      ELSE
         H1T = HMAX1
      ENDIF
      IF (S.EQ.0.D0) THEN
         TEML = 10**(-0.00065*ABS(Z-H1T))
         F = TEML*F
      ENDIF
*
*     CALCULATING TOTAL RAIN ATTENUATION
*
      CALL RAIN_TOTAL_ATTENUATION(HMAX1,HFR,HM,HMIN,FREQ,T,
     &     QUANTITY,X,Y,Z,X11,Y11,Z11,RTATT,XH,YH,RMAX,R0,DECISION,
     &     TASKNUMBER1,NARR,A1NUM,ANUM,BNUM,XR,YR,ZR,H_THICKNESS,
     &     RAD,XTHE_T)
*
*     TRANSLATING X,Y,Z TO THE RECEIVER AXIS. SINCE THE COORDINATES (X,Y,Z)
*     ARE MEASURED FROM AN AXIS AT (0,0,0) ALL I HAVE TO DO IS SUBTRACT
*     THE POSITION OF THE RECEIVER FROM THE POINT AND THUS GET THE
*     TRANSLATED POINT.
*
      XN=X-XR
      YN=Y-YR
      ZN=Z-ZR
*
*     CALCULATING ANGLE BETWEEN UNIT VECTOR AND RECEIVER MAIN LOBE
*
      CALL ANGLE(XN,YN,ZN,R_X,R_Y,R_Z,ANGI)
      CALL ANTENNA_GAIN(ANGI,HBW1,HBW2,K,G)
*      CALL RECEIVING_GAIN(G2,ANGI,GE)
      CALL GAS_HUMIDITY_ATTENUATION(AG,AH)
*
      VARDUM=10**(-0.1D0*(TATT+RTATT+AG+AH))
      VAR=VAR+((F*G*D_RHO/(DPRHO**2))*VARDUM)
      RHO=RHO+D_RHO
*
      IF (RHO.LT.RI) GOTO 600
*
      CALL CONST_RADAR(FREQ,TR_HALF_THETA,G1,G2,GT,RADAR_CONST)
      VAR=VAR*RADAR_CONST
      VAR = 10.*DLOG10(VAR)
      PRINT*, VAR
*
      RETURN
```

```
      END
*****************************************************************************
***************SUBROUTINE ROT_PARAMETERS ************************************
*****************************************************************************
*     THIS SUBROUTINE FINDS THE PARAMETERS IN ORDER TO ROTATE THE X-AXIS
*     IN THE DIRECTION OF PROPAGATION.
*****************************************************************************
*
      SUBROUTINE ROT_PARAMETERS(T_X,T_Y,T_Z,A_X,A_Y,A_Z,T)
*
      DOUBLE PRECISION T_X,T_Y,T_Z,A_X,A_Y,A_Z,
     &     DUMMY,X,Y,Z,N_X,N_Y,N_Z,T(3,3),
     &     Z_X,Z_Y,Z_Z,Y_X,Y_Y,Y_Z
*
      N_X=0
      IF ((T_X.EQ.1).AND.(T_Y.EQ.0).AND.(T_Z.EQ.0))THEN
         Z_X=A_X
         Z_Y=A_Y
         Z_Z=A_Z
      ELSE
         N_Y=-T_Z/DSQRT(T_Z**2+T_Y**2)
         N_Z=T_Y/DSQRT(T_Z**2+T_Y**2)
         DUMMY=(A_Y*N_Y+N_Z*A_Z)*(1-T_X)
         Z_X=T_X*A_X
         Z_Y=N_Y*DUMMY+T_X*A_Y
         Z_Z=N_Z*DUMMY+T_X*A_Z
         CALL CROSS_PRODUCT(A_X,A_Y,A_Z,N_X,N_Y,N_Z,X,Y,Z)
         Z_X=Z_X-X*DSQRT(1-T_X**2)
         Z_Y=Z_Y-Y*DSQRT(1-T_X**2)
         Z_Z=Z_Z-Z*DSQRT(1-T_X**2)
      ENDIF
      CALL CROSS_PRODUCT(Z_X,Z_Y,Z_Z,T_X,T_Y,T_Z,Y_X,Y_Y,Y_Z)
*
      T(1,1)=T_X
      T(1,2)=T_Y
      T(1,3)=T_Z
      T(2,1)=Y_X
      T(2,2)=Y_Y
      T(2,3)=Y_Z
      T(3,1)=Z_X
      T(3,2)=Z_Y
      T(3,3)=Z_Z
*
      RETURN
      END
*****************************************************************************
********** SUBROUTINE ANTENNA_GAIN ******************************************
*****************************************************************************
*     THIS SUBROUTINE CALCULATES THE GAIN OF AN ANTENNA BY IMPLEMENTING
*     AN ANTENNA LOB THROUGH THE USE OF TWO GAUSSIAN APPROXIMATIONS.
*              G1(theta)=exp(-4ln2(theta/hbw1)^2)
*              G2(theta) = 10^(K/10)*exp(-4ln2(theta/hbw2)^2)
*
*              G(theta) = G1(theta) + G2(theta)
*              G(theta) = G(theta)/G(0)
*
*     THETA      - ANGLE OF RECEPTION
*     HBW1,HBW2  - HALF BEAM WIDTHS OF G1,G2 RESPECTIVELY
*     K          - INPUT PARAMETER TO HELP DETERMINE THE SHAPE OF THE ANTENNA
*                  GAIN PARAMETERS.
*
*****************************************************************************
*
      SUBROUTINE ANTENNA_GAIN(THETA,HBW1,HBW2,K,G)
*
```

```
      DOUBLE PRECISION THETA, HBW1,HBW2,K,G,G1,G2
*
*     CALCULATING G1(THETA) AND G2(THETA).
*
      THETA = ABS(THETA)
      G1=DEXP(-4.0D0*DLOG(2.0D0)*((THETA/HBW1)**2))
      G2=10**(K/10)*DEXP(-4.0D0*DLOG(2.0D0)*((THETA/HBW2)**2))
*
*     CALCULATING FINAL GAIN - G.
*     NOTE:  G(0) HAS BEEN ALREADY SIMPLIFIED.
*
      G=(G1+G2)/(1+10**(K/10))
*
      RETURN
      END
*******************************************************************************
*************** SUBROUTINE GAS_HUMIDITY_ATTENUATION ***************************
*******************************************************************************
*
      SUBROUTINE GAS_HUMIDITY_ATTENUATION(AG,AH)
*
      DOUBLE PRECISION AG,AH
*
      AG = 0.D0
      AH = 0.D0
*
      RETURN
      END
*************** SUBROUTINE GET_S ******************************************
*******************************************************************************
*     THIS SUBROUTINE CALCULATES THE VALUE OF S IN THE TRANSITION STAGE
*     FROM SNOW TO RAIN AT ANY HEIGHT OF THE RAIN CELL.
*******************************************************************************
*
      SUBROUTINE GET_S(HMAX1,HFR,HM,HMIN,HEIGHT,S,DECISION)
*
      DOUBLE PRECISION HMAX1,HFR,HM,HMIN,HEIGHT,S
      CHARACTER*2 DECISION
*
      IF (DECISION.EQ.'Y') THEN
         IF ((HEIGHT.GE.HMIN).AND.(HEIGHT.LE.HM))THEN
            S=1.D0
         ELSEIF ((HEIGHT.GE.HM).AND.(HEIGHT.LE.HFR)) THEN
            S=(HFR-HEIGHT)/(HFR-HM)
         ELSEIF (HEIGHT.GT.HFR) THEN
            S=0.D0
         ENDIF
      ELSE
         IF (HEIGHT.LE.HMAX1) THEN
            S = 1.0D0
         ELSE
            S = 0.D0
         ENDIF
      ENDIF
*
      RETURN
      END
*******************************************************************************
*************** SUBROUTINE LINE_CYLINDER_INTERSECT ****************************
*******************************************************************************
*     THIS SUBROUTINE COMPUTES THE INTERSECTION BETWEEN A LINE IN
*     THREE SPACE AND A CYLINDER.  THE CYLINDER IS IN THE Z-DIRECTION
*     X0,Y0,Z0 ARE THE POSITION WHERE THE LINE BEGINS, A,B ARE THE CENTER
*     OF THE CYLINDER AT X,Y RESPECTIVELY, H IS THE HEIGHT OF THE CYLINDER,
*     AND X1,Y1,Z1 AND X2,Y2,Z2 ARE THE INTERSECTION POINTS.  FLAG IS
```

```
*     A VARIABLE RETURNED TO TELL US IF THERE IS ONE INTERSECTION, TWO
*     INTERSECTIONS OR NO INTERSECTIONS FOR FLAG =0,1,-1 RESPECIVELY.
*     IN ADDITION, XD,YD,ZD GIVES THE DIRECTION OF THE LINE, R IS
*     THE RADIUS OF THE CYLINDER AND H IS THE HEIGHT OF THE CYLINDER.
*     T1 AND T2 ARE THE VARIABLES USED FOR THE PARAMETRIC EQUATIONS
*
*     NOTE*** IF THE LINE GOES STRAIGHT THROUGHT THE MIDDLE OF THE CYLINDER
*     IT WILL NOT SHOW INTERSECTION, SO IT IS EASY TO PUT THE LINE ON A
*     SMALL ANGLE.  THE RESULTS SHOULD BE VERY CLOSE.
*
*******************************************************************************
*
      SUBROUTINE LINE_CYLINDER_INTERSECT(X0,Y0,Z0,A,B,C,R,HH,X1,Y1,Z1,
     &     X2,Y2,Z2,XD,YD,ZD,FLAG)
*
      DOUBLE PRECISION X0,Y0,Z0,A,B,C,R,H,X1,Y1,Z1,X2,Y2,Z2,
     &     DISCRIMINANT,AA,BB,CC,T1,T2,XD,YD,ZD,HH,A1X,A1Y,
     &     A1Z,A2X,A2Y,A2Z,A11,A22,R1B,R2B,PHI1,PHI2,B11
      INTEGER FLAG
*
      H=HH+C
      AA=XD**2.0D0+YD**2.0D0
      BB=2.0D0*(X0*XD-A*XD+Y0*YD-B*YD)
      CC=X0**2.0D0+Y0**2.0D0+A**2.0D0+B**2.0D0-2*A*X0-2*B*Y0
      CC=CC-R**2.0D0
*
      DISCRIMINANT=BB**2.0D0-4*AA*CC
*
      IF (DISCRIMINANT .LT. 0) THEN
         FLAG=-1
*
      ELSEIF (DISCRIMINANT .EQ.0) THEN
         FLAG=0
         T1=-BB/(2.0D0*AA)
         Z1=XD*T+Z0
         IF ((Z1.LT.C) .OR. (Z1 .GT. H)) THEN
            FLAG=-1
         ELSE
            X1=XD*T1+X0
            Y1=XD*T1+Y0
            X2=X1
            Y2=Y1
            Z2=Z1
         ENDIF
*
      ELSEIF (DISCRIMINANT .GT. 0) THEN
         FLAG=1
         T1=(-BB-DSQRT(DISCRIMINANT))/(2*AA)
         T2=(-BB+DSQRT(DISCRIMINANT))/(2*AA)
         Z1=ZD*T1+Z0
         Z2=ZD*T2+Z0
         IF (((Z1.LT.C).AND.(Z2.LT.C)).OR.((Z1.GT.H).AND.(Z2.GT.H)))
     &        THEN
            FLAG=-1
         ELSEIF ((Z1.EQ.H).AND.(Z2.GT.H)) THEN
            FLAG=0
            X1=XD*T1+X0
            Y1=YD*T1+Y0
            X2=X1
            Y2=Y1
            Z2=Z1
         ELSEIF ((Z1.EQ.C).AND.(Z2.LT.C)) THEN
            FLAG=0
            X1=XD*T1+X0
            Y1=YD*T1+Y0
```

```
    X2=X1
    Y2=Y1
    Z2=Z1
 ELSEIF ((Z1.GT.H).AND.(Z2.EQ.H)) THEN
    FLAG=0
    X2=XD*T2+X0
    Y2=YD*T2+Y0
    X1=X2
    Y1=Y2
    Z1=Z2
 ELSEIF ((Z1.LT.C).AND.(Z2.EQ.C)) THEN
    FLAG=0
    X2=XD*T2+X0
    Y2=YD*T2+Y0
    X1=X2
    Y1=Y2
    Z1=Z2
 ELSEIF ((Z1.GT.H).AND.((Z2.LE.H).AND.(Z2.GE.C))) THEN
    X2=XD*T2+X0
    Y2=YD*T2+Y0
    Z1=H
    T1=(Z1-Z0)/ZD
    X1=XD*T1+X0
    Y1=YD*T1+Y0
 ELSEIF ((Z1.LT.C).AND.((Z2.LE.H).AND.(Z2.GE.C))) THEN
    X2=XD*T2+X0
    Y2=YD*T2+Y0
    Z1=C
    T1=(Z1-Z0)/ZD
    X1=XD*T1+X0
    Y1=YD*T1+Y0
 ELSEIF ((Z1.LT.C).AND.(Z2.GT.H)) THEN
    Z1=C
    Z2=H
    T1=(Z1-Z0)/ZD
    T2=(Z2-Z0)/ZD
    X1=XD*T1+X0
    Y1=YD*T1+Y0
    X2=XD*T2+X0
    Y2=YD*T2+Y0
 ELSEIF ((Z2.LT.C).AND.(Z1.GT.H)) THEN
    Z2=C
    Z1=H
    T1=(Z1-Z0)/ZD
    T2=(Z2-Z0)/ZD
    X1=XD*T1+X0
    Y1=YD*T1+Y0
    X2=XD*T2+X0
    Y2=YD*T2+Y0
 ELSEIF(((Z1.LE.H).AND.(Z1.GE.C)).AND.(Z2.GT.H)) THEN
    Z2=H
    T2=(Z2-Z0)/ZD
    X1=XD*T1+X0
    Y1=YD*T1+Y0
    X2=XD*T2+X0
    Y2=YD*T2+Y0
 ELSEIF(((Z1.GE.C).AND.(Z1.LE.H)).AND.(Z2.LT.C)) THEN
    Z2=C
    T2=(Z2-Z0)/ZD
    X1=XD*T1+X0
    Y1=YD*T1+Y0
    X2=XD*T2+X0
    Y2=YD*T2+Y0
 ELSE
    X1=XD*T1+X0
```

```
            Y1=YD*T1+Y0
            X2=XD*T2+X0
            Y2=YD*T2+Y0
         ENDIF
      ENDIF
      IF (ABS(ZD).EQ.(1.0)) THEN
         FLAG = 1
         X1 = XD
         Y1 = YD
         Z1 = C
         X2 = XD
         Y2 = YD
         Z2 = C + HH
      ENDIF
      IF (FLAG.EQ.1) THEN
         A1X = X1 - X0
         A1Y = Y1 - Y0
         A1Z = Z1 - Z0
         A2X = X2 - X0
         A2Y = Y2 - Y0
         A2Z = Z2 - Z0
         A11 = DSQRT(A1X**2 + A1Y**2 + A1Z**2)
         A22 = DSQRT(A2X**2 + A2Y**2 + A2Z**2)
         B11 = DSQRT(XD**2 + YD**2 + ZD**2)
         R1B = A1X*XD + A1Y*YD + A1Z*ZD
         R2B = A2X*XD + A2Y*YD + A2Z*ZD
         PHI1 = R1B/(A11*B11)
         PHI2 = R2B/(A22*B11)
         IF (A11.EQ.0.D0) THEN
            PHI1 = R1B/B11
         ENDIF
         IF (A22.EQ.0.D0) THEN
            PHI2 = R2B/B11
         ENDIF
         IF ((PHI1.LT.0.D0).AND.(PHI2.GE.0.D0)) THEN
            X1 = X0
            Y1 = Y0
            Z1 = Z0
         ELSEIF ((PHI2.LT.0.D0).AND.(PHI1.GE.0.D0)) THEN
            X2 = X1
            Y2 = Y1
            Z2 = Z1
            X1 = X0
            Y1 = Y0
            Z1 = Z0
         ELSEIF ((PHI1.LT.0.D0).AND.(PHI2.LT.0.D0)) THEN
            FLAG = -1
         ENDIF
      ENDIF
      RETURN
      END
*****************************************************************************
*****************************************************************************
*************** SUBROUTINE POSITIONINPUT ************************************
*****************************************************************************
*     THIS SUBROUTINE INPUTS THE POSITION OF THE RAIN CELL (XN,YN,ZN),
*     POSITION OF TRANSMITTER (XT,YT,ZT), DIRECTION OF TRANSMISSION
*     (XTHE_T,XPHI_T), POSITION OF RECEIVER (XR,YR,ZR), AND DIRECTION
*     OF RECEPTION (XXXXXX,YYYYYY)
*****************************************************************************
*
      SUBROUTINE POSITIONINPUT(XH,YH,ZH,XTHE_T,XPHI_T,
     &     XR,YR,ZR,XXXXXX,YYYYYY)
*
      DOUBLE PRECISION XH,YH,ZH,XTHE_T,XPHI_T,XR,YR,ZR,
```

```
     &      XXXXXX,YYYYYY
*
      READ*,XH
      READ*,YH
      READ*,ZH
      READ*,XTHE_T
      READ*,XPHI_T
      READ*,XR
      READ*,YR
      READ*,ZR
      READ*,XXXXXX
      READ*,YYYYYY
*
      RETURN
      END
*****************************************************************************
*****************************************************************************
*************** SUBROUTINE ROTATION ******************************************
*****************************************************************************
*     THIS ROUTINE CALCULATES THE VALUES OF THE POINT TRANSFORMED TO THE
*     NEW COORDINATE SYSTEM.  X,Y,Z ARE THE VALUES IN THE OLD COORDINATE
*     SYSTEM. XB,YB,ZB ARE THE VALUES OF X,Y,Z IN THE NEW COORDINATE SYSTEM.
*     THE TRANSFORMATION MATRIX IS:
*                                  |T11 T12 T13|
*                                  |T21 T22 T23|
*                                  |T31 T32 T33|
*****************************************************************************
*
      SUBROUTINE ROTATION(T11,T12,T13,T21,T22,T23,T31,T32,T33,
     &      X,Y,Z,XB,YB,ZB)
*
      DOUBLE PRECISION T11,T12,T13,T21,T22,T23,T31,T32,T33,
     &      X,Y,Z,XB,YB,ZB
*
*     COMPUTING THE NEW X,Y,Z FROM THE TRANSFORMATION MATRIX
*
      XB=T11*X+T12*Y+T13*Z
      YB=T21*X+T22*Y+T23*Z
      ZB=T31*X+T32*Y*T33*Z
*
      RETURN
      END
*****************************************************************************
*************** SUBROUTINE UNIT_VECTOR ***************************************
*****************************************************************************
*     THIS SUBROUTINE CALCULATES THE UNIT VECTOR BETWEEN TWO POINT IN
*     SPACE.
*****************************************************************************
*
      SUBROUTINE UNIT_VECTOR(X1,Y1,Z1,X2,Y2,Z2,X,Y,Z)
*
      DOUBLE PRECISION X1,Y1,Z1,X2,Y2,Z2,X,Y,Z,DUMMY,DISTANCE
*
      DUMMY=DISTANCE(X1,Y1,Z1,X2,Y2,Z2)
      X=(X2-X1)/DUMMY
      Y=(Y2-Y1)/DUMMY
      Z=(Z2-Z1)/DUMMY
*
      RETURN
      END
*****************************************************************************
*************** FUNCTION DISTANCE ********************************************
*****************************************************************************
*     THIS FUNCTION  CALCULATES THE DISTANCE BETWEEN TWO POINTS IN SPACE.
*     AND THE UNIT VECTOR BETWEEN THE TWO POINTS
```

```
*****************************************************************************
*
      DOUBLE PRECISION FUNCTION DISTANCE(X1,Y1,Z1,X2,Y2,Z2)
*
      DOUBLE PRECISION X1,Y1,Z1,X2,Y2,Z2,X,Y,Z
*
      X=(X1-X2)**2.D0
      Y=(Y1-Y2)**2.D0
      Z=(Z1-Z2)**2.D0
      DISTANCE=DSQRT(X+Y+Z)
*
      RETURN
      END
*****************************************************************************
*************** FUNCTION RADAR_CONST ****************************************
*****************************************************************************
*     THIS FUNCTION COMPUTES THE RADAR CONSTANT FROM THE INPUTS HALF_THETA
*     G1,G2,GT (GAINS) AND FREQUENCY IN GHz.
*****************************************************************************
*
      SUBROUTINE CONST_RADAR(FREQ,HALF_THETA,G1,G2,GT,RADAR_CONST)
*
      DOUBLE PRECISION FREQ,HALF_THETA,G1,G2,GT,RADAR_CONST
      PARAMETER(PI=3.14159265359D0,C=2.9979244574D8)
*
      GT=1.D0
      RADAR_CONST=(1/(256*PI**2.D0))*((C/(FREQ*1.D9))**2.D0)
      RADAR_CONST=RADAR_CONST*(HALF_THETA**2.D0)*G1*G2*GT
*
      RETURN
      END
*****************************************************************************
*****************************************************************************
*************** SUBROUTINE TRANSLATION **************************************
*****************************************************************************
*     THIS SUBROUTINE GIVES THE NEW COORDINATES XTRAN,YTRAN,ZTRAN OF THE POINT
*     X,Y,Z IN RELATION A NEW SET OF AXES X0,Y0,Z0.
*****************************************************************************
*
      SUBROUTINE TRANSLATION(X0,Y0,Z0,X,Y,Z,XTRAN,YTRAN,ZTRAN)
*
      DOUBLE PRECISION X0,Y0,Z0,X,Y,Z,XTRAN,YTRAN,ZTRAN
*
      XTRAN=X-X0
      YTRAN=Y-Y0
      ZTRAN=Z-Z0
      RETURN
      END
*****************************************************************************
*****************************************************************************
*************** SUBROUTINE ANGLE ********************************************
*****************************************************************************
*     THIS SUBROUTINE COMPUTES THE ANGLE BETWEEN TWO 3-DIMENSIONAL
*     VECTORS.  THE EQUATION USED IS COS(PHI)=X1*X2+Y1*Y2+Z1*Z2
*                                            ----------------
*                                            SQRT(|A1||A2|)
*     WHERE PHI IS THE ANGLE BETWEEN THE VECTORS.
*****************************************************************************
*
      SUBROUTINE ANGLE(X1,Y1,Z1,X2,Y2,Z2,PHI)
*
      DOUBLE PRECISION X1,Y1,Z1,X2,Y2,Z2,NUM,DEN,PI,PHI,
     &                 TEMP1
      PARAMETER(PI=3.14159265359D0)
*
```

```
      NUM=X1*X2+Y1*Y2+Z1*Z2
      DEN=DSQRT((X1*X1+Y1*Y1+Z1*Z1)*(X2*X2+Y2*Y2+Z2*Z2))
      TEMP1 = NUM/DEN
      IF (TEMP1.GT.1.D0) TEMP1 = 1.D0
      PHI=DACOSD(TEMP1)
*
      RETURN
      END

*****************************************************************************
*************** SUBROUTINE CROSS_PRODUCT ************************************
*****************************************************************************
*     THIS ROUTINE COMPUTES THE CROSS PRODUCT OF TWO VECTORS.
*     FOR EXAMPLE A=X1+Y1+Z1, B=X2+Y2+Z2
*     THE CROSS PRODUCT OF A X B IS COMPUTED.
*****************************************************************************
*
      SUBROUTINE CROSS_PRODUCT(X1,Y1,Z1,X2,Y2,Z2,X,Y,Z)
*
      DOUBLE PRECISION X1,Y1,Z1,X2,Y2,Z2,X,Y,Z
*
      X=Y1*Z2-Y2*Z1
      Y=X2*Z1-X1*Z2
      Z=X1*Y2-X2*Y1
*
      RETURN
      END
*****************************************************************************
*****************************************************************************
*************** SUBROUTINE SPHERE2RECT **************************************
*****************************************************************************
*     THIS ROUTINE CONVERTS THE SPHERICAL COORDINATES ENTERED TO
*     RECTANGULAR COORDINATES.  WHERE THE INPUTS ARE THETA(DEG),PHI(DEG),
*     RHO AND THE OUTPUTS ARE X,Y,Z
*****************************************************************************
*
      SUBROUTINE SPHERE2RECT(X,Y,Z,THETA,PHI,RHO)
*
      DOUBLE PRECISION X,Y,Z,THETA,PHI,RHO
*
      X=RHO*DSIND(THETA)*DCOSD(PHI)
      Y=RHO*DSIND(THETA)*DSIND(PHI)
      Z=RHO*DCOSD(THETA)
*
      RETURN
      END
*****************************************************************************
*****************************************************************************
*************** SUBROUTINE RECT2SPHERE **************************************
*****************************************************************************
*     THIS ROUTINE CONVERTS THE RECTANGULA4R COORDINATES ENTERED TO
*     SPHERICAL COORDINATES.  WHERE THE INPUTS ARE X,Y,Z AND
*     THE OUTPUTS ARE RHO, THETA(DEG), PHI(DEG).
*****************************************************************************
*
      SUBROUTINE RECT2SPHERE(X,Y,Z,THETA,PHI,RHO)
*
      DOUBLE PRECISION X,Y,Z,THETA,PHI,RHO
*
      THETA=DATAND(DSQRT(X*X+Y*Y)/Z)
      PHI=DATAND(Y/X)
      RHO=DSQRT(X*X+Y*Y+Z*Z)
      IF ((X.LE.0).AND.(Y.GE.0)) THEN
         PHI = 180.D0 + PHI
      ELSEIF ((X.LE.0).AND.(X.LE.0)) THEN
```

```
         PHI = PHI + 180.D0
      ELSEIF ((X.GE.0).AND.(Y.LE.0)) THEN
         PHI = PHI + 360.D0
      ENDIF
      IF ((ABS(Z).GT.0).AND.(X.EQ.0).AND.(Y.EQ.0))THEN
         PHI=0
      ENDIF
      IF (Z.LT.0) THEN
        THETA = 180.D0 + THETA
      ENDIF
*
      RETURN
      END
*******************************************************************************
*************** SUBROUTINE SCAT_TASK ****************************************
*******************************************************************************
*
      SUBROUTINE SCAT_TASK(F,THETA,PHI,S,RATE,FREQ,T,QUANTITY,
     &     TASKNUMBER2,DECISION,H_THICKNESS)
*
      DOUBLE PRECISION F,THETA,PHI,S,RATE,FREQ,T,QUANTITY,
     &                 H_THICKNESS
      INTEGER TASKNUMBER2
      CHARACTER*2 DECISION
*
      IF (TASKNUMBER2.EQ.1) THEN
         CALL SCATTERING(F,THETA,PHI,S,RATE,FREQ,T,QUANTITY,DECISION,
     &                   H_THICKNESS)
      ENDIF
*
      RETURN
      END
*******************************************************************************
**************** SUBROUTINE SCATTERING ******************************************
*******************************************************************************
*     THIS SUBROUTINE COMPUTES F0, F(D)
*
*******************************************************************************
*
      SUBROUTINE SCATTERING(F,THETA,PHI,S,RATE,FREQ,T,QUANTITY,DECISION,
     &                      H_THICKNESS)
*
      DOUBLE PRECISION F,THETA,PHI,S,RATE,F0,F_THETA_PHI,QUANTITY,
     &     FMDP,FD,FS,FD1,FD2,FD3,PI,T,FREQ,A_REP,FREQUENCY,FREQR,
     &     N,NUM,F01,F02,F03,K,C,XI,STEMP,H_THICKNESS,RTEMP,REF
      COMPLEX*16 E,M,MDP
      CHARACTER*2 DECISION
      PARAMETER(PI=3.14159265359D0,C=2.9979244574D10)
*
      STEMP=1.D0
      IF (THETA.GT.90.D0) THEN
         THETA=180.D0-THETA
      ENDIF
      IF (PHI.GT.180.D0) THEN
         PHI=360.D0-PHI
      ENDIF
      IF (S.LT.0.008D0) THEN
         STEMP=S
         S=1.D0
      ENDIF
      IF (RATE .LT. 0.25D0) THEN
         RTEMP = RATE
         RATE = 0.25D0
      ENDIF
      CALL A(S,RATE,A_REP,QUANTITY)
```

```
      XI=0.866D0*(1.D0+FREQ*1.5D-4)
      FREQR=C*XI/(2.D0*PI*A_REP)
      FREQUENCY=FREQ*1.D9
      K=FREQUENCY/FREQR
      N=(2.D0+200.D0*(K)**3.D0)/(1.D0+201.D0*(K)**3.D0)
*
      CALL NUMBER(RATE,NUM,S,QUANTITY)
      CALL PERMATIVITY(T,FREQUENCY,E,M)
*
      F01=400.D0*NUM*(XI**(2.D0*N))*PI*A_REP**2.D0
      F02=(ABS((E-1.D0)/(E+2.D0)))**2.D0
      F03=((K)**(2.D0*N))/(1.D0+(K)**(2.D0*N))
      F0=F01*F02*F03
*
      FD1=((1.D0+N)**2.D0)/(2.D0*N*(2.5D0*N-1.D0))
      FD2=((N**2.D0+K)/(1.D0+(N**2.D0)*K))**N
      FD3=(1.D0+RATE/300.D0)/2.D0
      FD3=FD3+((K**2.D0)/(1.D0+K**2.D0))*(1.D0-RATE/150.D0)
      FD=FD1*FD2*FD3
*
      MDP=-DIMAG(M)
      CALL FTP_FM_FS(F_THETA_PHI,FMDP,FS,XI,K,N,RATE,S,THETA,PHI,MDP)
*
      F =F0*F_THETA_PHI*FD*FMDP*FS
      IF (STEMP.LT.0.008D0) THEN
         S=STEMP
         F=F/1.D0
         IF (DECISION.NE.'Y') THEN
            F = F*1.D0
         ENDIF
         IF ((DECISION.EQ.'Y').AND.(H_THICKNESS.EQ.0.D0)) THEN
            F = F*1.D0
         ENDIF
      ENDIF
      IF (RATE .LT. 0.25D0) THEN
         F = F*RTEMP/0.25D0
         RATE = RTEMP
      ENDIF
*
      IF (S.EQ.0.D0) THEN
         REF = 400.D0*RATE**1.4
         F = F02*REF*(PI**5)*(1.D-18)*(FREQUENCY/(C*0.01D0))**4
      ENDIF
      RETURN
      END
*****************************************************************************
*****************************************************************************
********* SUBROUTINE FTP_FM_FS ************************************************
*****************************************************************************
*
      SUBROUTINE FTP_FM_FS(F_THETA_PHI,FMDP,FS,XI,K,N,RATE,S,THETA,
     &     PHI,MDP)
*
      DOUBLE PRECISION F_THETA_PHI,FMDP,FS,XI,K,N,RATE,S,THETA,
     &     PHI,MDP,F_TH1,F_TH2,F_TH3,FMDP1,FMDP2,FS1,FS2,FS3
*
      F_TH1=(DSIND(THETA))**(2.D0/N)
      F_TH2=(K/(1.D0+K))*(XI**2.D0)
      F_TH3=(((DSIND(THETA))**3.D0)*DCOSD(PHI))
      F_TH3=F_TH3+.5D0*(DCOSD(THETA))**4.D0
      F_THETA_PHI=(F_TH1+F_TH2*F_TH3)**N
*
      FMDP1=1.D0-(MDP/2.6D0)*(1.D0+RATE/600.D0)
      FMDP2=(MDP/2.6D0)*DSIND(THETA)*DCOSD(PHI)
      FMDP=1.D0+FMDP1*FMDP2
```

```
*
      FS1=((150.D0/(150.D0+RATE))*25.D0*S/(1.D0+K**2.D0))
      FS1=(N**2.D0)*FS1**((1.D0-S)**4.D0)
      FS1=FS1*DSQRT(RATE/100.D0)
      FS2=((RATE+100.D0)/100.D0)*(1.D0-.5D0*K*(DSIND(PHI))**2.D0)
      FS3=((1.D0+K**2.D0)/(2.D0*N**2.D0))*DCOSD(PHI)*DSIND(THETA)
      FS=(FS1*(FS2+FS3))**(1.D0-S)
*
      RETURN
      END
*******************************************************************************
********** SUBROUTINE GET_ATTEN ***********************************************
*******************************************************************************
*     THIS SUBROUTINE INTERPOLATES THE ATTENUATION TABLE TO FIND THE
*     ATTENUATION FOR ANY RAIN RATE BETWEEN 1.25 AND 150 mm/hr. AND
*     ANY S BETWEEN 0.0 AND 1.0.
*     NOTE:  IF THE RAIN RATE IS GREATER THAN 50 mm/hr. AND S IS NOT
*     EQUAL TO 1.0 THEN THE RESULT WILL BE INCORRECT.  WE DO NOT HAVE VALUES
*     FOR THESE RAIN RATES AND S.
*     AT_TABLE IS THE RETURNED ATTENUATION VALUE FROM THE TABLE.
*
*     AT        - ARRAY OF ATTENUATION FOR DIFFERENT RAIN RATES AND S
*     RATE      - THE ENTERED RAIN RATE
*     S         - THE ENTERED S
*     AT_TABLE  - THE RETRIEVED ATTENUATION FROM THE ARRAY AT
*                 (INCLUDING INTERPOLATION)
*     R,SS      - ARRAYS OF RAIN RATE AND S TO FIND POSITION IN ARRAY
*     DUM1,DUM2- DUMMY VARIABLE TO HELP CALCULATE THE INTERPOLATED RESULT.
*
*******************************************************************************
*
      SUBROUTINE GET_ATTEN(AT,RATE,S,AT_TABLE)
*
      DOUBLE PRECISION AT(19,9),RATE,S,AT_TABLE,R(9),SS(19),
     &     DUM1,DUM2
      INTEGER I,R1,R2,S1,S2
*
*     RAIN RATE AND S ARRAYS RESPECTIVELY TO FIND POSITION IN ARRAY
*
      DATA R/0,1.25,2.5,5,12.5,25,50,100,150/
      DATA SS/0,.02,.04,.06,.08,0.1,.12,.14,.16,.18,.2,.3,.4,.5,.6,
     &     .7,.8,.9,1.0/
      AT(0,0)=0
*
*     FINDING POSITION OF ELEMENT.
*
      DO 10 I=1,8
         IF ((RATE.GT.R(I)).AND.(RATE.LE.R(I+1))) THEN
            R1=I
            R2=I+1
         ENDIF
 10   CONTINUE
      DO 20 I=1,18
         IF ((S.GT.SS(I)).AND.(S.LE.SS(I+1))) THEN
            S1=I
            S2=I+1
         ENDIF
 20   CONTINUE
*
      IF ((RATE.EQ.0).OR.(S.EQ.0))THEN
         AT_TABLE=0
      ELSE
         DUM1=(AT(S1,R2)-AT(S1,R1))*(RATE-R(R1))/(R(R2)-R(R1))
     &        +AT(S1,R1)
         DUM2=(AT(S2,R2)-AT(S2,R1))*(RATE-R(R1))/(R(R2)-R(R1))
```

```
     &          +AT(S2,R1)
         AT_TABLE=(DUM2-DUM1)*(S-SS(S1))/(SS(S2)-SS(S1))+DUM1
      ENDIF
*
      RETURN
      END
*******************************************************************************
********* SUBROUTINE GET_ARRAY ************************************************
*******************************************************************************
*     THIS SUBROUTINE READS FROM THE FILE 'DATA1' ALL THE S AND RAIN RATE
*     VALUES FOR ONE FREQUENCY.  IT THEN STORES THESE VALUES IN AN ARRAY
*     CALLED AT(S,RATE).
*******************************************************************************
*
      SUBROUTINE GET_ARRAY(FREQ,AT)
*
      DOUBLE PRECISION FREQ,AT(19,9),F(28),FR,R,SS
      INTEGER I,J,K
*
      DATA F/1,1.5,2,2.5,3,3.5,4,5,6,7,8,9,9.6,10,11,12,15,20,25,
     &     30,35,40,50,60,70,80,90,100/
      OPEN(UNIT=10,FILE='data1',STATUS='OLD')
*
      DO 20 J=1,28
         IF (F(J).EQ.FREQ) THEN
            K=J
            J=28
         ENDIF
 20         CONTINUE
      J=153*(K-1)
      DO 10 I=1,J
         READ(10,*)
 10         CONTINUE
      READ(10,*),FR
      DO 30 I=2,9
         READ(10,*),R
         DO 40 J=2,19
            READ(10,*),SS,AT(J,I)
 40      CONTINUE
 30   CONTINUE
      DO 50 I=1,9
         AT(1,I)=0
 50   CONTINUE
      DO 60 I=1,19
         AT(I,1)=0
 60   CONTINUE
*
      CLOSE(UNIT=10,STATUS='KEEP')
*
      RETURN
      END
*******************************************************************************
********* SUBROUTINE GET_AFB **************************************************
*******************************************************************************
*     THIS SUBROUTINE INTERPOLATES THE ATTENUATION, FORWARD, AND BACKWARD
*     SCATTERING FOR ANY RAIN RATE BETWEEN 1.25 AND 150 mm/hr. AND
*     ANY S BETWEEN 0.0 AND 1.0.
*     NOTE:  IF THE RAIN RATE IS GREATER THAN 50 mm/hr. AND S IS NOT
*     EQUAL TO 1.0 THEN THE RESULT WILL BE INCORRECT.  WE DO NOT HAVE VALUES
*     FOR THESE RAIN RATES AND S.
*     AFB_TABLE IS THE RETURNED ARRAY FORM 'data1'
*     ARRY      - THE ARRAY IN WHICH THE VALUES OF ATTENUATION,
*                 100 * FORWARD, AND 100* BACKWARD SCATTERING.
*     RATE      - THE ENTERED RAIN RATE
*     S         - THE ENTERED VALUE OF S
```

```
*     AFB_TABLE- THE VALUE OBTAINED FROM THE ARRAY AFTER INTERPOLATION,
*                (1) ATTENUATION, (2) FORWARD SCATTERING,(3) BACKWARD
*                SCATTERING
*     R,SS     - THE VALUES TO WHICH THE ENTERED RAIN RATE AND S ARE COMPARED.
*     DUM1,DUM2- DUMMY VARIABLES
*     R1,R2    - INDEX VALUES TO GIVE POSITION OF ENTERED RAIN RATE IN ARRAY R
*     S1,S2    - INDEX VALUES TO GIVE POSITION OF ENTERED S IN ARRAY SS
*
*******************************************************************************
*
      SUBROUTINE GET_AFB(ARRY,RATE,S,AFB_TABLE)
*
      DOUBLE PRECISION ARRY(19,9,3),RATE,S,AFB_TABLE(3),R(9),SS(19),
     &     DUM1(3),DUM2(3)
      INTEGER I,R1,R2,S1,S2
*
*     DATA TO WHICH ENTERED RATE AND S WILL BE COMPARED TO FIND POSITION
*
      DATA R/0,1.25,2.5,5,12.5,25,50,100,150/
      DATA SS/0,.02,.04,.06,.08,0.1,.12,.14,.16,.18,.2,.3,.4,.5,.6,
     &     .7,.8,.9,1.0/
*
*     IF THE RAIN RATE OR S = 0 THEN RETURN ZERO FOR ATTENUATION,
*     FORWARD SCATTERING, AND BACKWARD SCATTERING
*
      IF ((RATE.EQ.0).OR.(S.EQ.0)) THEN
         AFB_TABLE(1)=0
         AFB_TABLE(2)=0
         AFB_TABLE(3)=0
      ELSE
*
*     FINDING POSITION OF RAIN RATE ELEMENT.
*
         DO 10 I=1,8
            IF ((RATE.GT.R(I)).AND.(RATE.LE.R(I+1))) THEN
               R1=I
               R2=I+1
            ENDIF
 10      CONTINUE
*
*     FINDING POSITION OF S ELEMENT.
*
         DO 20 I=1,18
            IF ((S.GT.SS(I)).AND.(S.LE.SS(I+1))) THEN
               S1=I
               S2=I+1
            ENDIF
 20      CONTINUE
*
*     LINEARLY INTERPOLATING TO FIND VALUE OF ATTENUATION,
*     FORWARD SCATTERING, AND BACKWARD SCATTERING.
*
         DO 30 I=1,3
            DUM1(I)=(ARRY(S1,R2,I)-ARRY(S1,R1,I))*(RATE-R(R1))
     &           /(R(R2)-R(R1))+ARRY(S1,R1,I)
            DUM2(I)=(ARRY(S2,R2,I)-ARRY(S2,R1,I))*(RATE-R(R1))
     &           /(R(R2)-R(R1))+ARRY(S2,R1,I)
*
*     CALCULATING ACTUAL RESULT.
*
            AFB_TABLE(I)=(DUM2(I)-DUM1(I))*(S-SS(S1))/(SS(S2)-SS(S1))
     &           +DUM1(I)
 30   CONTINUE
      ENDIF
*
```

```
      RETURN
      END
*******************************************************************************
********* SUBROUTINE GET_AFBARRY*********************************************
*******************************************************************************
*     THIS SUBROUTINE READS FROM THE FILE 'DATA1' ALL THE S AND RAIN RATE
*     VALUES FOR ONE FREQUENCY.  IT THEN STORES THESE VALUES IN AN ARRAY
*     CALLED ARRY(S,RATE).
*
*     F         - POSSIBLE FREQUENCIES
*     FREQ      - CORRECT FREQUENCY USED
*     ARRY      - ARRAY CONTAINING VALUES FOR ATTENUATION, FORWARD SCATTERING,
*                 AND BACK SCATTERING
*     FR        - FREQUENCY IN 'data1' FILE (NOT USED)
*
*******************************************************************************
*
      SUBROUTINE GET_AFBARRY(FREQ,ARRY)
*
      DOUBLE PRECISION FREQ,ARRY(19,9,3),F(28),FR,R,SS
      INTEGER I,J,K
*
*     F - THE FREQUENCIES USED
*
      DATA F/1,1.5,2,2.5,3,3.5,4,5,6,7,8,9,9.6,10,11,12,15,20,25,
     &     30,35,40,50,60,70,80,90,100/
*
*     OPENING FILE 'data1' TO READ ATTENUATION, FORWARD SCATTERING, AND
*     BACK SCATTERING.
*
      OPEN(UNIT=10,FILE='data1',STATUS='OLD')
*
*     FINDING POSITION OF FREQUENCY
*
      DO 20 J=1,28
         IF (F(J).EQ.FREQ) THEN
            K=J
            J=28
         ENDIF
 20   CONTINUE
*
*     SKIPPING THROUGH FILE 'data1' TO CORRECT FREQUENCY.
*
      J=153*(K-1)
      DO 10 I=1,J
         READ(10,*)
 10   CONTINUE
*
*     READING FREQUENCY
*
      READ(10,*),FR
*
*     READING IN ATTENUATION,FORWARD SCATTERING, AND BACK SCATTERING
*     FOR DIFFERENT RAIN RATES.
*
      DO 30 I=2,9
         READ(10,*),R
         DO 40 J=2,19
            READ(10,*),SS,ARRY(J,I,1),ARRY(J,I,2),ARRY(J,I,3)
            ARRY(J,I,2)=ARRY(J,I,2)*100
            ARRY(J,I,3)=ARRY(J,I,3)*100
 40      CONTINUE
 30   CONTINUE
*
*     SETTING ATTENUATION, FORWARD SCATTERING, AND BACK SCATTERING TO ZERO
```

```
*     WHEN S=0 AND/OR RAIN RATE =0
*
      DO 50 I=1,9
         ARRY(1,I,1)=0
         ARRY(1,I,2)=0
         ARRY(1,I,3)=0
 50   CONTINUE
      DO 60 I=1,19
         ARRY(I,1,1)=0
         ARRY(I,1,2)=0
         ARRY(I,1,3)=0
 60   CONTINUE
*
      CLOSE(UNIT=10,STATUS='KEEP')
*
      RETURN
      END
*******************************************************************************
**************** SUBROUTINE RAIN_TOTAL_ATTENUATION ****************************
*******************************************************************************
*
*     THIS SUBROUTINE CALCULATES THE TOTAL RAIN ATTENUATION ALONG THE
*     LINE CONNECTING THE RECEIVER AND THE POINT TO WHICH THE TRANSMITTER
*     TRANSMITS TO.
*
*     X11,Y11,Z11  - COORDINATES OF INTERSECTION OF MAIN BEAM OF RECEIVER
*                    AND RAIN CYLINDER
*     X,Y,Z        - COORDINATES WHERE TRANSMITTER TRANSMITS TO
*     RTATT        - TOTAL RAIN ATTENUATION
*     DT           - SMALL INCREMENT OF T ALONG BEAM AXIS
*     XD,YD,ZD     - DIRECTION OF LINE CONNECTING (X11,Y11,Z11) AND (X,Y,Z)
*     XT,YT,ZT     - COORDINATES OF FIRST POINT BETWEEN OTHER COORDINATES
*     XA,YA,ZA     - POINTS ALONG LINE CONNECTING THE TWO POINTS
*     RATE         - CALCULATED RAIN RATE
*     XH,YH        - CENTER OF RAIN CELL
*     RMAX         - MAX RAIN RATE (AT CENTER OF CELL)
*     R0           - RAIN RATE DISTRIBUTION VARIABLE
*     DECISION     - IS THERE A MELTING LAYER?
*
*******************************************************************************
*
      SUBROUTINE RAIN_TOTAL_ATTENUATION(HMAX1,HFR,HM,HMIN,FREQ,
     &     TE11,QUANTITY,X,Y,Z,X11,Y11,Z11,RTATT,XH,YH,RMAX,R0,DECISION,
     &     TASKNUMBER1,NARR,A1NUM,ANUM,BNUM,XR,YR,ZR,H_THICKNESS,RAD,
     &     XTHE_T)
*
      DOUBLE PRECISION X11,Y11,Z11,X,Y,Z,T,RTATT,DT,XD,YD,ZD,
     &     XT,YT,ZT,DR,XA1,YA1,ZA1,TP1,HMAX1,HFR,HM,HMIN,S,RATE,
     &     RTATT,FREQ,TEMP,QUANTITY,XH,YH,RMAX,R0,HMAX1,
     &     NARR(2,3),A1NUM,ANUM,BNUM,R0M,D,XR,YR,ZR,ANGEP,
     &     H_THICKNESS,XP1,YP1,ZP1,XM1,YM1,ZM1,MELTATTEN,XA2,YA2,
     &     ZA2,RAD,XTHE_T,TP2,TE11,ATTEN
      CHARACTER*2 DECISION
      INTEGER I,TASKNUMBER1
*
      XD=X11-X
      YD=Y11-Y
      ZD=Z11-Z
      T=(Z11-Z)/ZD
      RTATT=0
      DT=T/20.0D0
      XT=XD*DT+X
      YT=YD*DT+Y
      ZT=YD*DT+Z
      DR=DSQRT((XT-X)**2+(YT-Y)**2+(ZT-Z)**2)
```

```
      TP1 = -DT/2.D0
      DO 10 I=1,20
         TP1=DT+TP1
         XA1=XD*TP1+X
         YA1=YD*TP1+Y
         ZA1=ZD*TP1+Z
*
         CALL GET_S(HMAX1,HFR,HM,HMIN,ZA1,S,DECISION)
*
         CALL RAINRATE(XH,YH,X11,Y11,RMAX,R0,RATE)
*
         CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &                 NARR,A1NUM,ANUM,BNUM)
*
         RTATT=RTATT+ATTEN*DR/1000
 10   CONTINUE
      RETURN
      END
*****************************************************************************
**************** ATT_TASK ***************************************************
*****************************************************************************
*
      SUBROUTINE ATT_TASK(FREQ,T,RATE,S,ATTEN,QUANTITY,
     &                    TASKNUMBER1,NARR,A1NUM,ANUM,BNUM)
*
      DOUBLE PRECISION FREQ,T,RATE,S,ATTEN,QUANTITY,ATTE2,
     &                 NARR(2,3),A1NUM,ANUM,BNUM
      INTEGER TASKNUMBER1
*
      IF (TASKNUMBER1.EQ.1) THEN
         CALL  LP(FREQ,T,RATE,S,ATTEN,QUANTITY)
      ELSEIF (TASKNUMBER1.EQ.2) THEN
         CALL C_LP(FREQ,T,RATE,S,ATTEN,QUANTITY)
      ELSEIF (TASKNUMBER1.EQ.3) THEN
         CALL M_ATTENUATION(FREQ,T,RATE,S,ATTEN,ATTE2,QUANTITY)
      ELSEIF (TASKNUMBER1.EQ.4) THEN
         CALL MC_ATTENUATION(FREQ,T,RATE,S,ATTEN,ATTE2,QUANTITY)
      ELSEIF (TASKNUMBER1.EQ.5) THEN
         CALL SATTCALC(S,NARR,RATE,A1NUM,ANUM,BNUM,ATTEN)
      ENDIF
*
      RETURN
      END
*
*****************************************************************************
**************** SUBROUTINE EMPIRICAL1_ATTENUATION***************************
*****************************************************************************
*
*

      SUBROUTINE SATTCALC(S,N,RATE,A1,A,BNUM,ALPHA)
*
      DOUBLE PRECISION S,N(2,3),RATE,A1,M1,M2,FS,
     &     A2,M3,B3,B2,B1,A,BNUM,ALPHA
      PARAMETER(A2=1.7,M3=1,B3=230,B2=6,B1=20)
*
      IF (S.LT.1.0D0) THEN
*
*
         M1=N(1,1)+N(1,2)*RATE**.003+N(1,3)*RATE**.0002
         M2=N(2,1)+N(2,2)*RATE**.003+N(2,3)*RATE**.0002
*
         FS=M1*DEXP(-B1*S**A1)*S**(A1-1)
         FS=FS+M2*DEXP(-B2*S**A2)*S**(A2-1)
         FS=FS-M3*DEXP(-B3*S)+1
```

```
*
      ELSE
         FS=1.0D0
      ENDIF
*
      ALPHA=FS*A*RATE**BNUM
      RETURN
      END
*
*******************************************************************************
*************** A1_CALC ******************************************************
*******************************************************************************
*     THIS SUBROUTINE CALCULATES a1 FOR THE SUBROUTINE SATTCALC TO USE
*     IN THE EQUATION FOR F(S) (SEE SATTCALC)
*
*******************************************************************************
*
      SUBROUTINE A1_CALC(FREQUENCY,A1)
*
      DOUBLE PRECISION FREQUENCY,F,C(6),A1
*
      DATA C/1.680592398562237e+00,
     &       -2.790804733796220e-03,
     &       -3.417061223974332e+00,
     &        5.049293127489146e+00,
     &        4.707754939384348e-01,
     &       -2.262928752321020e+00/

      F=FREQUENCY
*
      A1=C(1)+C(2)*F+C(3)*F**-1+C(4)*F**-2+C(5)*DEXP(-F)*F**2.1
      A1=A1+C(6)*F**-3
*
      RETURN
      END
*
*******************************************************************************
***************** N_CALC *****************************************************
*******************************************************************************
*     THIS SUBROUTINE CALCULATES N1 AND N2 WHICH ARE NEEDED TO CALCULATE
*     M1 AND M2.
*
*     N[1]([2],[3])
*     1.  1 OR 2 FROM M1 OR M2 RESPECTIVELY
*     2.  1 or 2 FOR LOW AND HIGH FREQUENCY RANGES.
*         1=1-12 GHz., 2=12-100  GHz. IF [1] = 1 (M1)
*         1=1-20 GHz., 2=20-100  GHz. IF [1] = 2 (M2)
*     3.  CAN BE 1,2,OR 3 FOR THE VARIABLE N1,N2,OR N3.
*
*******************************************************************************
*
      SUBROUTINE N_CALC(FREQUENCY,N)
*
      DOUBLE PRECISION F,FREQUENCY,N1(2,3,7),N2(2,3,8),N(2,3)
      INTEGER I
*
      DATA (N1(1,1,I),I=1,7)/-4.468710233696790e+10,
     &                 1.403226146957391e+08,
     &                -6.960027662822775e+08,
     &                 4.506558794171744e+10,
     &                -6.421292889699095e+07,
     &                 8.731179500736722e+08,
     &                 1.401495928213695e+06/
*
      DATA (N1(2,1,I),I=1,7)/-6.295278387177499e+10,
```

```
     &              6.296355557484093e+10,
     &              5.966553195229598e+05,
     &             -3.888357198437326e+05,
     &             -1.923936894943743e+08,
     &             -1.822301639050625e+05,
     &              8.656888811513758e+04/
*
      DATA (N1(1,2,I),I=1,7)/-3.174987655808701e+09,
     &              1.000814015141864e+07,
     &             -4.938711808841844e+07,
     &              3.201787180190318e+09,
     &             -4.565132790730321e+06,
     &              6.211655984741843e+07,
     &              9.948011000116054e+04/
*
      DATA (N1(2,2,I),I=1,7)/-4.084602058168248e+09,
     &              4.085333281240790e+09,
     &              4.259904738584688e+04,
     &             -2.783771486082181e+04,
     &             -1.248919873419444e+07,
     &             -1.281758620243883e+04,
     &              6.233978784040986e+03/
*
      DATA (N1(1,3,I),I=1,7)/ 4.786234527835458e+10,
     &             -1.503307914573111e+08,
     &              7.454010806448646e+08,
     &             -4.826764045492385e+10,
     &              6.877779221467581e+07,
     &             -9.352359718254586e+08,
     &             -1.500976973852585e+06/
*
      DATA (N1(2,3,I),I=1,7)/6.702815890731934e+10,
     &             -6.703966103497658e+10,
     &             -6.392557379690040e+05,
     &              4.166781931398259e+05,
     &              2.048548402103934e+08,
     &              1.950457764835905e+05,
     &             -9.280180321809524e+04/
*
      DATA (N2(1,1,I),I=1,8)/-2.099142532327721e+07,
     &              1.400026226688738e+07,
     &             -8.882786193005802e+05,
     &              1.989261675140147e+04,
     &              4.174527682005403e+06,
     &              1.593655028099594e+07,
     &              7.501240296862618e+05,
     &             -2.083589564285219e+07/
*
      DATA (N2(2,1,I),I=1,8)/-4.439610851013492e+07,
     &             -8.943850388853900e+05,
     &              6.292344533547490e+03,
     &             -1.902820302670007e+01,
     &             -2.522716953072156e+15,
     &              1.276598780066267e+14,
     &             -2.293117873033613e+04,
     &              1.952254679706120e+07/
*
      DATA (N2(1,2,I),I=1,8)/-1.493679774541824e+06,
     &              9.956472852260806e+05,
     &             -6.314103317406768e+04,
     &              1.413509106519248e+03,
     &              2.972144450610339e+05,
     &              1.134692648445301e+06,
     &              5.317895603908228e+04,
     &             -1.482614399143066e+06/
```

```
*
      DATA (N2(2,2,I),I=1,8)/-3.150283332144003e+06,
     &              -6.334729039970136e+04,
     &               4.455018565359137e+02,
     &              -1.346924157214865e+00,
     &              -1.803394805985552e+14,
     &               9.125776857644061e+12,
     &              -1.623153722957795e+03,
     &               1.384227230004449e+06/
*
      DATA (N2(1,3,I),I=1,8)/ 2.248517939626698e+07,
     &              -1.499594585442772e+07,
     &               9.514215725554167e+05,
     &              -2.130616396424133e+04,
     &              -4.471624512634573e+06,
     &              -1.707130423100917e+07,
     &              -8.033028871120176e+05,
     &               2.231858202049057e+07/
*
      DATA (N2(2,3,I),I=1,8)/4.754646862535044e+07,
     &               9.577316084775798e+05,
     &              -6.737837935928022e+03,
     &               2.037509693681765e+01,
     &               2.703059184218280e+15,
     &              -1.367857979044508e+14,
     &               2.455407948296932e+04,
     &              -2.090678544294405e+07/
*
      F=FREQUENCY
*
      IF ((F.GE.1).AND.(F.LT.12)) THEN
         DO 10 I=1,3
            N(1,I)=N1(1,I,1)+N1(1,I,2)*F*F*DEXP(-F)+N1(1,I,3)*F**.2
            N(1,I)=N(1,I)+N1(1,I,4)*F**.01+N1(1,I,5)*F**.7
            N(1,I)=N(1,I)+N1(1,I,6)*DEXP(-F)+N1(1,I,7)*DSIN(F/.9)
 10      CONTINUE
      ELSEIF ((F.GE.12).AND.(F.LE.100)) THEN
         DO 20 I=1,3
            N(1,I)=N1(2,I,1)+N1(2,I,2)*F**.003+N1(2,I,3)*EXP(-100+F)
            N(1,I)=N(1,I)+N1(2,I,4)*(1/DCOSH(F-20))+N1(2,I,5)*DLOG(F)
            N(1,I)=N(1,I)+N1(2,I,6)*(1/DCOSH(F-40))
            N(1,I)=N(1,I)+N1(2,I,7)*DSIN(F/.08)
 20      CONTINUE
      ENDIF
*
      IF ((F.GE.1).AND.(F.LT.20)) THEN
         DO 30 I=1,3
            N(2,I)=N2(1,I,1)+N2(1,I,2)*F+N2(1,I,3)*F**2+N2(1,I,4)*F**3
            N(2,I)=N(2,I)+N2(1,I,5)*F*DEXP(-F)+N2(1,I,6)*F*F*DEXP(-F)
            N(2,I)=N(2,I)+N2(1,I,7)*DSIN(.6*(F-2.8))+N2(1,I,8)*DLOG(F)
 30      CONTINUE
      ELSEIF ((F.GE.20) .AND.(F.LE.100)) THEN
         DO 40 I=1,3
            N(2,I)=N2(2,I,1)+N2(2,I,2)*F+N2(2,I,3)*F**2+N2(2,I,4)*F**3
            N(2,I)=N(2,I)+N2(2,I,5)*F*DEXP(-F)+N2(2,I,6)*F*F*DEXP(-F)
            N(2,I)=N(2,I)+N2(2,I,7)*DSIN(.6*(F-2.8))+N2(2,I,8)*DLOG(F)
 40      CONTINUE
      ENDIF
*
*
         RETURN
         END
*
*******************************************************************************
***************** A_B ********************************************************
```

```
*****************************************************************************
*     THIS SUBROUTINE COMPUTES THE VALUE OF a AND B FROM THE EQUATION
*                                                b
*                         ATTENUATION = a*r
*
*****************************************************************************
*
*     r        - RAIN RATE
*     a        - VARIABLE DEPENDENT UPON FREQUENCY.
*     b        - VARIABLE DEPENDENT UPON FREQUENCY.
*     C1       - CONSTANTS FOR b
*     C2       - CONSTANTS FOR a
*
*****************************************************************************
*
      SUBROUTINE A_B(FREQUENCY,A,B)
*
      DOUBLE PRECISION FREQUENCY,F,A,B,C1(9),C2(11)
*
      DATA C1/1.175693749863705D+00,
     &       -5.372610249096163D-03,
     &       -1.451430379276010D-04,
     &        2.483615756859940D-06,
     &       -1.052429358496198D-08,
     &       -4.112419378557529D-01,
     &       -1.202673982695477D-01,
     &        3.133414878851311D-02,
     &       -2.717811349173657D-02/

      DATA C2/3.432142878826195D-03,
     &        2.930235190132424D-09,
     &       -9.239923589608143D-11,
     &        9.776864619131741D-13,
     &       -3.485507759140589D-15,
     &        6.906393023884164D-04,
     &        5.450508196170798D-06,
     &       -1.023109914867535D-02,
     &        1.232762310835401D-02,
     &        1.752618764932525D-02,
     &        1.566935461598425D-04/
*
      F=FREQUENCY
*
*     CALCULATING b
*
      B=C1(1)+C1(2)*F+C1(3)*F**2+C1(4)*F**3+C1(5)*F**4
      B=B+C1(6)*F*F*DEXP(-F)+C1(7)*F**(-2)+C1(8)*DLOG(F)
      B=B+C1(9)*(1/(DCOSH(.2*(F-13))))
*
*     CALCULATING a
*
      A=C2(1)*F**1.4+C2(2)*F**5+C2(3)*F**6+C2(4)*F**7+C2(5)*F**8
      A=A+C2(6)*DEXP(-F)*F**3+C2(7)+C2(8)*F+C2(9)*DLOG(F)
      A=A+C2(10)*DEXP(-F)+C2(11)*F**-9
*
      RETURN
      END
*****************************************************************************
**************** SUBROUTINE M_ATTENUATION (M L&P) ****************************
*****************************************************************************
*
      SUBROUTINE M_ATTENUATION(FREQ,T,RATE,S,ATTEN,ATTE2,QUANTITY)
*
      DOUBLE PRECISION FREQ,T,RATE,S,A_REP,N,FREQR,ATTEN,GEDP,NUM,EA
      DOUBLE PRECISION FREQUENCY,QUANTITY,ATTE2,C,RTEMP
```

```
      COMPLEX*16 G,GE,EPSILON,GAMMA
      PARAMETER(PI=3.14159265359D0,EA=1.D0,C=2.9979244574D10)
*
      IF (RATE .LT. 0.25D0) THEN
         RTEMP = RATE
         RATE = 0.25D0
      ENDIF
      IF (S.LT..002) THEN
         ATTEN=0
         ATTE2=0
         RETURN
      ENDIF
      FREQUENCY=FREQ*1.D9
      CALL A(S,RATE,A_REP,QUANTITY)
      FREQR=0.866D0*C/(2.D0*PI*A_REP)
      N=(2.D0+100.D0*(FREQUENCY/FREQR)**2.D0)
      N=N/(1.D0+101.D0*(FREQUENCY/FREQR)**2.D0)
*
      CALL NUMBER(RATE,NUM,S,QUANTITY)
      CALL G_LOWCASE(S,A_REP,G,T,FREQUENCY)
      GE=G/DCMPLX(1.D0,(FREQUENCY/FREQR)**N)
      GEDP=-DIMAG(GE)
      ATTEN=9.1D0*GEDP*NUM*1.D4*FREQ
      EPSILON=EA*(1.D0+GE*NUM)
      GAMMA=2.D0*PI*FREQUENCY*CDSQRT(-4.D0*PI*1.D-7*EPSILON)
      ATTE2=DREAL(GAMMA)
*
      IF (RATE .LT. 0.25D0) THEN
         ATTEN = ATTEN*RTEMP/0.25D0
         RATE = RTEMP
      ENDIF
*
      RETURN
      END
*
*******************************************************************************
**************** SUBROUTINE MC_ATTENUATION (MC L&P)****************************
*******************************************************************************
*
      SUBROUTINE MC_ATTENUATION(FREQ,T,RATE,S,ATTEN,ATTE2,QUANTITY)
*
      DOUBLE PRECISION FREQ,T,RATE,S,A_REP,N,FREQR,ATTEN,GEDP,NUM,EA
      DOUBLE PRECISION FREQUENCY,QUANTITY,ATTE2,C,FACTOR,GAM,RTEMP
      COMPLEX*16 G,GE,EPSILON,GAMMA,E,M
      PARAMETER(PI=3.14159265359D0,EA=1.D0,C=2.9979244574D10,
     &     C1=20.958228)
*
      IF (RATE .LT. 0.25D0) THEN
         RTEMP = RATE
         RATE = 0.25D0
      ENDIF
*
      IF (S.LT..002) THEN
         ATTEN=0
         ATTE2=0
         RETURN
      ENDIF
      FREQUENCY=FREQ*1.D9
      CALL A(S,RATE,A_REP,QUANTITY)
      FREQR=0.866D0*C/(2.D0*PI*A_REP)
      N=(2.D0+100.D0*(FREQUENCY/FREQR)**2.D0)
      N=N/(1.D0+101.D0*(FREQUENCY/FREQR)**2.D0)
*
      CALL NUMBER(RATE,NUM,S,QUANTITY)
      CALL G_LOWCASE(S,A_REP,G,T,FREQUENCY)
```

```
      GE=G/DCMPLX(1.D0, (FREQUENCY/FREQR)**N)
      GEDP=-DIMAG(GE)
      ATTEN=9.1D0*GEDP*NUM*1.D4*FREQ
      EPSILON=EA*(1.D0+GE*NUM)
      GAMMA=2.D0*PI*FREQUENCY*CDSQRT(-4.D0*PI*1.D-7*EPSILON)
      ATTE2=DREAL(GAMMA)
*
      CALL PERMATIVITY(T,FREQUENCY,E,M)
      GAM=100/REAL(FREQ*C1*CDSQRT(-E))
      FACTOR=1+((1-5*S)/5)*FREQUENCY/FREQR
      FACTOR=FACTOR*((N**2)*A_REP*(1-S)/(2*GAM))+1
      FACTOR=(FACTOR*(N+S*(1-N)))**(1-S)
      ATTEN=ATTEN*FACTOR
*
      IF (RATE .LT. 0.25D0) THEN
         ATTEN = ATTEN*RTEMP/0.25D0
         RATE = RTEMP
      ENDIF
*
      RETURN
      END
*
*******************************************************************************
*************** SUBROUTINE LP *************************************************
*******************************************************************************
*
      SUBROUTINE LP(FREQ,T,RATE,S,ATTEN,QUANTITY)
*
      DOUBLE PRECISION FREQ,T,RATE,S,A_REP,N,FREQR,ATTEN,GEDP,NUM,EA
      DOUBLE PRECISION FREQUENCY,QUANTITY,C,RTEMP
      COMPLEX*16 G,GE
      PARAMETER(PI=3.14159265359D0,EA=1.D0,C=2.9979244574D10)
*
      IF (RATE .LT. 0.25D0) THEN
         RTEMP = RATE
         RATE = 0.25D0
      ENDIF
*
      IF (S.LT..002) THEN
         ATTEN=0
         RETURN
      ENDIF
      FREQUENCY=FREQ*1.D9
      CALL NUMBER2(RATE,NUM,S,A_REP,QUANTITY)
      FREQR=0.866D0*C/(2.D0*PI*A_REP)
      N=(2.D0+100.D0*(FREQUENCY/FREQR)**2.D0)
      N=N/(1.D0+101.D0*(FREQUENCY/FREQR)**2.D0)
*
      CALL NUMBER(RATE,NUM,S,QUANTITY)
      CALL G_LOWCASE(S,A_REP,G,T,FREQUENCY)
      GE=G/DCMPLX(1.D0, (FREQUENCY/FREQR)**N)
      GEDP=-DIMAG(GE)
      ATTEN=9.1D0*GEDP*NUM*1.D4*FREQ
*
      IF (RATE .LT. 0.25D0) THEN
         ATTEN = ATTEN*RTEMP/0.25D0
         RATE = RTEMP
      ENDIF
*
      RETURN
      END
*
*******************************************************************************
*************** SUBROUTINE C_LP (CORRECTED) ***********************************
*******************************************************************************
```

```
*
      SUBROUTINE C_LP(FREQ,T,RATE,S,ATTEN,QUANTITY)
*
      DOUBLE PRECISION FREQ,T,RATE,S,A_REP,N,FREQR,ATTEN,GEDP,NUM,EA
      DOUBLE PRECISION FREQUENCY,QUANTITY,C,RTEMP
      COMPLEX*16 G,GE
      PARAMETER(PI=3.14159265359D0,EA=1.D0,C=2.9979244574D10)
*
      IF (RATE .LT. 0.25D0) THEN
         RTEMP = RATE
         RATE = 0.25D0
      ENDIF
*
      IF (S.LT..002) THEN
         ATTEN=0
         RETURN
      ENDIF
      FREQUENCY=FREQ*1.D9
      CALL NUMBER2(RATE,NUM,S,A_REP,QUANTITY)
      FREQR=0.866D0*C/(2.D0*PI*A_REP)
      N=(2.D0+100.D0*(FREQUENCY/FREQR)**2.D0)
      N=N/(1.D0+101.D0*(FREQUENCY/FREQR)**2.D0)
*
      CALL NUMBER(RATE,NUM,S,QUANTITY)
      CALL G_LOWCASE(S,A_REP,G,T,FREQUENCY)
      GE=G/DCMPLX(1.D0,(FREQUENCY/FREQR)**N)
      GEDP=-DIMAG(GE)
      ATTEN=9.1D0*GEDP*NUM*1.D4*FREQ
*
      FACTOR=N*((2+S)*FREQUENCY/FREQR+1)/(FREQUENCY/FREQR+2-S)
      FACTOR=(FACTOR**(1-S**2))*((2-S)/(2+S))**(1-S)
      ATTEN=ATTEN*FACTOR
*
      IF (RATE .LT. 0.25D0) THEN
         ATTEN = ATTEN*RTEMP/0.25D0
         RATE = RTEMP
      ENDIF
      RETURN
      END
*
*******************************************************************************
*******************************************************************************
************** SUBROUTINE G_LOWCASE ******************************************
*******************************************************************************
*     THIS SUBROUTINE CALCULATES g FROM THE EQUATION IN TABLE III
*     PG. 295 OF  'IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION',
*     DATED FEB. 1988.   THE NAME OF THE ARTICLE IS "A SIMPLIFIED
*     APPROACH TO THE EVALUATION OF EMW PROPAGATION CHARACTERISTICS
*     IN RAIN AND MELTING SNOW.  IT USES THE SUBROUTINE 'PERMATIVITY'
*     TO GET THE PERMATIVITY OF OUTER LAYER.
*******************************************************************************
*
      SUBROUTINE G_LOWCASE(S,A_REP,G,T,FREQUENCY)
*
      COMPLEX*16 E,G,M,NUMER,DEN
      DOUBLE PRECISION S,A_REP,PI,Z,EA,E1,T,FREQUENCY
      PARAMETER(PI=3.14159265359D0,E1=1.20D0,EA=1.0D0)
*
      CALL PERMATIVITY(T,FREQUENCY,E,M)
*
      Z=4.D0*PI*A_REP**3.D0
      NUMER=(E-EA)*(2.D0*E+E1)-(1.D0-S)*(E-E1)*(2.D0*E+EA)
      DEN=(E+2.D0*EA)*(2.D0*E+E1)-2.D0*(1.D0-S)*(E-E1)*(E-EA)
      G=Z*NUMER/DEN
*
```

```
      RETURN
      END
*******************************************************************************
*******************************************************************************
***************** SUBROUTINE PERMATIVITY ******************************************
*******************************************************************************
*     THIS SUBROUTINE INPUTS THE TEMPERATURE T IN DEG CELSIUS AND THE
*     FREQUENCY IN Hz.
*******************************************************************************
*
      SUBROUTINE PERMATIVITY(T,FREQUENCY,E,M)
      REAL*8 LS,ALPHA,EI,TAO,ES,E1,E2,T,L,C,PI,ET
      REAL*8 FREQUENCY
      COMPLEX*16 M,E
*
*
      C = 2.997924574D+10
      PI = 3.141592654D0
      TAO = 12.5664D+08
*
      L = C/FREQUENCY
*
      LS=0.00033836D0*DEXP((2513.98D0/(T+273.D0)))
      ALPHA=-16.8129D0/(T+273.D0) + 0.0609265
      EI=5.27137D0+0.0216474*T-0.00131198*T**2
      ES=1.0D0-4.597D-03*(T-25.D0)
      ES= ES+1.19D-05*(T-25.D0)**2 - 2.8D-08*(T-25.D0)**3
      ES = ES*78.54D0
*
*234567890123456789012345678901234567890123456789012345678901234567890
      ET = 1.D0 + 2.D0*(LS/L)**(1.D0-ALPHA)*DSIN(ALPHA*PI/2.D0)
      ET = ET + (LS/L)**(2.D0*(1.D0-ALPHA))
      E1 = (ES-EI)*(1.D0+(LS/L)**(1.D0-ALPHA)*DSIN(ALPHA*PI/2.D0))
      E1 = E1/ET
      E1 = E1 + EI
*
      E2 = (ES-EI)*(LS/L)**(1-ALPHA)*DCOS(ALPHA*PI/2.D0)/ET
      E2 = TAO*L/18.8496D+10 + E2
*
      E= DCMPLX(E1,-E2)
      M = CDSQRT(E)
      END
*******************************************************************************
*******************************************************************************
***************** SUBROUTINE NUMBER ***********************************************
*******************************************************************************
*     THIS SUBROUTINE CALCULATES 'NUM', THE NUMBER OF DROPS PER UNIT VOLUME.
*     IT USES THE SUBROUTINES WHICH CALCULATE THE RAIN VELOCITY (VELRAIN)
*     AND REPRESENTATIVE RAIN RADIUS WHEN S=1 (NO SNOW).
*******************************************************************************
*
      SUBROUTINE NUMBER(RATE,NUM,S,QUANTITY)
*
      DOUBLE PRECISION RATE,VELR,S,NUM,A_REP,V,S2
      PARAMETER(PI=3.14159265359D0)
      S2=1.D0
*
      CALL A(S2,RATE,A_REP,QUANTITY)
      CALL VELRAIN(A_REP,VELR)
      V=(1.5D0+(VELR-1.5D0)*DSIN(S*PI/2.D0))
      NUM=RATE/(48.0D0*PI*1.0D5*V*(A_REP**3.D0))
*
      RETURN
      END
*******************************************************************************
```

```
***************** SUBROUTINE NUMBER2 ****************************************
*****************************************************************************
*     THIS SUBROUTINE CALCULATES 'NUM', THE NUMBER OF DROPS PER UNIT VOLUME.
*     IT USES THE SUBROUTINES WHICH CALCULATE THE RAIN VELOCITY (VELRAIN)
*     AND REPRESENTATIVE RAIN RADIUS WHEN S=1 (NO SNOW).
*****************************************************************************
*
      SUBROUTINE NUMBER2(RATE,NUM,S,A_REP,QUANTITY)
*
      DOUBLE PRECISION RATE,VELR,S,NUM,A_REP,V,S2,QUANTITY
      PARAMETER(PI=3.14159265359D0)
      S2=1.D0
*
      CALL A(S2,RATE,A_REP,QUANTITY)
      CALL VELRAIN(A_REP,VELR)
      NUM=RATE/(48.D0 *PI*1.0D5*VELR*(A_REP**3))
      V=(1.5D0+(VELR-1.5D0)*DSIN(S*PI/2.D0))
      A_REP=A_REP/(((1-QUANTITY)+QUANTITY*S)**.33333333333333D0)
      NUM=NUM*VELR/V
*
      RETURN
      END
*
*****************************************************************************
*************** SUBROUTINE A ************************************************
*****************************************************************************
*     THIS SUBROUTINE COMPUTES THE VALUE OF A_REP, WHICH IS THE
*     REPRESENTATIVE RADIUS OF THE SNOW AND RAIN MIXTURE.  IF S
*     IN THE FORMULA IS SET TO EQUAL '1', THIS ROUTINE WILL RETURN THE
*     VALUE OF A_RAIN (JUST THE RAIN RADIUS).  THE VARIABLE 'RATE'
*     IS THE RAIN RATE IN mm/hr.
*****************************************************************************
*
      SUBROUTINE A(S,RATE,A_REP,QUANTITY)
*
      DOUBLE PRECISION PI,DROP(15,11),RATE,P(14),DUMMY,A_REP,
     &     NORMALIZE,S,QUANTITY
      INTEGER I,J
      PARAMETER(PI=3.14159265359D0)
*
      OPEN(UNIT=10,FILE='hydro',STATUS='OLD')
*
 3000 FORMAT(10(D6.0,X),D6.0)
      READ(10,3000)((DROP(I,J),J=1,11),I=1,15)
      CLOSE(UNIT=10,STATUS='KEEP')
*
      DO 110 J=3,10
         IF ((DROP(1,J).LE.RATE).AND.(DROP(1,J+1).GE.RATE)) THEN
            DUMMY=(RATE-DROP(1,J))/(DROP(1,J+1)-DROP(1,J))
            DO 100 I=2,15
               P(I-1)=DUMMY*(DROP(I,J+1)-DROP(I,J))+DROP(I,J)
 100        CONTINUE
            J=10
         END IF
 110  CONTINUE
*
      NORMALIZE=0
      DO 120 I=1,14
         NORMALIZE=NORMALIZE+P(I)
 120  CONTINUE
*
      DUMMY=0
      DO 130 I=1,14
         VS=1.5+(DROP(I+1,2)-1.5)*DSIN(PI*S/2)
         DUMMY=DUMMY+DROP(I+1,2)*(P(I)/NORMALIZE)/
```

```
     &     (((DROP(I+1,1)/2)**3)*VS)
 130  CONTINUE
*
      A_REP=(DUMMY*((1.D0-QUANTITY)+QUANTITY*S))**(-.3333333333D0)
*
      RETURN
      END
*
*****************************************************************************
************** SUBROUTINE VELRAIN ******************************************
*****************************************************************************
*     RAIN VELOCITY WITH LINEAR INTERPOLATION.
*     THIS SUBROUTINE TAKES AS INPUT, THE DIAMETER OF THE RAINDROP (DIA),
*     AND ACCORDING TO THE TABLE ON PG.552 OF 'IEEE TRANSACTIONS ON
*     ANTENNAS AND PROPAGATION' AN ARTICLE CALLED "RAINFALL ATTENUATION OF
*     CENTIMETER WAVES: COMPARISON OF THEORY AND MEASUREMENT" BY
*     RICHARD G. MEDHURST, DATED JULY 1965, IT GIVES THE VELOCITY.
*     LINEAR INTERPOLATION IS USED TO GET THE VELOCITY
*     FOR WHICH THE DIAMETER IS NOT SPECIFIED IN THE TABLE.
*****************************************************************************
*
      SUBROUTINE VELRAIN(A_REP,VELR)
*
      DOUBLE PRECISION VELR,A_REP,AREP,DUMMY
*
      AREP=A_REP*2.D0
*
      DUMMY=DEXP(-DSQRT(115.D0)*(AREP+.05D0))
      VELR=5.44704233688D0-6.47412769848D0*DUMMY
      VELR=VELR-78.0827787323D0*(AREP+.05D0)*DUMMY
      VELR=VELR+6.883324065D0*DSQRT(AREP)-4.278474844D0*AREP**2.D0
*
      RETURN
      END
*
*****************************************************************************
************ SUBROUTINE RAINRATE *******************************************
*****************************************************************************
*     THIS SUBROUTINE CALCULATES THE RAIN RATE AT ANY POINT IN A RAIN CELL.
*
*     X0,Y0     - BOTTOM CENTER COORDINATE LOCATION OF THE RAIN CELL.
*     X,Y       - COORDINATE LOCATION WHERE RAIN RATE IS TO BE CALCULATED.
*     RMAX      - MAXIMUM RAIN RATE LOCATED AT (X0,Y0).
*     RATE      - RETURNED RAIN RATE
*     R0        - INPUT PARAMETER WHICH CONTROLS THE DISTRIBUTION OF THE
*                 RAIN RATE IN THE RAIN CELL.
*
*****************************************************************************
*
      SUBROUTINE RAINRATE(X0,Y0,X,Y,RMAX,R0,RATE)
*
      DOUBLE PRECISION X0,Y0,X,Y,RMAX,R0,RATE
*
*     CALCULATION OF RAIN RATE AT LOCATION (X,Y)
*
      RATE=RMAX*DEXP(-DSQRT((X-X0)**2+(Y-Y0)**2)/R0)
*
      RETURN

      END
```

To implement the COST 210 rain cell model, replace RAIN_TOTAL_ATTENUATION

by:

```
*****************************************************************************
**************** SUBROUTINE RAIN_TOTAL_ATTENUATION ****************************
*****************************************************************************
*
*     THIS SUBROUTINE CALCULATES THE TOTAL RAIN ATTENUATION ALONG THE
*     LINE CONNECTING THE RECEIVER AND THE POINT TO WHICH THE TRANSMITTER
*     TRANSMITS TO.
*
*     X11,Y11,Z11  - COORDINATES OF INTERSECTION OF MAIN BEAM OF RECEIVER
*                    AND RAIN CYLINDER
*     X,Y,Z        - COORDINATES WHERE TRANSMITTER TRANSMITS TO
*     RTATT        - TOTAL RAIN ATTENUATION
*     DT           - SMALL INCREMENT OF T ALONG BEAM AXIS
*     XD,YD,ZD     - DIRECTION OF LINE CONNECTING (X11,Y11,Z11) AND (X,Y,Z)
*     XT,YT,ZT     - COORDINATES OF FIRST POINT BETWEEN OTHER COORDINATES
*     XA,YA,ZA     - POINTS ALONG LINE CONNECTING THE TWO POINTS
*     RATE         - CALCULATED RAIN RATE
*     XH,YH        - CENTER OF RAIN CELL
*     RMAX         - MAX RAIN RATE (AT CENTER OF CELL)
*     R0           - RAIN RATE DISTRIBUTION VARIABLE
*     DECISION     - IS THERE A MELTING LAYER?
*
*****************************************************************************
*
      SUBROUTINE RAIN_TOTAL_ATTENUATION(HMAX1,HFR,HM,HMIN,FREQ,
     &     TE11,QUANTITY,X,Y,Z,X11,Y11,Z11,RTATT,XH,YH,RMAX,R0,DECISION,
     &     TASKNUMBER1,NARR,A1NUM,ANUM,BNUM,XR,YR,ZR,H_THICKNESS,RAD,
     &     XTHE_T)
*
      DOUBLE PRECISION X11,Y11,Z11,X,Y,Z,T,RTATT,DT,XD,YD,ZD,
     &     XT,YT,ZT,DR,XA1,YA1,ZA1,TP1,HMAX1,HFR,HM,HMIN,S,RATE,
     &     RTATT,FREQ,TEMP,QUANTITY,XH,YH,RMAX,R0,HMAX1,
     &     NARR(2,3),A1NUM,ANUM,BNUM,R0M,D,XR,YR,ZR,ANGEP,
     &     H_THICKNESS,XP1,YP1,ZP1,XM1,YM1,ZM1,MELTATTEN,XA2,YA2,
     &     ZA2,RAD,XTHE_T,TP2,TE11,ATTEN
      CHARACTER*2 DECISION
      INTEGER I,TASKNUMBER1
*
      XD=X11-X
      YD=Y11-Y
      ZD=Z11-Z
      T=(Z11-Z)/ZD
      RTATT=0
      DT=T/20.0D0
      XT=XD*DT+X
      YT=YD*DT+Y
      ZT=YD*DT+Z
      DR=DSQRT((XT-X)**2+(YT-Y)**2+(ZT-Z)**2)
      TP1 = -DT/2.D0
      DO 10 I=1,20
         TP1=DT+TP1
         XA1=XD*TP1+X
         YA1=YD*TP1+Y
         ZA1=ZD*TP1+Z
*
         CALL GET_S(HMAX1,HFR,HM,HMIN,ZA1,S,DECISION)
*
         CALL RAINRATE(XH,YH,X11,Y11,RMAX,R0,RATE)
*
```

```
        CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &                NARR,A1NUM,ANUM,BNUM)
*
        RTATT=RTATT+ATTEN*DR/1000
 10   CONTINUE
      CALL GET_S(HMAX1,HFR,HM,HMIN,Z11,S,DECISION)
      CALL RAINRATE(XH,YH,X11,Y11,RMAX,R0,RATE)
      R0M = 600.D0*RATE**(-0.5)*10.D0**(-(RATE+1.D0)**0.19)
      R0M = R0M*1000.D0
      IF (S.EQ.1.0D0) THEN
       D = DSQRT((X11-XR)**2+(Y11-YR)**2)
       CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &                NARR,A1NUM,ANUM,BNUM)
       ATTEN = ATTEN*R0M*(1.D0-DEXP(-D/R0M))/1000.D0
       ANGEP = D/DSQRT((X11-XR)**2+(Y11-YR)**2 +
     &                          (Z11-ZR)**2)
       ATTEN = ATTEN/ANGEP
      ENDIF
      IF (S.EQ.0.D0.AND.H_THICKNESS.EQ.0.D0) THEN
       ZP1 = HFR
       S = 1.D0
       D = DSQRT((X11-XR)**2+(Y11-YR)**2)
       CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &                NARR,A1NUM,ANUM,BNUM)
       XD = X11-X
       YD = Y11-Y
       ZD = Z11-Z
       XP1 = XD*(ZP1-Z)/ZD + X
       YP1 = YD*(ZP1-Z)/ZD + Y
       ZP1 = ZD*(ZP1-Z)/ZD + Z
       D2 = DSQRT((X11-XR)**2+(Y11-YR)**2)
       D1 = DSQRT((X11-XP1)**2+(Y11-YP1)**2)
       ATTEN = ATTEN*(DEXP(-D1/R0M) - DEXP(-D2/R0M))/1000.D0
       ANGEP = D/DSQRT((X11-XR)**2+(Y11-YR)**2 +
     &                          (Z11-ZR)**2)
       ATTEN = ATTEN*R0M/ANGEP
      ENDIF
      IF (S.LT.1.D0.AND.S.GT.0.D0) THEN
       ZM1 = HM
       XD = X11-X
       YD = Y11-Y
       ZD = Z11-Z
       XM1 = XD*(ZM1-Z)/ZD + X
       YM1 = YD*(ZM1-Z)/ZD + Y
       ZM1 = ZD*(ZM1-Z)/ZD + Z
       T=(ZM1-Z11)/(ZM1-Z11)
       MELTATTEN = 0.D0
       DT=T/20.0D0
       TP1 = -DT/2.D0
       DO 420 I=1,20
         TP1=DT+TP1
         XA1=(XM1-X11)*TP1+X11
         YA1=(YM1-Y11)*TP1+Y11
         ZA1=(ZM1-Z11)*TP1+Z11
         CALL GET_S(HMAX1,HFR,HM,HMIN,ZA1,S,DECISION)
         CALL RAINRATE(XH,YH,X11,Y11,RMAX,R0,RATE)
         CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &                NARR,A1NUM,ANUM,BNUM)
         D2 = DSQRT((X11-XA1)**2+(Y11-YA1)**2)
         IF (I.EQ.1) THEN
          D1 = 0
         ELSE
          TP2 = TP1 - DT
          XA2 = (XM1-X11)*TP2 + X11
          YA2 = (YM1-Y11)*TP2 + Y11
```

```
          ZA2 = (ZM1-Z11)*TP2 + Z11
          D1 = DSQRT((X11-XA2)**2+(Y11-YA2)**2)
         ENDIF
         ATTEN = ATTEN*(DEXP(-D1/R0M) - DEXP(-D2/R0M))/1000.D0
         D = DSQRT((X11-XR)**2+(Y11-YR)**2)
         ANGEP = D/DSQRT((X11-XR)**2+(Y11-YR)**2 +
     &                    (Z11-ZR)**2)
         ATTEN = ATTEN*R0M/ANGEP
         MELTATTEN = MELTATTEN + ATTEN
420     CONTINUE
        S = 1.D0
        CALL RAINRATE(XH,YH,X11,Y11,RMAX,R0,RATE)
        CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &                  NARR,A1NUM,ANUM,BNUM)
        D2 = DSQRT((X11-XR)**2+(Y11-YR)**2)
        D1 = DSQRT((X11-XM1)**2+(Y11-YM1)**2)
        ATTEN = ATTEN*(DEXP(-D1/R0M) - DEXP(-D2/R0M))/1000.D0
        ANGEP = D2/DSQRT((X11-XR)**2+(Y11-YR)**2 +
     &                           (Z11-ZR)**2)
        ATTEN = ATTEN*R0M/ANGEP
        ATTEN = ATTEN + MELTATTEN
       ENDIF
       IF (S.EQ.0.D0.AND.H_THICKNESS.NE.0.D0) THEN
        ZP1 = HFR
        ZM1 = HM
        XD = X11-X
        YD = Y11-Y
        ZD = Z11-Z
        XP1 = XD*(ZP1-Z)/ZD + X
        YP1 = YD*(ZP1-Z)/ZD + Y
        ZP1 = ZD*(ZP1-Z)/ZD + Z
        XM1 = XD*(ZM1-Z)/ZD + X
        YM1 = YD*(ZM1-Z)/ZD + Y
        ZM1 = ZD*(ZM1-Z)/ZD + Z
        T=(ZM1-ZP1)/(ZM1-ZP1)
        MELTATTEN = 0.D0
        DT=T/20.0D0
        TP1 = -DT/2.D0
        DO 40 I=1,20
          TP1=DT+TP1
          XA1 = (XM1-XP1)*TP1+XP1
          YA1 = (YM1-YP1)*TP1+YP1
          ZA1 = (ZM1-ZP1)*TP1+ZP1
          CALL GET_S(HMAX1,HFR,HM,HMIN,ZA1,S,DECISION)
          CALL RAINRATE(XH,YH,X11,Y11,RMAX,R0,RATE)
          CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &                  NARR,A1NUM,ANUM,BNUM)
          D2 = DSQRT((X11-XA1)**2+(Y11-YA1)**2)
          IF (I.EQ.1) THEN
           D1 = DSQRT((X11-XP1)**2 + (Y11-YP1)**2)
          ELSE
           TP2 = TP1 - DT
           XA2 = (XM1-XP1)*TP2+XP1
           YA2 = (YM1-YP1)*TP2+YP1
           ZA2 = (ZM1-ZP1)*TP2+ZP1
           D1 = DSQRT((X11-XA2)**2+(Y11-YA2)**2)
          ENDIF
          ATTEN = ATTEN*(DEXP(-D1/R0M) - DEXP(-D2/R0M))/1000.D0
          D = DSQRT((X11-XR)**2+(Y11-YR)**2)
          ANGEP = D/DSQRT((X11-XR)**2+(Y11-YR)**2 +
     &                    (Z11-ZR)**2)
          ATTEN = ATTEN*R0M/ANGEP
          MELTATTEN = MELTATTEN + ATTEN
40      CONTINUE
        S = 1.D0
```

```
      CALL RAINRATE(XH,YH,X11,Y11,RMAX,R0,RATE)
      CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &              NARR,A1NUM,ANUM,BNUM)
      D2 = DSQRT((X11-XR)**2+(Y11-YR)**2)
      D1 = DSQRT((X11-XM1)**2+(Y11-YM1)**2)
      ATTEN = ATTEN*(DEXP(-D1/R0M) - DEXP(-D2/R0M))/1000.D0
      ANGEP = D2/DSQRT((X11-XR)**2+(Y11-YR)**2 +
     &                      (Z11-ZR)**2)
      ATTEN = ATTEN*R0M/ANGEP
      ATTEN = ATTEN + MELTATTEN
     ENDIF
     RTATT = RTATT + ATTEN
     D = SQRT(XH**2 + YH**2)
     ATTEN = 0.D0
     IF (D.GT.RAD) THEN
      D = D - RAD
      S = 1.D0
      CALL RAINRATE(XH,YH,X11,Y11,RMAX,R0,RATE)
      CALL ATT_TASK(FREQ,TE11,RATE,S,ATTEN,QUANTITY,TASKNUMBER1,
     &              NARR,A1NUM,ANUM,BNUM)
      ATTEN = ATTEN*R0M*(1.D0-DEXP(-D/R0M))/1000.D0
      ANGEP = 90.D0 - XTHE_T
      ANGEP = DCOSD(ANGEP)
      ATTEN = ATTEN/ANGEP
     ENDIF
     RTATT = RTATT + ATTEN
     RETURN

     END
```

The following is a sample input to the program:

```
5        , Select attenuation model          [note 1]
1        , Select Scattering model           [note 2]
0        , (x,
0        ,  y,
0        ,  z) of the centre of the rain cell
60       , THE_T                             [note 3]
0        , PHI_T                             [note 3]
200000   , (x,
0        ,  y,
0        ,  z) of the receiver
89.14063, THE_R                              [note 4]
180      , PHI_R                             [note 4]
0        , TR_ALPHA                          [note 5]
0.02     , TR_HALF_THETA                     [note 6]
0        , RE_ALPHA                          [note 7]
0.02     , RE_HALF_THETA                     [note 7]
Y        , Is there a melting snow layer     [note 8]
```

```
5200    , height of melting layer (Hm - T)
800     , thickness of melting layer (T)
6000    , Hc
20000   , radius of the rain cell
10000   , ro
12.5    , The maximum rain rate at the centre of the rain cell
1       , Frequency in GHz
0       , Temperature in degrees Celcius
.9      , m                                    [note 9]
50      , Steps of integrations in meters
100000  , Transmitter gain
50000   , Receiver gain
0.4     ,                                      [note 10]
5.5     ,                                      [note 10]
-18     ,                                      [note 10]
6000    , Hc
```

note 1 : An input to select the attenuation model to be used in the calculations.

"1" is used for Kharadly's first attenuation model

"2" is used for Kharadly's third attenuation model

"3" is used for Kharadly's second attenuation model

"4" is used for Kharadly's fourth attenuation model

"5" is used for the empirical formula

note 2 : An input to select the Scattering model to be used in the calculations.

Cuurentelly, we have only one scattering model (Kharadly's).

note 3 : THE_T is θ_t

PHI_T is ϕ_t

note 4 : THE_R is θ_r

PHI_R is ϕ_r

note 5	:	Determine the polarization of the transmitting antenna
		"0", "180", "360" is for vertical polarization
		"90", "270" is for horizental polarization
		A number can be chosen between 0 to 360.
note 6	:	The double-sided half-power bandwidth of the transmitter
note 7	:	parameter that currentelly does not enter into calculations
note 8	:	Is there a melting snow layer:
		If "N"o, then skip ignore the next two lines (do not enter them)
		If "Y"es, then enter (Hm - T) and T
		The No case need not be used since we can enter T = 0
note 9	:	$m = 1 - \rho_s$
		m ranges between 0.7 to 0.9
		The empirical formula will treat m to be 0.9 whatever the input is
note 10	:	In this case:
		$(\alpha_1, \alpha_2, \mathbf{K}) = (0.4, 5.5, -18)$ for the receiver antenna
note	:	The Transmitter is assumed to be at the centre of the main coordinate system.

The program can be (and should be) further refined as to make it more efficient and to incorporate more features.

Appendix F CCIR Document 12–3/29 (Rev. 1) and supplement

Canada's contribution to CCIR Study group (Working Party 5C), document 12–3/29 (Rev. 1) titled EFFECT OF THE MELTING LAYER ON HYDROMETEOR SCATTER INTERFERENCE AND COORDINATION DISTANCE is reproduced on p. 139–148. [4]

The error statistics for COST 210 [7] paths, extracted from a paper to be submitted to the IEEE Proceedings, is reproduced on p. 149–152.*

* Olsen, R.L., Kharadly, M.M.Z. and Hulays, R.A, "Effect of hydrometeors in and above the melting layer on scatter interference," IEEE Proceedings on Electromagnetic Propagation in Rain, early 1993.

Documents
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EFFECT OF THE MELTING LAYER ON HYDROMETEOR SCATTER INTERFERENCE AND COORDINATION DISTANCE

1. Introduction

The Working Party 5C Revision of Recommendation 620 (Doc. 5C/TEMP6) includes a simple modification to the model for the hydrometeor scatter mechanism of Report 724-2 to take into account the 6.5 dB/km fall off in reflectivity above the rain height. Because the old method in Report 724-2 assumed a constant reflectivity up to heights above the rain height, the effect of the modification is to significantly reduce the coordination distance in many circumstances. The intent of the modification to bring the model into better agreement with physical reality in a relatively simple way is believed to be a good one. Unfortunately, the modification may now err too much in the optimistic direction, particularly for the 4-6 GHz band, because it ignores the effect of the melting layer. A Canadian document considered by Working Party 5C at its recent meeting gave some preliminary model calculations of the effect of the melting layer on relative interference levels. The predicted enhancement of interference as a result of the melting layer was the same order as that indicated by some limited experimental results available at the time [COST 210, 1991]. This document presents some additional model calculations that illustrate the effect of both melting layer scattering and attenuation on coordination distance. Further comparison is also made with experimental results available for frequencies above 11 GHz [COST 210, 1991].

1. Model for scattering cross-section of melting snowflakes

The model for the scattering cross-section of melting snowflakes [Kharadly, 1990] is based on an extension of three main physically-based empirical approximations investigated by Kharadly and Choi [1988] for attenuation by melting snow flakes. First of all, it is assumed for the purposes of interference calculations that the melting snow flakes can be approximately represented by water-coated snow spheres (The density of 0.1 g/cm^3 of the snow core was based on measurements of Matsumoto and Nishitsujo [1971].) Secondly, a physically-based empirical extension of the Rayleigh scattering cross-section is introduced for frequencies above the Rayleigh region. Thirdly, it is assumed that a distribution of particle sizes can be replaced by a single particle of representative size. Three additional empirical correction factors were also introduced by Kharadly [1990] to give improved agreement with Mie scattering calculations. The particle-size distribution used to determine the representative particle size for the melting layer is such that it reduces to a Laws and Parsons drop-size distribution for the rain below and satisfies the conservation of mass criterion [Kharadly and Kishk, 1991]. (The initial distribution used by Kharadly and Choi [1988] for melting snow particles violated conservation of mass.)

Example comparisons between the model cross-sections (Model I) and Mie scattering cross sections for the forward scattering direction are given in Figures 1 and 2 for rain (degree of melting S=1) and a modelled melting snow medium with 10% by volume of the outer shell of the particle melted (S=0.1). (The Model II curves given are based on a different set of assumptions and are not used here [Kharadly, 1990].) These results indicate the validity of all approximations noted above except the first, the shape and composition of the particles themselves. An additional investigation [Kharadly, 1991a] has demonstrated that uniformly-randomly-oriented (and even to some extent non-uniformly-

randomly-oriented) water-coated snow spheroids can be adequately approximated by water-coated snow spheres for the purposes of interference calculations.

The water-coated snow sphere model employed results in a radar reflectivity peak in the melting layer of about 16 dB with respect to that of rain of equivalent rain rate. This compares with some values of about 12 dB observed from radar measurements [Klassen, 1988]. Any such measurements, however, will tend to reduce the peak value because of volumetric averaging. Even more averaging will occur in radar measurements of statistical reflectivity profiles [e.g., COST 210, 1991]. The model is sufficiently flexible, however, so as to allow the peak reflectivity to be adjusted to fit the data. An increase in the snow core density, for example, will reduce the size of the model snow scatterers and therefore the reflectivity peak. Such adjustments can also be made to obtain best fits to actual melting layer attenuation data [Kharadly and Kishk, 1991].

2. Models for specific attenuation by melting snowflakes

Three models have been developed for specific attenuation of melting snowflakes [Kharadly 1991b], all of which employ the three main physically-based empirical approximations noted above. The differences between the models are the additional empirical correction factors which have been introduced to give improved agreement between the model calculations and Mie calculations for water coated snow spheres. Finally, a totally empirical model has been developed [Hulays, 1991] of the form

$$A = A_n(R,S)\, aR^b \qquad (1)$$

where R is the precipitation rate and S is the degree of melting, with aR^b the well-known form for rain [Olsen *et al.*, 1978]. This model, which also gives good agreement with Mie scattering calculations, is conveniently used for the interference calculations presented in this document.

3. Macroscopic meteorological models

The horizontal structure of the fixed-position rain cell employed in the rain scatter and rain attenuation calculations is that currently assumed in Revised Recommendation 452-4 (Doc. 5C/TEMP9) and used previously in Report 569-4 and also by COST 210 [1991]. The center of the cell is positioned at the intersection of the antenna beam axes. The diameter of the melting layer cell is assumed to be the same as that of the rain cell below it, and the melting layer attenuation is assumed to reduce at the same exponential rate as the rain attenuation outside the core cell. Since the specific melting layer attenuation varies with height within the melting layer, a numerical integration is carried out in the vertical direction.

The depth D_m of the melting layer is assumed to vary with reflectivity factor Z of the rain in the form [Klassen, 1988]

$$D_m = 100\, Z^{0.17} \qquad (2)$$

D_m is related to the precipitation rate R through the relation $Z = 400R^{1.4}$.

The height of the melting layer is assumed to be fixed, but the effect of different values of this fixed height have been calculated. As demonstrated elsewhere [COST 210, 1991], the height of the melting layer varies considerably and the most accurate calculations should assume a distribution of heights. However, within any given month such as the worst month, the range in distribution of heights will be smaller and the use of a fixed height should give a reasonably close upper bound to the effect of the melting layer.

The variation in the melting profile of the melting layer (i.e., variation in S between 0 at the top and 1 at the bottom) is assumed to be linear [Kharadly and Choi, 1988]. Other profiles are considered elsewhere [Kharadly and Kishk, 1991].

The effect of the ice and dry snow medium above the melting layer was not included in the calculations of the earlier Canadian document considered by Working Party 5C. This approximation has now been eliminated. Rayleigh scattering by the ice and snow medium above the melting layer is assumed along with a reflectivity of $Z = 400R^{1.4}$ at the lower boundary of this medium (the so-called "rain height") decreasing with height at the rate of -6.5 dB/km as required in Revised Recommendations 620 (Doc. 5C/TEMP9) and 452-4 (Doc. 5C/TEMP9). The elimination of this approximation has turned out to be more important than previously believed since the attenuation of an intervening melting layer tends to reduce the contribution of this ice and snow region relative to its contribution without a melting layer, the effect of course increasing with increasing frequency. The overall result at the higher frequencies is that the relative effect of including the melting layer in the model calculations is less, even when the melting layer is at the optimum height. However, since existing experimental data [COST 210, 1991] are used as a reference, the difference does not change the conclusions.

4. Other assumptions

Other assumptions made in the calculations are consistent with the "extended CCIR model" discussed elsewhere [COST 210, 1991]. These include an assumption of no polarization mismatch, a narrow-beam approximation for the earth-station antenna, and Gaussian-shaped main-lobe and side-lobe patterns (highest side-lobe gain of 15 dB down assumed) for the terrestrial antenna. Atmospheric attenuation, ignored in the calculations of the earlier Canadian document, is now included using the model in Revised Recommendation 452-4 (Doc. 5C/TEMP9), although the contribution is small at the frequencies considered.

5. Results for sample interference geometries

Two curves of transmission loss as a function of rainrate are given in Figure 3 for the experimental parameters of the Chilbolton-Baldock link [COST 210, 1991] (e.g., frequency of 11.2 GHz and a station separation of 131 km). The solid curve is for rain only and the dashed curve for rain plus melting layer. The latter is not shown above 30 mm/h because the existance of a melting layer above this precipitation rate is considered unlikely. The terrestrial and earth-station elevation angles of 1.0° and 20°, respectively, place the center of the common volume at a height of about 3.0 km. The bottom of the melting layer is positioned at this height, which approximately maximizes the interference effect of the melting layer. Other parameters are indicated in the caption.

As seen from Figure 3, the effect of the melting layer increases with increasing rainrate (and increasing melting layer thickness) until above about 5 mm/h, where the effect of attenuation in the melting layer begins to outweigh the effect of increased scattering cross section. At rainrates of 8, 13, 15, 19, and 29 mm/h, the interference level is approximately 2.5, 2.2, 2.0, 1.8, and 1.5 dB higher, respectively, than it would be if there were rain in place of the melting layer. This compares with melting layer enhancements of 1.7 and 2.7 dB exceeded for 0.1% and 0.01% of the time in the worst season (summer). These values were estimated from a comparison of actual data for summer and winter at two common volume altitudes (data provided courtesy of Rutherford-Appleton Laboratory; see also Revised Recommendation 452-4 (Doc. 5C/TEMP9)). In composite rain climate C,D,E, these exceedances correspond to rainrates of 8 and 19 mm/h on an annual basis, or about 13 and 29 mm/h on a worst season basis. A rainrate of about 15 mm/h is exceeded for 0.1% of the worst month in the same rain climate. The worst season enhancements of 1.7 and 2.7 dB at the 0.1% and 0.01% exceedance levels will also be observed in the annual distributions but at smaller exceedance levels. It is interesting, but possibly a coincidence, that the annual distributions of interference level predicted for the Chilbolton-Baldock link by the method of Revised Recommendation 452-4 (Doc. 5C/TEMP9) underestimate the measured distributions by about the amount of the melting layer enhancement obtained from the seasonal measurements.

As evident from the comparison of model and experimental estimates of the enhancement in interference caused by the presence of the melting layer, the latter is close

to the optimum estimated value (1.7 versus 2.0 dB) at 0.1% of the worst season and greater than the optimum estimated value (2.7 dB versus 1.5 dB) at 0.01%. This suggests that either the height variation of the melting layer in the summer is not large or that the experimental estimates are a little on the high side, at least at 0.01% of the worst season. (The melting layer was known to occur approximately at the common volume height on Chilbolton-Baldock link during the summer months [COST 210, 1991].) It should be noted, however, that it is possible in principal for melting layer and associated precipitation scatter a low precipitation rates to contribute to the interference levels exceeded for smaller percentages of time than the corresponding precipitation rate. There will be some instances, for example, when the melting layer and rain attenuation associated with the scattering will be smaller than that predicted by a model estimating the average attenuation (e.g., if the scatter volume were on the edge of the precipitation cell without much attenuation outside the common volume). In any case, the combined experimental and model results suggest that the effect of the melting layer is too significant to ignore when the scatter volume is at about the height of the melting layer in any given month or season, even at 11.2 GHz. The increase in coordination distance required to offset the effect of the melting layer enhancement of 1.7 dB exceeded for 0.1% of the time in the worst season is 21 km.

Results are given in Figure 4 for the same parameters of the Chilbolton-Baldock link, but at a frequency of 4 GHz. Here the height of the center of the melting layer is positioned at the height of the center of the common volume, which approximately "optimizes" the enhancement of the melting layer. The "optimum" enhancements are 6.6, 7.5, 7.8, 8.3, and 9.2 dB at rainrates of 8, 13, 15, 19, and 29 mm/h, respectively. On the basis of a frequency scale factor of 3.4 derived from the enhancement ratio 7.5/2.2 at a rainrate of 13 mm/h, the measured enhancement of 1.7 dB at 11.2 GHz scales to 5.8 dB at 4 GHz. Similarly, the measured enhancement of 2.7 dB ("optimum" estimated value of 1.5 dB) at 11.2 GHz scales to 16 dB (9.2 dB for "optimum" value) at 4 GHz on the basis of a frequency scale factor of 9.2/1.5=6.1 derived from the enhancement ratio at 29 mm/h. A more optimistic scale factor of 3.9 derived from the enhancement ratio of 7.8/2.0 at 15 mm/h would reduce the latter figure to 5.9 dB. The increase in coordination distance needed to offset a 5.9 dB enhancement for a rainrate of 15 mm/h at 4 GHz is 66 km.

In agreement with calculations obtained elsewhere [COST 210, 1991], calculations for higher frequencies using the current model indicate that the effect of the melting layer on interference continues to diminish as a result of increasing attenuation both in the rain and the melting layer. The 2.8 dB "optimum" enhancement estimated at 11.2 GHz from Figure 3, for example, is reduced to about 0.7 dB at 20 GHz.

Certain geometries for which the effect of attenuation outside the common volume is reduced should pose problems up to quite high frequencies. One such geometry is that of an intersection or near-intersection between two earth-station beams pointed at elevation angles significantly higher than that of the average terrestrial station antenna. Such a geometry was investigated at 11.4 GHz on a 9.3 km side-scatter link near Graz [COST 210, 1991]. The model calculations for this link, with and without the melting layer, are given in Figure 5. Here the top of the melting layer is positioned 0.1 times its thickness from the center of the common volume at 2.9 km height to obtain "optimum" enhancements of 5.8, 6.4, and 2.9 dB at 2, 10, and 30 mm/h, respectively. (Corresponding figures for a frequency of 20 GHz are 1.9, 1.5, and 0 dB.) Rainrates of 2, 10, and 32 mm/h are exceeded for 1%, 0.1%, and 0.01% of the year for composite rain climate F-K corresponding to that of Graz. It is interesting that the annual distributions of interference level predicted for the Graz link by the method of Revised Recommendation 452-4 (Doc. 5C/TEMP9) underestimate the measured distributions by amounts ranging from 12 dB to 6 dB between the corresponding exceedance levels of 1% and 0.01% of the time on an annual basis [COST 210, 1991]. The enhancement caused by the melting layer can perhaps explain much of this large discrepancy.

6. Discussion and Conclusions

The model results given and supporting comparisons with experimental data suggest that the effect of the melting layer should be taken into account in both coordination distance calculations (such as those obtained from Revised Recommendation 620 (Doc. 5C/TEMP6)) and detailed interference calculations (such as those obtained from Revised Recommendation 452-4 (Doc. 5C/TEMP9)). This is most important for the 4-6 GHz band where the effects of rain and melting layer attenuation are least significant with respect to that of the scattering. Another way of looking at the results is that the apparent increase in the interference level introduced by the presence of the melting layer is larger than that in changing from one composite rain climate to another (e.g., climate C,D,E to Climate F-K). If the use of such "fine" climatic differences is justified, then the introduction of the apparent effect of the melting layer would seem even more justified.

Of course scattering from rain and the dry snow and ice region above the melting layer are only important from an interference coordination viewpoint if there is a main beam intersection. Clearly the chance of such a main-beam intersection occurring is very small, which is no doubt one reason that interference due to hydrometeor scatter has apparently not been observed in practice. Even if an interference causing main-beam intersection or near-intersection had occurred in the past, it would not be surprising for the interference to have remained unobserved. Interference due to hydrometer scatter is not generally as long lasting as that resulting from the clear-air mechanisms. Furthermore, performance monitoring has not been generally carried out. Even if a deterioration in performance were observed, there would be no easy way of knowing if it were due to interference or to attenuation of the wanted signal.

At first sight the chances of having a main-beam intersection and a melting layer occurring within it at the time of year when precipitation intensities are greatest would seem to be even smaller than having a main-beam intersection occurring within rain. This is no doubt true for short distances between terminals with the main-beam intersections occurring at low altitudes. However, at the 100 km and larger distances for coordination the main-beam intersections occur at altitudes for which the melting layer also occurs in the summer months, at least at temperate latitudes. Thus, it would appear that the melting layer should always have some influence on coordination at these latitudes in the frequency bands including and below the 11-14 GHz band.

At low latitudes in rain climates for which convective rain clearly dominates the interference statistics at the critical time percentages (e.g., 0.01%), the melting layer should not be a factor in either coordination or detailed interference prediction. Composite rain climates L,M and N,P are believed to be in this category. Melting layer scatter is believed to be a factor in composite rain climate F-K because scatter from the less intense precipitation in the melting layer dominates that from some of the more intense precipitation in convective rain.

Although the possible effect of melting layer scatter on the accuracy of detailed interference calculations is mentioned in Revised Recommendation 452-4 (Doc. 5C/TEMP9)), there was insufficient data and other information available at the meeting of Working Party 5C to propose a suitable modification to the prediction technique for estimating hydrometeor scatter interference levels. Data and other information were similarly lacking to propose a suitable modification to the coordination procedure in Revised Recommendation 620 (Doc. 5C/TEMP6). A crude modification could be carried out on the basis of the information given in this document if it were desired to give designers of earth stations the option of including 100% of possible interference geometries. A difficulty is that there is no corresponding method as yet in Revised Recommendation 452-4. At the very least, the information in this document provides a much clearer indication than was previously available of the potential risks involved in ignoring the effects of the melting layer in interference coordination.

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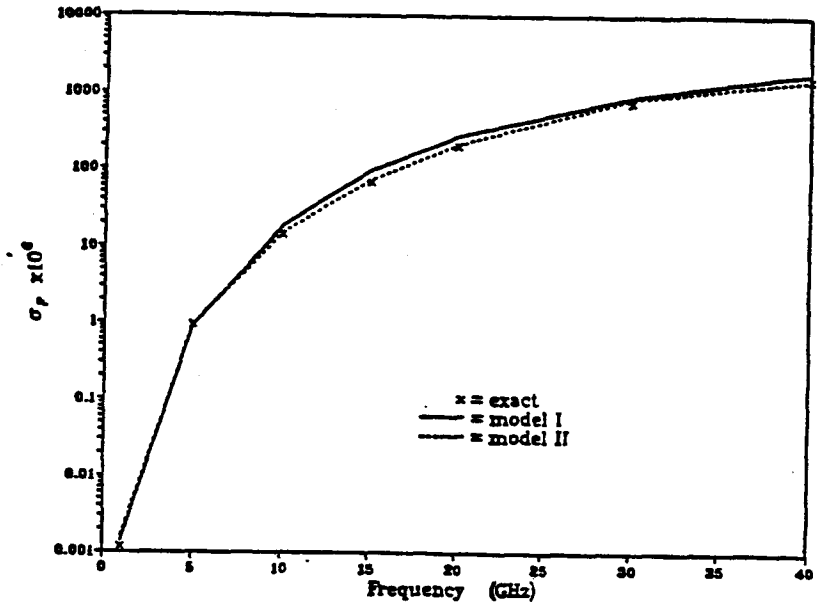

Figure 1. Comparison of model (Model I) and Mie scattering ("exact") forward scattering cross sections (m^2/m^3) of rain (S=1) as functions of frequency. R=25 mm/h, 0°C water temperature.

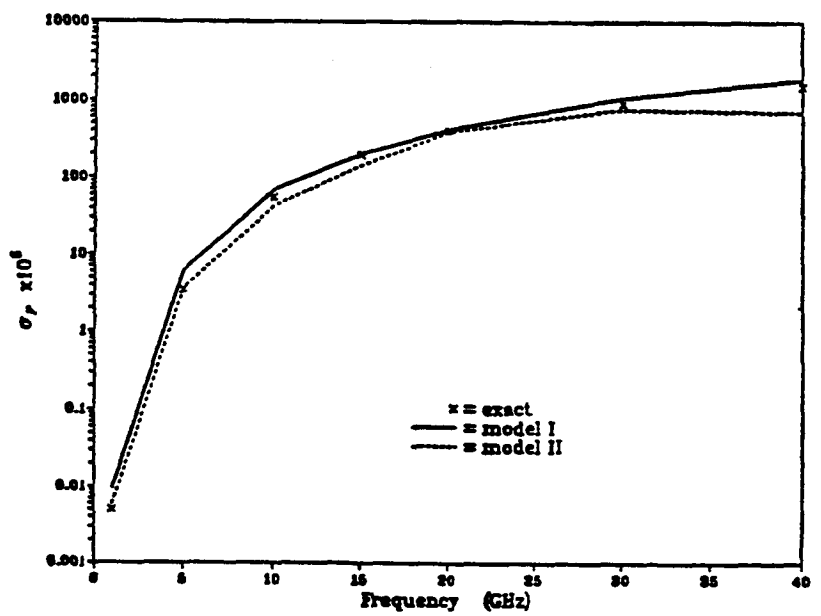

Figure 2. Comparison of model (Model I) and Mie scattering ("exact") forward scattering cross sections (m^2/m^3) of melting snowflakes (S=0.1) as functions of frequency. R=25 mm/h, 0°C water temperature.

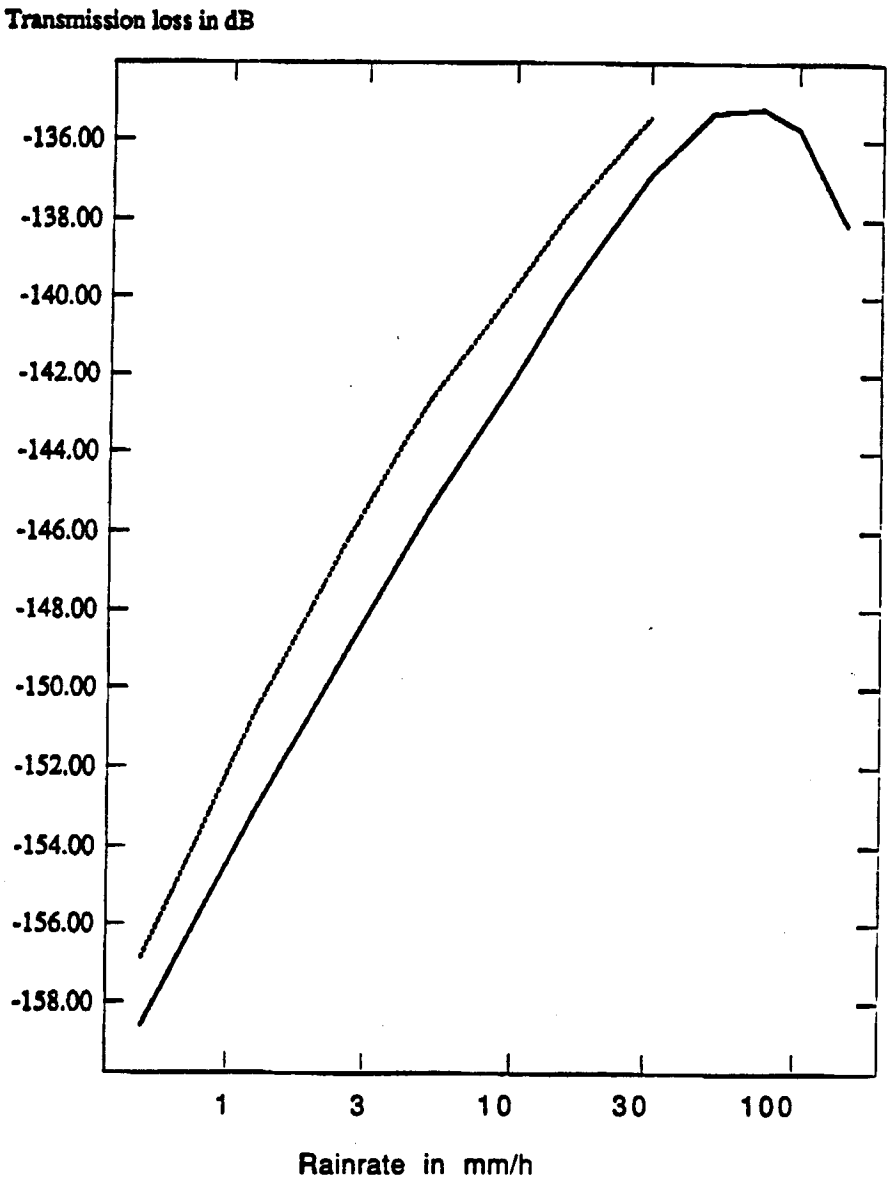

Figure 3. Comparison of transmission loss with and without the melting layer as a function of rainrate at 11.2 GHz for parameters of Chilbolton-Baldock link. —— rain only, ····· rain with melting layer; 131 km station separation, 20° earth-station elevation angle, 1.0° terrestrial-station elevation angle, 3.0 km common-volume height, $3.0+D_m$ km height to melting layer top ("rain height"), 40.5 dB terrestrial antenna gain (1.6° half-power beamwidth), 59 dB earth-station gain (0.18° half-power beamwidth, 55% efficiency).

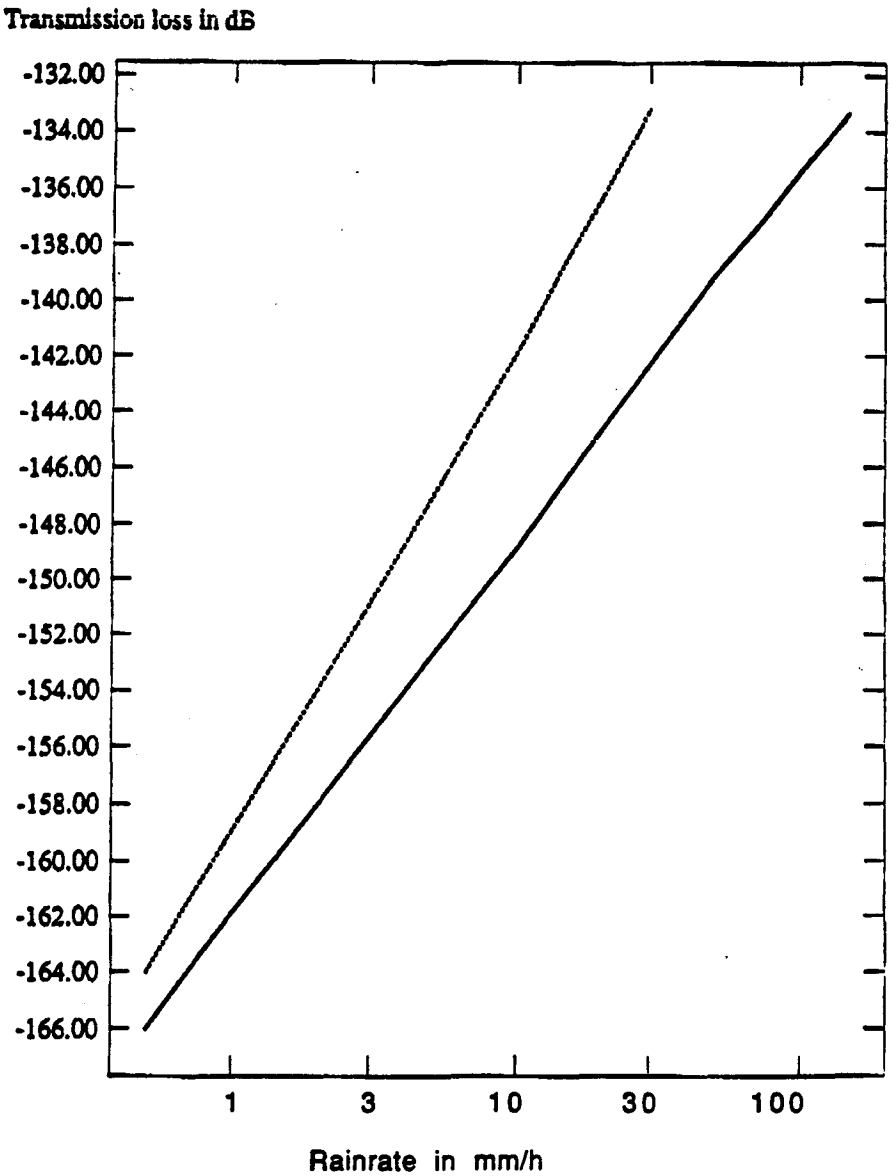

Figure 4. Comparison of transmission loss with and without the melting layer as a function of rainrate at 4 GHz GHz for parameters of Chilbolton-Baldock link. —— rain only, ····· rain with melting layer; 131 km station separation, 20° earth-station elevation angle, 1.0° terrestrial-station elevation angle, 3.0 km common-volume height, $3.0+0.5D_m$ km height to melting layer top ("rain height"), 40.5 dB terrestrial antenna gain (1.6° half-power beamwidth), 59.0 dB earth-station gain (0.18° half-power beamwidth, 55% efficiency).

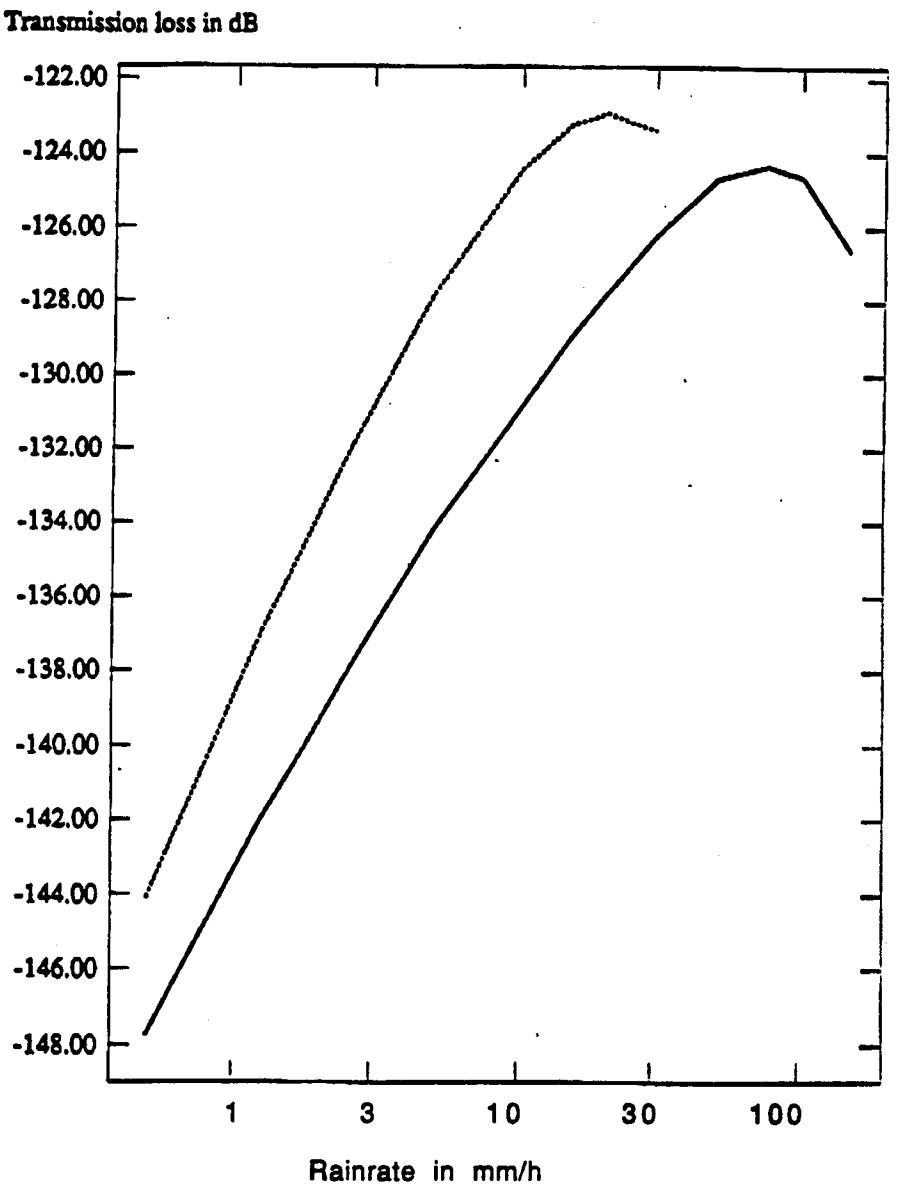

Figure 5. Comparison of transmission loss with and without the melting layer as a function of rainrate at 11.4 GHz for parameters of Graz link. —— rain only, ····· rain with melting layer; 9.3 km station separation, 16.8° transmitter elevation angle, 36.3° receiver elevation angle, 2.9 km common-volume height, $2.9+0.1 D_m$ km height to melting layer top ("rain height"), 37 dB transmitting antenna gain (3.0° half-power beamwidth), 47 dB receiving antenna gain (0.6° half-power beamwidth, 55% efficiency assumed).

Long-Path Error Statistics* for COST 210 Links at 1%

Path	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Chilbolton-Baldock, Bf	2.0 dB	-3.9 (-1.9)	-2.50 (-0.50)	-2.05 (-0.05)	-1.60 (0.40)	-1.15 (0.85)
Chilbolton-Baldock, Bb	5.0	-5.4	-3.00	-2.20	-1.40	-0.6
Cap d'Antifer - Chilbolton	-3.9	-3.9 (-1.9)	-3.9 (-1.9)	-3.9 (-1.9)	-3.9 (-1.9)	-3.9 (-1.9)
Fulda, Ff	-	-	-	-	-	-
Fulda, Fb	-	-	-	-	-	-
Radar Simul., S2	0.0	0.0	0.0	0.0	0.0	0.0
Radar Simul., S3	0.8	0.8	0.8	0.8	0.8	0.8
Radar Simul., S4	3.9	3.2	3.35	3.41	3.46	3.52
Radar Simul., S5	11.0	2.5	4.45	5.11	5.76	6.42
Mean	2.7	-1.0 (-0.4)	-0.1 (0.5)	0.2 (0.7)	0.4 (1.0)	0.7 (1.3)
Standard Dev.	4.7	3.42 (2.96)	3.22 (2.68)	3.23 (2.68)	3.27 (2.72)	3.35 (2.80)

Short-Path Error Statistics* for COST 210 Links at 1%

Path	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Leidschendam, L1	10.8	10.8	10.8	10.8	10.8	10.8
Leidschendam, L2	11.4	11.4 (11.9)	11.4 (11.9)	11.4 (11.9)	11.4 (11.9)	11.4 (11.9)
Leidschendam, L3	12.4	12.4 (12.9)	12.4 (12.9)	12.4 (12.9)	12.4 (12.9)	12.4 (12.9)
Leidschendam, L4	14.0	14.0 (14.5)	14.0 (14.5)	14.0 (14.5)	14.0 (14.5)	14.0 (14.5)
Leidschendam, L5	16.1	12.2 (12.7)	13.1 (13.6)	13.4 (13.9)	13.7 (14.2)	14.0 (14.5)
Leidschendam, L6	18.5	10.7 (11.2)	12.5 (13.0)	13.1 (13.6)	13.7 (14.2)	14.3 (14.8)
Leidschendam, L7	21.1	7.5	10.6	11.7	12.7	13.8
Leidschendam, L8	22.9	2.8	7.4	9.0	10.5	12.1
Darmstadt, D1	5.7	5.7	5.7	5.7	5.7	5.7
Darmstadt, D2	11.7	8.5	9.2	9.5	9.7	10.0
Darmstadt, D3	14.0	4.9	7.0	7.7	8.4	9.1
Darmstadt, D4	18.3	2.7	6.3	7.5	8.7	9.9
Darmstadt, D5	7.0	7.0	7.0	7.0	7.0	7.0
Darmstadt, D6	10.8	-4.2	-0.7	0.5	1.6	2.8
Graz	-0.6	-3.9 (2.5)	-3.1 (3.3)	-2.9 (3.5)	-2.6 (3.8)	-2.4 (4.0)
Radar Simul., S1	3.1	3.1	3.1	3.1	3.1	3.1
Mean	12.3	6.6 (7.1)	7.9 (8.5)	8.4 (8.9)	8.8 (9.4)	9.3 (9.8)
Standard Dev.	6.4	5.50 (5.07)	4.92 (4.34)	4.83 (4.21)	4.80 (4.14)	4.83 (4.15)

Combined Long- and Short-Path Error Statistics* (dB) for COST 210 Links at 1%

	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Combined Standard Dev.	5.8	4.88 (4.46)	4.39 (3.85)	4.33 (3.75)	4.32 (3.70)	4.36 (3.73)

* Predicted interference levels minus measured levels. Values in parentheses include rough correction for melting layer.

Long-Path Error Statistics* (dB) for COST 210 Links at 0.1%

Path	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.5 dB/km)	Rpt 724 Mod (-5.0 dB/km	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Chilbolton-Baldock, Bf	0.0	-5.9 (-3.9)	-4.95 (-2.95)	-4.50 (-2.50)	-4.05 (-2.05)	-3.60 (-1.60)	-3.15 (-1.15)
Chilbolton-Baldock, Bb	3.9	-6.5	-4.90	-4.10	-3.30	-2.50	-1.70
Cap d'Antifer - Chilbolton	-4.7	-4.7 (-2.7)	-4.7 (-2.7)	-4.7 (-2.7)	-4.7 (-2.7)	-4.7 (-2.7)	-4.7 (-2.7)
Fulda, Ff	-	-	-	-	-	-	-
Fulda, Fb	-	-	-	-	-	-	-
Radar Simul., S2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Radar Simul., S3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Radar Simul., S4	2.8	2.1	2.20	2.25	2.31	2.36	2.42
Radar Simul., S5	8.9	0.4	1.70	2.35	3.01	3.66	4.32
Mean	1.6	-2.1 (-1.5)	-1.5 (-0.7)	-1.2 (-0.7)	-1.0 (-0.4)	-0.7 (-0.1)	-0.4 (0.2)
Standard Dev.	4.2	3.49 (2.98))	3.22 (2.75)	3.13 (2.51)	3.09 (2.44)	3.08 (2.41)	3.12 (2.44)

Short-Path Error Statistics* (dB) for COST 210 Links at 0.1%

Path	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Leidschendam, L1	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Leidschendam, L2	7.8	7.8 (8.3)	7.8 (8.3)	7.8 (8.3)	7.8 (8.3)	7.8 (8.3)	7.8 (8.3)
Leidschendam, L3	8.9	8.9 (9.4)	8.9 (9.4)	8.9 (9.4)	8.9 (9.4)	8.9 (9.4)	8.9 (9.4)
Leidschendam, L4	10.2	10.2 (10.8)	10.2 (10.8)	10.2 (10.8)	10.2 (10.8)	10.2 (10.8)	10.2 (10.8)
Leidschendam, L5	12.0	8.1 (8.6)	8.70 (9.20)	9.00 (9.50)	9.30 (9.80)	9.60 (10.1)	9.90 (10.4)
Leidschendam, L6	14.6	6.9 (7.4)	8.00 (8.50)	8.60 (9.10)	9.20 (9.70)	9.80 (10.3)	10.40 (10.9)
Leidschendam, L7	18.1	4.5	6.55	7.60	8.65	9.70	10.75
Leidschendam, L8	20.9	0.8	3.85	5.40	6.95	8.50	10.05
Darmstadt, D1	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Darmstadt, D2	8.5	5.3	5.75	6.00	6.25	6.50	6.75
Darmstadt, D3	9.6	0.5	1.90	2.60	3.30	4.00	4.70
Darmstadt, D4	13.3	-2.3	0.10	1.30	2.50	3.70	4.90
Darmstadt, D5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Darmstadt, D6	10.6	-4.3	-2.05	-0.90	0.25	1.40	2.55
Graz	-0.8	-4.0 (2.4)	-3.55 (2.85)	-3.30 (3.10)	-3.05 (3.35)	-2.80 (3.60)	-2.55 (3.85)
Radar Simul., S1	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Mean	9.3	3.6 (4.2)	4.5 (5.1)	4.9 (5.5)	5.4 (5.9)	5.8 (6.4)	6.3 (6.8)
Standard Dev.	5.8	4.56 (4.29)	4.07 (3.69)	3.91 (3.48)	3.81 (3.33)	3.79 (3.27)	3.84 (3.29)

Combined Long- and Short-Path Error Statistics* (dB) for COST 210 Links at 0.1%

	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Combined Standard Dev.	5.1	4.18 (3.87)	3.76 (3.37)	3.62 (3.16)	3.54 (3.03)	3.52 (2.98)	3.56 (3.00)

*Predicted interference levels minus measured levels. Values in parentheses include rough correction for melting layer.

Long-Path Error Statistics* (dB) for COST 210 Links at 0.01%

Path	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Chilbolton-Baldock, Bf	0	-5.9 (-3.9)	-4.95 (-2.95)	-4.50 (-2.50)	-4.05 (-2.05)	-3.60 (-1.60)	-3.15 (-1.15)
Chilbolton-Baldock, Bb	4.9	-5.5	-3.90	-3.10	-2.30	-1.50	-0.70
Cap d'Antifer - Chilbolton	-6.3	-6.3 (-4.3)	-6.3 (-4.3)	-6.3 (-4.3)	-6.3 (-4.3)	-6.3 (-4.3)	-6.3 (-4.3)
Fulda, Ff	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3
Fulda, Fb	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Radar Simul., S2	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Radar Simul., S3	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6
Radar Simul., S4	0.0	-0.7	-0.61	-0.55	-0.50	-0.44	-0.39
Radar Simul., S5	6.9	-1.6	-0.31	0.35	1.01	1.66	2.32
Mean	0.2	-2.6 (-2.2)	-2.2 (-1.7)	-2.0 (-1.5)	-1.7 (-1.3)	-1.5(-1.1)	-1.3 (-0.9)
Standard Dev.	3.8	2.53 (1.92)	2.29 (1.60)	2.24 (1.53)	2.24 (1.53)	2.28 (1.60)	2.37 (1.73)

Short-Path Error Statistics* (dB) for COST 210 Links at 0.01%

Path	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Leidschendam, L1	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Leidschendam, L2	4.1	4.1 (4.6)	4.1 (4.6)	4.1 (4.6)	4.1 (4.6)	4.1 (4.6)	4.1 (4.6)
Leidschendam, L3	5.6	5.6 (6.1)	5.6 (6.1)	5.6 (6.1)	5.6 (6.1)	5.6 (6.1)	5.6 (6.1)
Leidschendam, L4	7.1	7.1 (7.6)	7.1 (7.6)	7.1 (7.6)	7.1 (7.6)	7.1 (7.6)	7.1 (7.6)
Leidschendam, L5	8.7	4.8 (5.3)	5.4 (5.9)	5.7 (6.2)	6.0 (6.5)	6.3 (6.8)	6.6 (7.1)
Leidschendam, L6	9.8	2.0 (2.5)	3.2 (3.7)	3.8 (4.3)	4.4 (4.9)	5.0 (5.5)	5.6 (6.1)
Leidschendam, L7	15.4	1.8	3.9	4.9	6.0	7.0	8.1
Leidschendam, L8	18.1	-2.1	1.1	2.6	4.2	5.7	7.3
Darmstadt, D1	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Darmstadt, D2	7.9	4.6	5.2	5.4	5.7	5.9	6.2
Darmstadt, D3	9.2	0.1	1.5	2.2	2.9	3.6	4.3
Darmstadt, D4	11.4	-4.2	-1.8	-0.6	0.6	1.8	3.0
Darmstadt, D5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Darmstadt, D6	8.7	-5.1	-4.0	-2.8	-1.7	-0.5	0.7
Graz	0.2	-3.1 (3.3)	-2.6 (3.8)	-2.3 (4.1)	-2.1 (4.3)	-1.8 (4.6)	-1.6 (4.8)
Radar Simul., S1	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Mean	7.2	1.6 (2.1)	2.4 (3.0)	2.8 (3.4)	3.3 (3.8)	3.7 (4.3)	4.2 (4.7)
Standard Dev.	5.0	3.59 (3.53)	3.09 (2.95)	2.84 (2.64)	2.71 (2.45)	2.64 (2.32)	2.71 (2.33)

Combined Long- and Short-Path Error Statistics* (dB) for COST 210 Links at 0.01%

	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)
Combined Standard Dev.	4.5	3.19 (3.00)	2.78 (2.51)	2.59 (2.27)	2.50 (2.13)	2.48 (2.05)	2.54 (2.10)

* Predicted interference levels minus measured levels. Values in parentheses include rough correction for melting layer.

Long-Path Error Statistics* (dB) for COST 210 Links at 0.001%

Path	Rpt 724	Rpt 724 Mod (-6.5 dB/km)	Rpt 724 Mod (-5.5 dB/km)	Rpt 724 Mod (-5.0 dB/km)	Rpt 724 Mod (-4.5 dB/km)	Rpt 724 Mod (-4.0 dB/km)	Rpt 724 Mod (-3.5 dB/km)	Rpt 724 Mod (-3.0 dB/km)	Rpt 724 Mod (-2.5 dB/km)
Chilbolton-Baldock, Bl	0.4	-5.5	-4.55	-4.10	-3.65	-3.20	-2.75	-2.30	-1.85
Chilbolton-Baldock, Bb	5.1	-5.3	-3.70	-2.90	-2.10	-1.30	-0.50	0.30	1.10
Cap d'Antifer - Chilbolton	-5.9	-5.9	-5.9	-5.9	-5.9	-5.9	-5.9	-5.9	-5.9
Fulda, Fl	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7
Fulda, Fb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Radar Simul., S2	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6
Radar Simul., S3	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2
Radar Simul., S4	-5.2	-5.9	-5.81	-5.75	-5.70	-5.64	-5.59	-5.53	-5.48
Radar Simul., S5	2.9	-5.6	-4.31	-3.65	-3.00	-2.34	-1.69	-1.03	-0.38
Mean	-1.4	-4.2	-3.8	-3.5	-3.3	-3.1	-2.9	-2.7	-2.4
Standard Dev.	3.8	2.2	1.98	1.96	1.99	2.07	2.20	2.36	2.56

* Predicted interference levels minus measured levels. Values in parentheses include rough correction for melting layer.

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