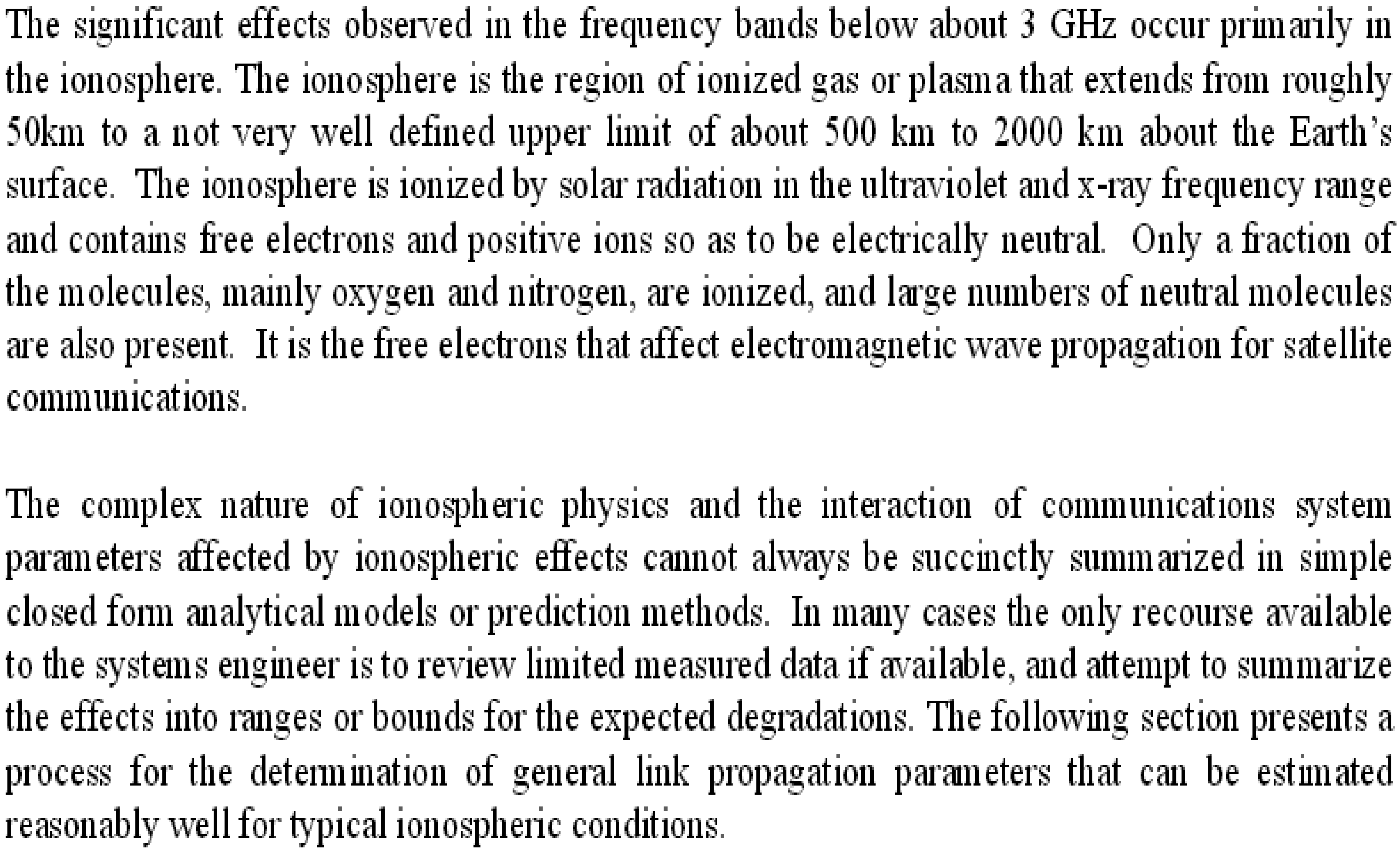
PROPAGATION EFFECTS ON SATELLITE SYSTEMS



The significant effects observed in the frequency bands below about 3 GHz occur primarily in the ionosphere. The ionosphere is the region of ionized gas or plasma that extends from roughly 50km to a not very well defined upper limit of about 500 km to 2000 km about the Earth's surface. The ionosphere is ionized by solar radiation in the ultraviolet and x-ray frequency range and contains free electrons and positive ions so as to be electrically neutral. Only a fraction of the molecules, mainly oxygen and nitrogen, are ionized, and large numbers of neutral molecules are also present. It is the free electrons that affect electromagnetic wave propagation for satellite communications.

The complex nature of ionospheric physics and the interaction of communications system parameters affected by ionospheric effects cannot always be succinctly summarized in simple closed form analytical models or prediction methods. In many cases the only recourse available to the systems engineer is to review limited measured data if available, and attempt to summarize the effects into ranges or bounds for the expected degradations. The following section presents a process for the determination of general link propagation parameters that can be estimated reasonably well for typical ionospheric conditions.

General Link Propagation Parameters

This section presents recommended procedures for the determination of several important propagation parameters for satellite systems operating in the frequency bands below about 3 GHz. The procedures employ the prediction methods described in detail in Section 2 of this handbook. They are generally applicable to fixed slant path conditions, i.e. fixed satellite service (FSS), broadcast satellite service (BSS), space operations (SO), space research (SR), and other applications, employing fixed ground terminals[1].

The link parameters that are degraded by background ionization are:

- Faraday Rotation
- Group Delay
- Time Delay Dispersion

- Ionospheric Scintillation
- Auroral Absorption
- Polar Cap Absorption

The recommended propagation analysis procedure for general link parameters for satellite systems operating below about 3 GHz is summarized in the flow chart of Exhibit 3.2.1-1. The applicable Section 2 references from this handbook are indicated on the chart.

The system parameters required for the propagation analyses are:

Frequency of operation, in GHz: f
Percent of Time (or times) to achieve desired performance [on annual basis]
Polarization tilt angle, in degrees: τ
Elevation angle to the satellite, in degrees: θ
Latitude of the ground station, in degrees N or S.: φ
Longitude of the ground station, in degrees E or W: δ
Altitude of the ground station above sea level, in km: h_s

Most of the parameters of interest for ionospheric propagation require a determination of total electron content (TEC) for the calculation, so that is the first step in the process. For satellite path effects prediction, the TEC value is usually quoted for a zenith path having a cross-section of 1 m^2. The TEC of this vertical column can vary between 10^{16} and 10^{18} electrons/m^2, with the peak occurring during the sunlit portion of the day. For many purposes it is sufficient to estimate electron content by multiplication of the peak electron density with an equivalent slab thickness value of 300 km. Use the value given in the flow chart if no other information is available.

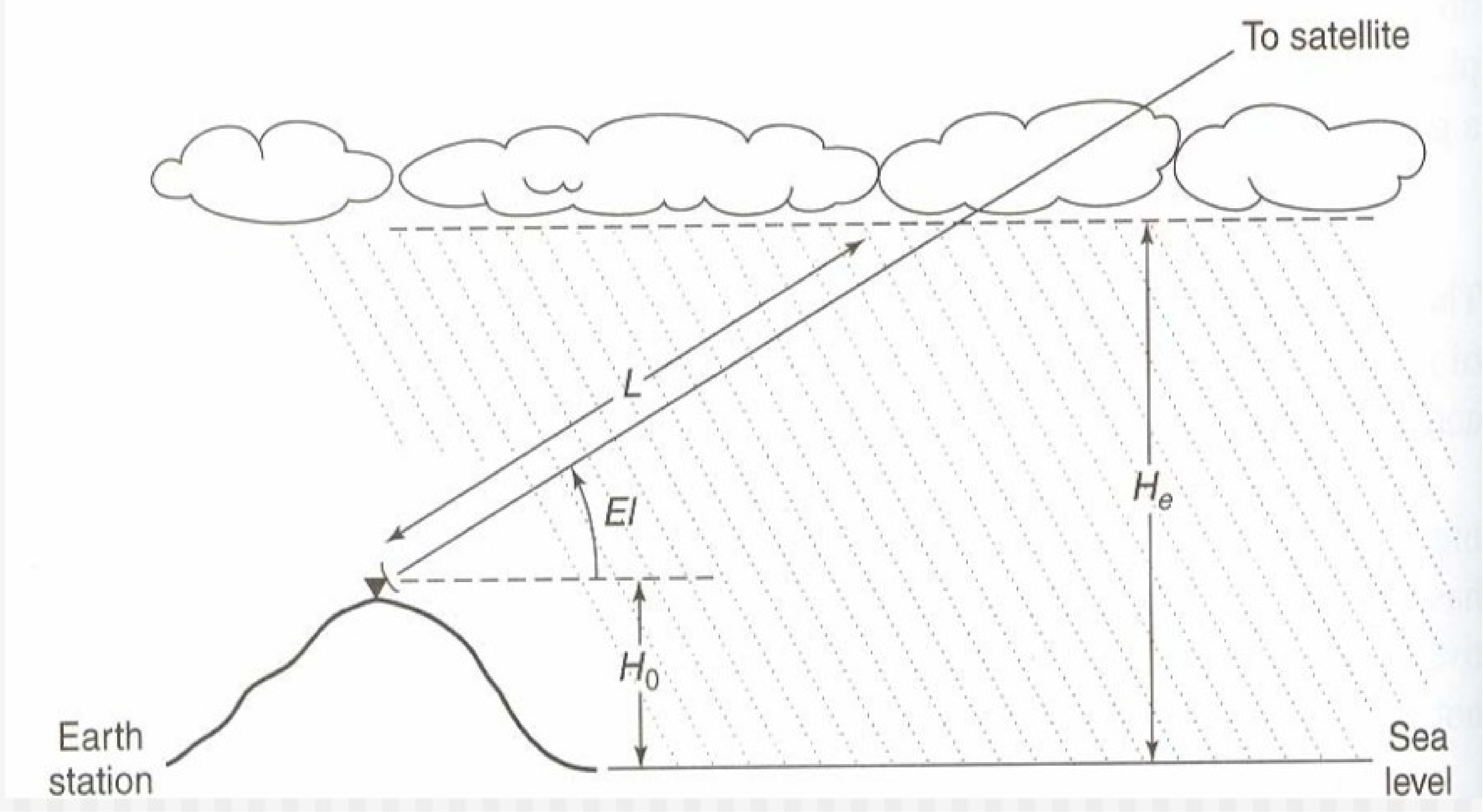
Satellite link design

- Uplink design is easier than the down link in many cases
  - earth station could use higher power transmitters
- Earth station transmitter power is set by the power level required at the input to the transporter, either
  - a specific flux density is required at the satellite
  - a specific power level is required at the input to the transporter
- analysis of the uplink requires calculation of the power level at the input to the transponder so that uplink C/N ratio can be found
- With small-diameter earth stations, a higher power earth station transmitter is required to achieve a similar satellite EIRP.
  - interference to other satellites rises due to wider beam of small antenna
- Uplink power control can be used to against uplink rain attenuation

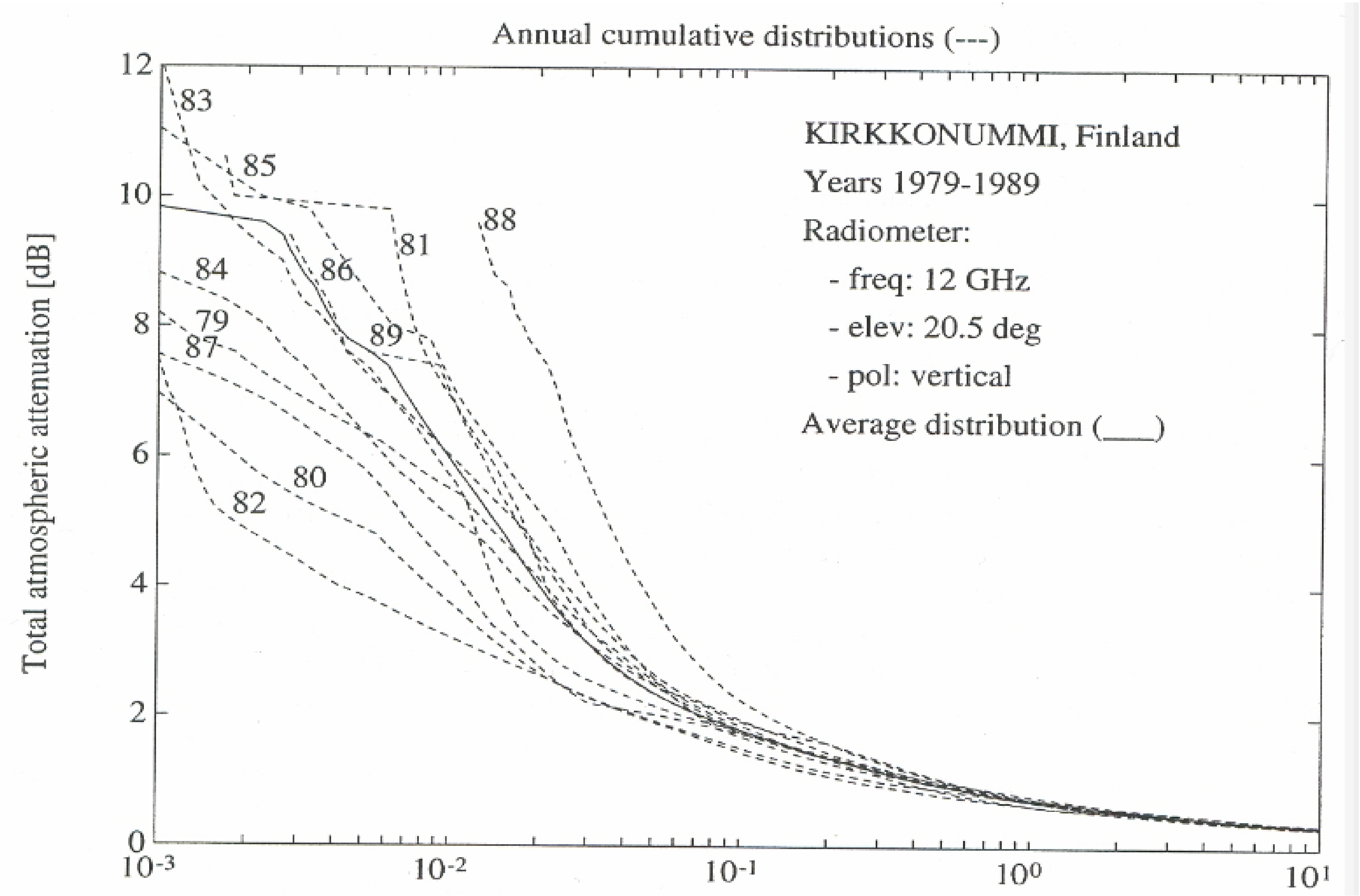
Propagation Effects and their impact

- Many phenomena causes lead signal loss on through the earths atmosphere:
  - Atmospheric Absorption (gaseous effects)
  - Cloud Attenuation (aerosolic and ice particles)
  - Tropospheric Scintillation (refractive effects)
  - Faraday Rotation (an ionospheric effect)
  - Ionospheric Scintillation (a second ionospheric effect)
  - Rain attenuation
  - Rain and Ice Crystal Depolarization
- The rain attenuation is the most important for frequencies above 10 GHz
  - Rain models are used to estimate the amount of degradation (or fading) of the signal when passing through rain.
  - Rain attenuation models: Crane 1982 & 1985; CCIR 1983; ITU-R P.618-5(7 & 8)

Geometry of satellite path through rain



attenuation



PROPAGATION EFFECTS ON DIRECT BROADCAST SATELLITE SYSTEMS

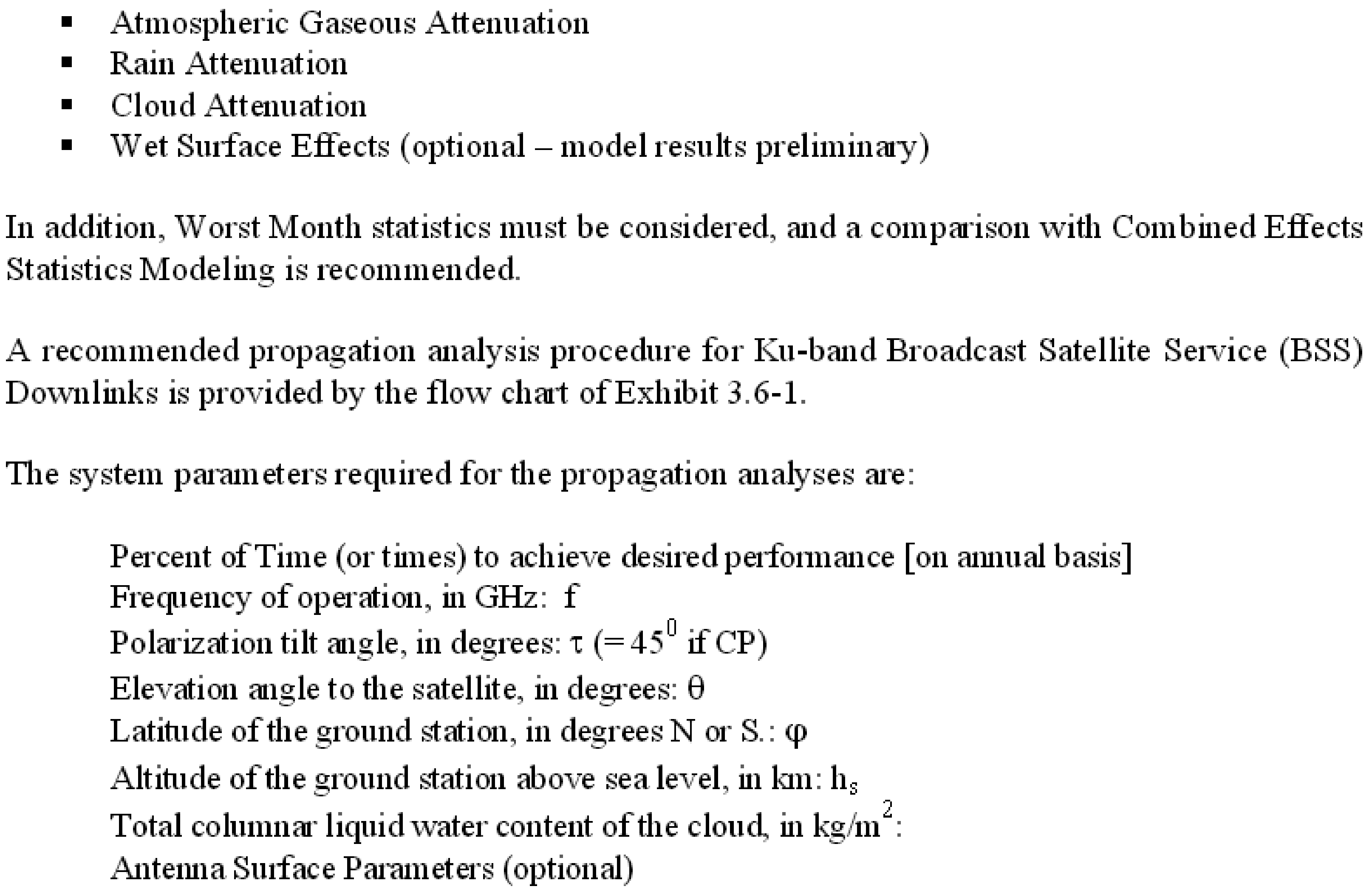
The majority of current direct to home broadcast satellite services (BSS) operate into the home with a Ku-band downlink. The allocated bands are 11.7-12.5 GHz in Region 1, 12.2 - 12.7 GHz in Region 2, and 11.7 -12.2 GHz for Region 3. The uplinks (feeder links) generally operate in the 17.3 - 18.1 GHz band. This section will present a propagation analysis procedure for the Ku-

band downlink. The uplink can be analyzed with the procedure described in Section 3.4.1, Ka-band FSS systems.

Direct to home systems generally operate with small aperture antennas, and are designed for unattended fixed pointed operation. BSS satellite EIRP for the downlink tends to be higher in power by 6 to 10 dB than for an FSS downlink. BSS system performance is often specified with reference to worst month link availability rather than an annual basis, and this must be taken into

account in the propagation analysis.

The critical propagation effects that must be included in the evaluation of a Ku-band broadcast satellite service downlink are



- Atmospheric Gaseous Attenuation
- Rain Attenuation
- Cloud Attenuation
- Wet Surface Effects (optional – model results preliminary)

In addition, Worst Month statistics must be considered, and a comparison with Combined Effects Statistics Modeling is recommended.

A recommended propagation analysis procedure for Ku-band Broadcast Satellite Service (BSS) Downlinks is provided by the flow chart of Exhibit 3.6-1.

The system parameters required for the propagation analyses are:

Percent of Time (or times) to achieve desired performance [on annual basis]
Frequency of operation, in GHz: f
Polarization tilt angle, in degrees: τ ($= 45^0$ if CP)
Elevation angle to the satellite, in degrees: θ
Latitude of the ground station, in degrees N or S.: φ
Altitude of the ground station above sea level, in km: h_s
Total columnar liquid water content of the cloud, in kg/m^2:
Antenna Surface Parameters (optional)

Rain Attenuation

This section focuses on NGSO links that are imp acted by rain attenuation, i.e. links operating above about 10 GHz. The consider ations described here would apply to Ku-band, Ka-band, and Q/V–band. Propagation considerations for NGS O links operating in the bands below 3 GHz involve other considerations, and are not discussed here.

The evaluation of propagation effects involving NGS O satellites is complicated by the fact that the slant path to the satellite is no longer fixed, but is a time variable parameter (Ippolito & Russell, 1993). The statistical prediction models for rain attenuation, rain and ice depolarization, tropospheric scintillation, etc. provided in Section 2 all are based on a fixed elevation angle to the satellite. This will, of course, not be the case for NGSO satellite links. LEO satellites, for example, typically have orbital periods of 1.5 to 2 hours, and the satellite will ‘pass over’ an area on the Earth’s surface several times per day. The elevation angle statistics must therefore be integrated into the propagation prediction procedure to assure the proper evaluation of propagation margins is achieved.

Consider a low earth orbit (LEO) satellite in a circular polar orbit at an altitude of 765 km , with and ascending node at 1000W .This is a typical orbit for a MSS Big LEO satellite. Let us assume the satellite has a feeder link operating in the Ka-band, with a feeder link term inal located at 106.6 0W and 32.5 0N latitude (White Sands, NM). Assum ethat the 20 GHz downlink has a fixed power margin of 74 dB available for free space path loss and propagation losses.

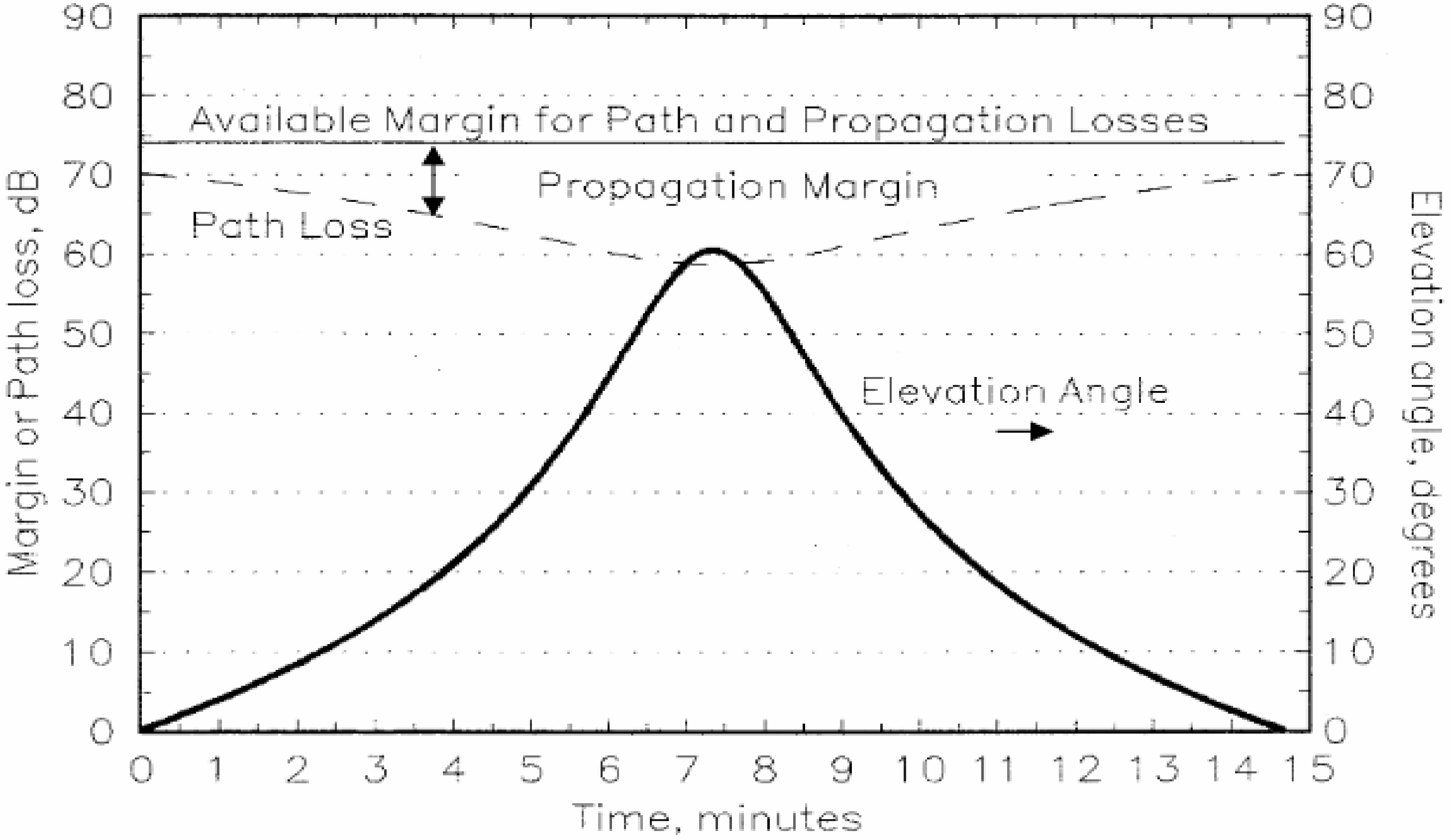


Exhibit 3.7-1
Elevation Angle and Path Losses for a Single Pass of a LEO Satellite
Frequency = 20 GHz, Altitude = 765 km

The next step in the evaluation process is to determine a reasonable estimation of the link availability from the time variable available propagation margin, which we found ranges from 4 to 15 dB. Let us assume that there are two propagation effects of concern for this location; gaseous attenuation and rain attenuation. If we assume a homogeneous atmosphere with a 7.5-g/m^3 water vapor density, the gaseous attenuation will vary only with path length.

Exhibit 3.7-2 shows the available propagation margin (solid line) for the example link as a function of time. The dotted line shows the gaseous attenuation determined from the ITU-R Gaseous Attenuation Model [Section 2.2.1.2.2]. The propagation margin minus the gaseous attenuation, which is the margin left for rain attenuation, is plotted as the dashed line labeled Rain Margin.

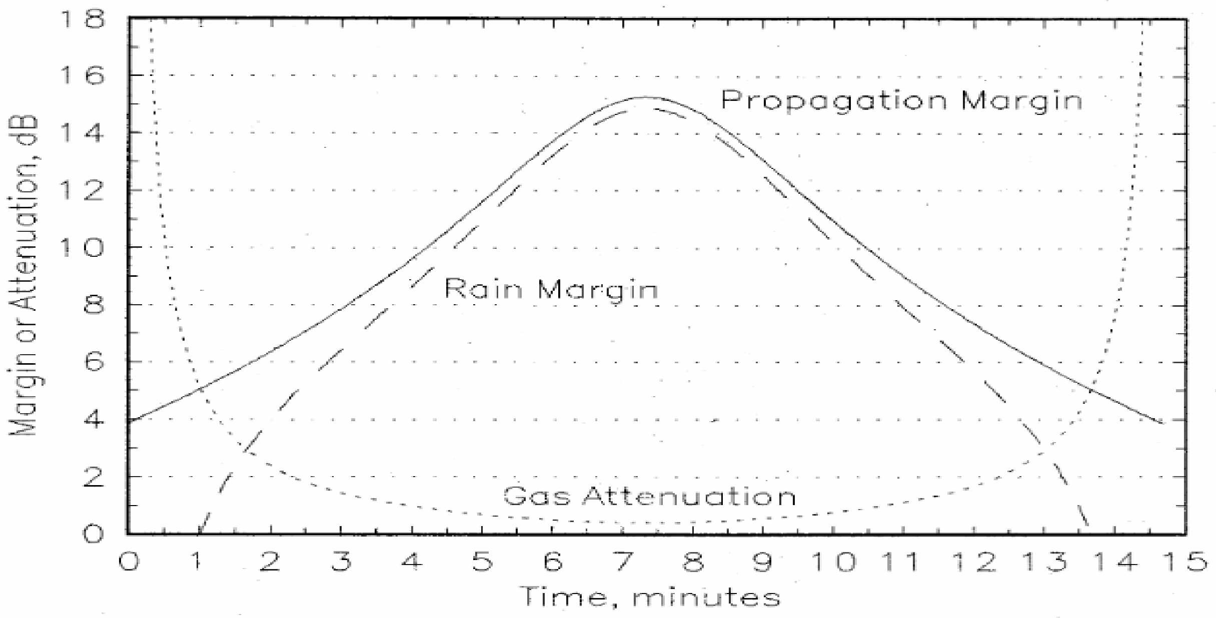


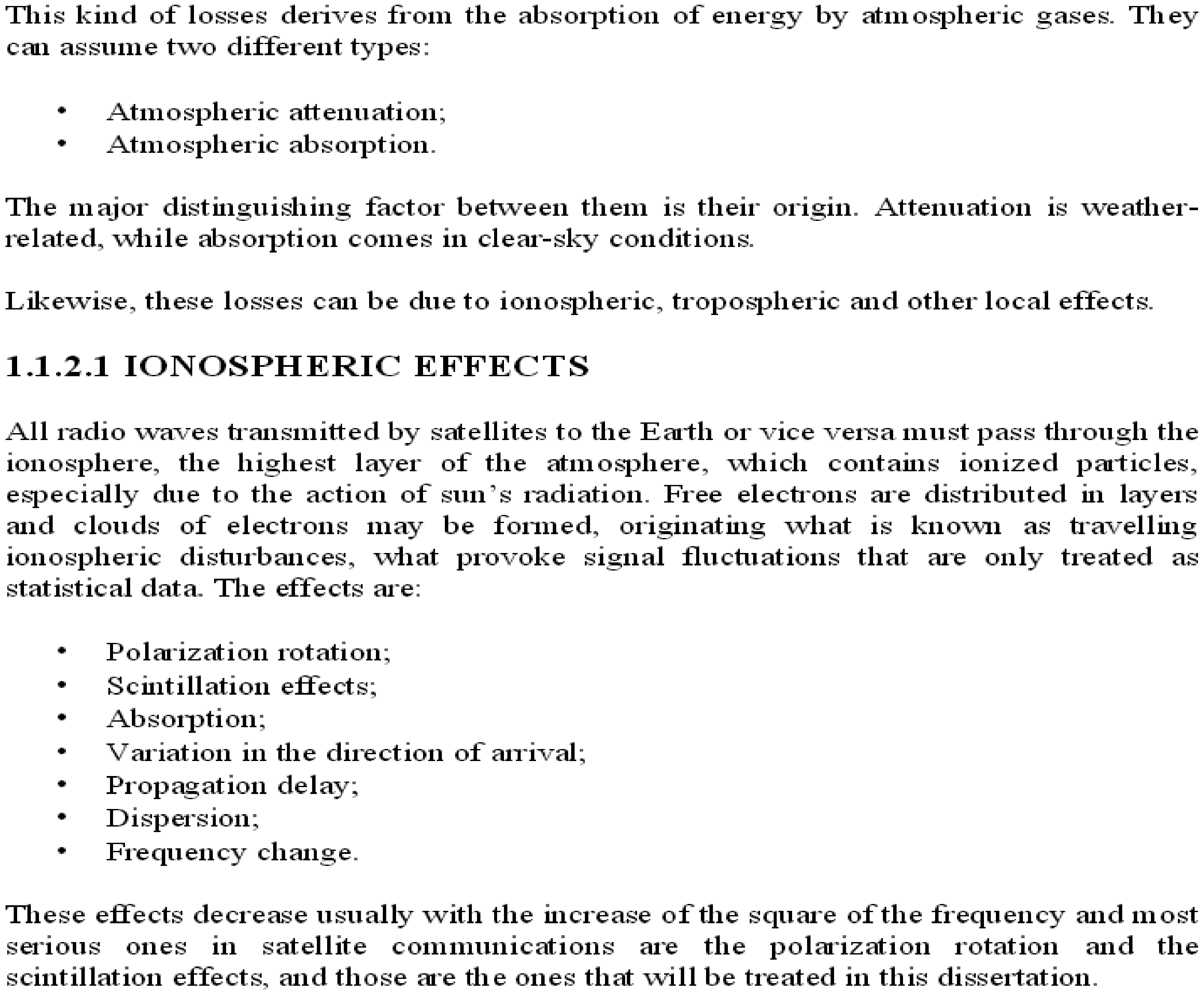
Exhibit 3.7-2
Total Propagation Margin and Allocation of Margin to Gaseous Attenuation and Rain Attenuation, for Single Pass of a LEO Satellite
Frequency = 20 GHz

DEPOLARIZATION

Rain depolarization is calculated via same techniques applied to rain attenuation. The difference lies in examining depolarization, we assume the rain drops to be oblate spheroids. The raindrop is generally at a random orientation with respect to the wave propagation direction. The orientation specified is denoted by q angle, between vector of propagation and the axis of symmetry of rain drops. The component which is vertical is parallel to the minor axis of the rain drop and therefore has less water content and it's the case of quite opposite for the horizontal component. As a result, there will be a difference between the attenuation and phase shift of each electric field component. This is known as differential attenuation and differentia phase shift and they leads to depolarization of the signal. For a Geostationary earth orbiting satellite transmitting a linear polarized wave, horizontal polarization is the case where electric field is parallel to Earth's equatorial plane and vertical polarization is where its Eart

h's electric field is parallel to the Earth's polar axis. The main purpose of polarization is to bring down the interference between different signals belongs to different frequencies and introduce frequency reuse but when the signal passes through atmosphere, sometimes an additional orthogonal signal might get generated which leads to the effect of depolarization and interference. The cross-polarization discrimination (ratio of received co- polar and generated cross-polar component) in dB due to rain is given by

ATMOSPHERIC LOSSES



This kind of losses derives from the absorption of energy by atmospheric gases. They can assume two different types:

- Atmospheric attenuation;
- Atmospheric absorption.

The major distinguishing factor between them is their origin. Attenuation is weather-related, while absorption comes in clear-sky conditions.

Likewise, these losses can be due to ionospheric, tropospheric and other local effects.

1.1.2.1 IONOSPHERIC EFFECTS

All radio waves transmitted by satellites to the Earth or vice versa must pass through the ionosphere, the highest layer of the atmosphere, which contains ionized particles, especially due to the action of sun's radiation. Free electrons are distributed in layers and clouds of electrons may be formed, originating what is known as travelling ionospheric disturbances, what provoke signal fluctuations that are only treated as statistical data. The effects are:

- Polarization rotation;
- Scintillation effects;
- Absorption;
- Variation in the direction of arrival;
- Propagation delay;
- Dispersion;
- Frequency change.

These effects decrease usually with the increase of the square of the frequency and most serious ones in satellite communications are the polarization rotation and the scintillation effects, and those are the ones that will be treated in this dissertation.

Clouds and Fog

Clouds and fog can be categorized as ***hydrosols*** – suspended droplets of liquid water – which are typically less than 0.01 cm in diameter. The attenuation caused by hydrosols becomes significant particularly for systems operating above 20 GHz. The attenuation increases with increasing frequency and decreasing elevation angle. Portions of clouds and fogs that are frozen do not cause significant attenuation though they may be responsible for signal depolarization.

For high margin systems, rain attenuation is the dominant impairment. However, for low margin systems and higher frequencies, clouds represent an important impairment. Rain occurs less than about 5–8 % of the time, whereas clouds are present 50 % of the time on average and can have constant coverage for continuous intervals up to several weeks [9].

Modeling cloud attenuation requires knowledge of cloud characteristics along the slant path. Liquid water droplets are the main source of attenuation. Ice particles are also present as plates and needles in cirrus clouds or as larger particles above the melting layer in rain clouds. However, ice is not a significant source of attenuation and is usually neglected. The main interest is in non-precipitating clouds with spherical water droplets less than 100 μm diameter. This upper bound is a requirement for the droplet to be suspended in clouds without strong internal updrafts.

The models described in this section are based on the ***Rayleigh approximation***, which holds for frequencies up to about 300 GHz for particles under the 100 μm size limit. Cloud liquid water drops in the Rayleigh regime attenuate the radiowave mainly through absorption; scattering effects are negligible in comparison. As a result, the attenuation properties of a cloud can be related to the ***cloud liquid water*** (CLW) content rather than the individual drop sizes. The accurate measurement of CLW is an important requirement in determining cloud attenuation. The cloud temperature is also needed to compute the dielectric constant of water.

Two models that provide estimates of cloud and fog attenuation on a satellite path – the ITU-R Cloud Attenuation Model and the Slobin Cloud Model – are described in the following two sections.

Cloud Attenuation Model

The ITU-R provides a model to calculate the attenuation along an earth-space path for both clouds and fog in Recommendation ITU-R P.840 [10]. The model was originally adopted into Recommendation P.840 in 1992 and has been updated in 1994, 1997, and 1999. It is valid for liquid water only and is applicable for systems operating at up to 200 GHz.

The input parameters required for the calculations are

f: frequency (GHz)
θ: elevation angle (degrees)
T: surface temperature (K) (see discussion below)
L: total columnar liquid water content (kg/m^2)

An intermediate parameter required for the calculation is the inverse temperature constant, Φ, determined from

$$\Phi = \frac{300}{T} \tag{7.40}$$

where T is the temperature in K.

For cloud attenuation, assume T = 273.15 K, therefore

$$\Phi = 1.098 \tag{7.41}$$

For fog attenuation, T is equal to the ground temperature, and Equation (7.40) is used.

The step-by-step procedure now follows.

Step 1: Calculate the relaxation frequencies

Calculate the principal and secondary relaxation frequencies, f_p and f_s, of the double-Debye model for the dielectric permittivity of water:

$$\begin{aligned} f_p &= 20.09 - 142(\Phi - 1) + 294(\Phi - 1^2)\ \text{GHz} \\ f_s &= 590 - 1500(\Phi - 1) \end{aligned} \tag{7.42}$$

Step 2: Complex dielectric permittivity

Calculate the real and imaginary components of the complex dielectric permittivity of water from

$$\begin{aligned} \varepsilon''(f) &= \frac{f \cdot (\varepsilon_0 - \varepsilon_1)}{f_p \cdot \left[1 + \left(\frac{f}{f_p}\right)^2\right]} + \frac{f \cdot (\varepsilon_1 - \varepsilon_2)}{f_s \cdot \left[1 + \left(\frac{f}{f_s}\right)^2\right]} \\ \varepsilon'(f) &= \frac{(\varepsilon_0 - \varepsilon_1)}{\left[1 + \left(\frac{f}{f_p}\right)^2\right]} + \frac{(\varepsilon_1 - \varepsilon_2)}{\left[1 + \left(\frac{f}{f_s}\right)^2\right]} + \varepsilon_2 \end{aligned} \tag{7.43}$$

where $\varepsilon_0 = 77.6 + 103.3 \cdot (\Phi - 1)$; $\varepsilon_1 = 5.48$; and $\varepsilon_2 = 3.51$.

RAIN AND ICE EFFECTS

At frequencies above 10 GHz, rain is the dominant factor in satellite propagation. The long-term behavior of rain rate is described by what is properly called a *cumulative probability distribution* and popularly known as *exceedance curve*. This gives the percentage time that rain rate exceeds a given value. Mathematical models are available that give the exceedance curve for a given location based on the total rain accumulation and other meteorological data. CCIR publishes maps showing contours of rain exceeded for selected percentages of time.

Rain attenuation and depolarization occur because individual raindrops absorb energy from radio waves and because some energy in the waves is scattered out of the propagation path. These interactions depend on the number of raindrops encountered and on their distribution of sizes and shapes.

If rain rate R is constant over a path length L km, the attenuation A caused by the rain is given by

$$A = aR^{b}L \text{ dB} \tag{3.12}$$

The quantity aR^{b} is called the *specific attenuation*. The coefficients a and b depend strongly on frequency and weakly on polarization, raindrop temperature, and other factors. In practice, the following approximations are valid

$$a = \begin{cases} 4.21 \times 10^{-5} f^{2.42}, \ 2.9 \le f \le 54\,\text{GHz} \\ 4.09 \times 10^{-2} f^{0.699}, \ 54 \le f \le 180\,\text{GHz} \end{cases} \tag{3.13}$$

$$b = \begin{cases} 1.41 f^{-0.0799}, \ 8.5 \le f \le 25\ \text{GHz} \\ 2.63 f^{-0.272}, \ 25 \le f \le 164\,\text{GHz} \end{cases} \tag{3.14}$$

where f is in GHz.

If the rain rate were constant along the path of known length, then calculating the attenuation for a given ground rainfall rate would be straightforward. Even though this is true with terrestrial radio links, the rain rate changes with position and time and length L of the portion of path that contains rain is also variable in case of satellite links. If this length is $L(t)$, and $R(y, t)$ is the rain rate in mm per hour at time t at a distance y km measured from the ground along the path, then the attenuation $A(t)$ is given by

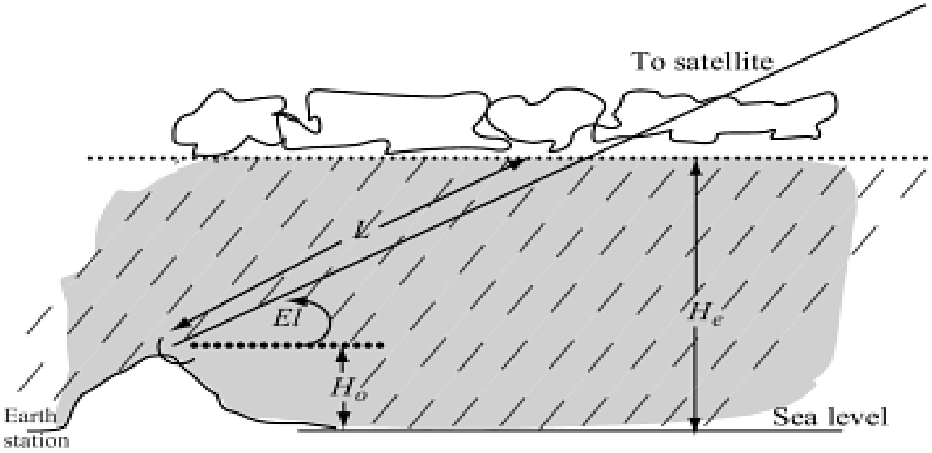
$$A(t) = \int_{o}^{L(t)} a\ [\ R(y,t)\ ]^{b}\ dy \text{ dB} \tag{3.15}$$

Since attenuation is caused by rain, both A and R exhibit the same kind of statistical behavior and both are described by exceedance plots. All the rain that passes through the propagation path should ultimately reach the ground. Hence, the exceedance curve of the path average rain rate average should be the same as the exceedance curve of ground point rain rate. Therefore, the attenuation value $A(P)$ equaled or exceeded P percent of time. The proportionality factor between $A(P)$ and $a[R(P)]^b$ has units of km and is called the *effective path length,* L_{eff}. Thus

$$A(P) \; = \; a\,[R(P)]^{\,b}\, L_{eff}\ \text{dB} \tag{3.16}$$

From the Fig. 3.5, for an elevation angle El, the path length L in rain is given by

$$L \; = \; \frac{H_e - H_o}{\sin(El)}\ \text{km} \tag{3.17}$$



In addition to absorption and depolarization that it causes, rain also degrades the performance of satellite communications system by increasing the earth station antenna noise temperature. In clear weather, the antenna sees the cold background of space, but in rain, it receives thermal radiation from the raindrops.

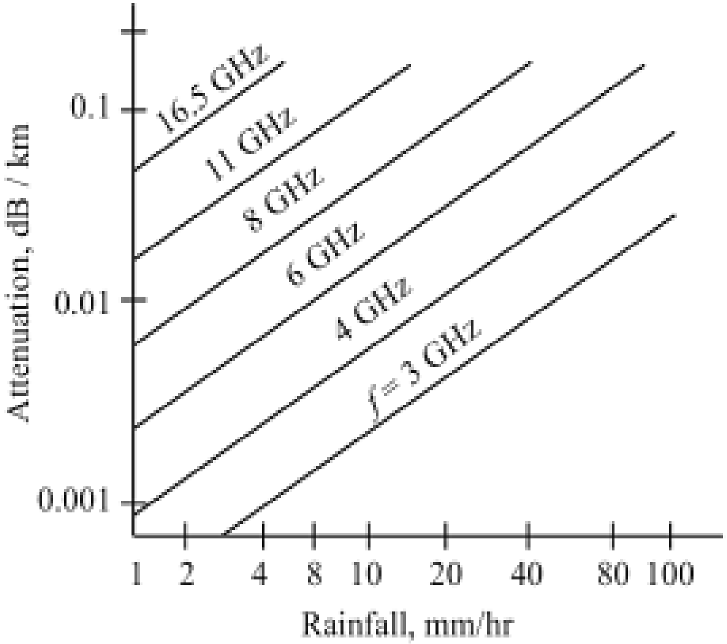
The increase in antenna noise temperature due to rain, T_b, may be estimated by

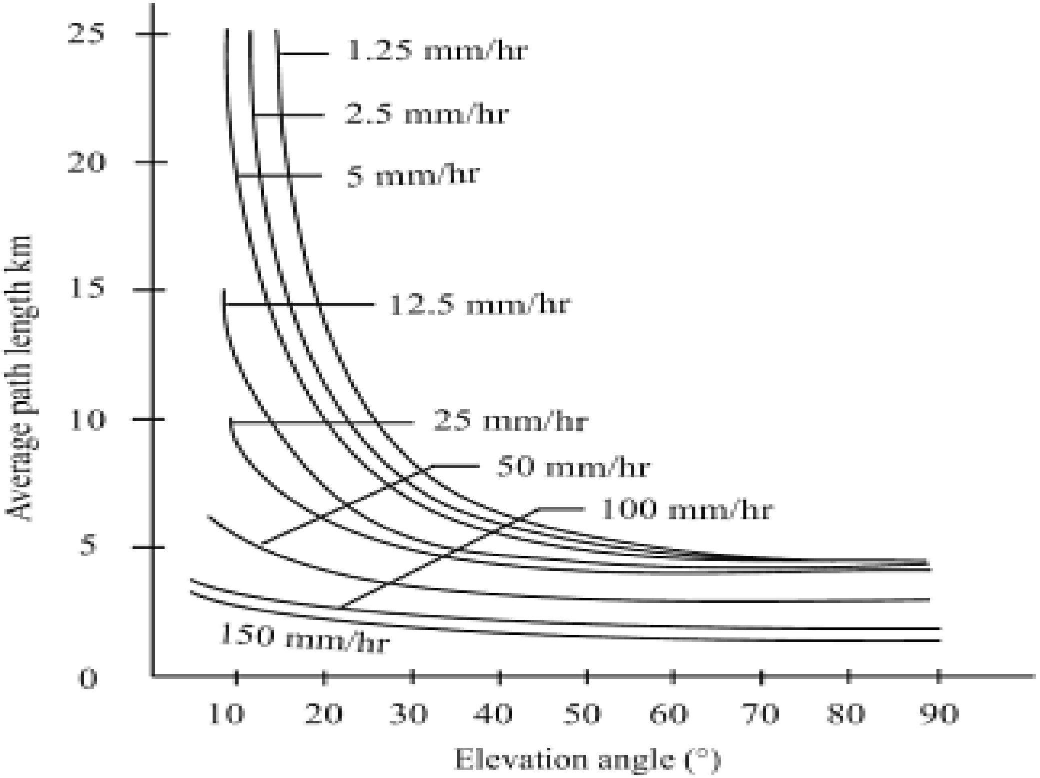
$$T_b = 280\,(1 - e^{-A/4.34})\text{ K} \tag{3.18}$$

where A is the rain attenuation in dB. This should be added to the clear weather antenna noise temperature when calculating (C/N) in rain. The number 280 in the above equation is called *effective temperature* of rain; it differs from true temperature because of scattering and antenna effects.

In some conditions, increase in temperature may be more dominant than attenuation caused due to rain.

If a satellite link is to be maintained during rainfall, it is necessary that enough extra power called *power margin* be transmitted to overcome the maximum additional attenuation induced by the rain. Figure 3.6 gives the rain attenuation as function of rainfall for different frequencies. These curves presented are generated based on the empirical data and mathematical models. The mean path length of the rain is determined for the given elevation angle. This length also depends on rainfall rate as shown in Fig. 3.7. With the mean path distance estimated, expected rainfall attenuation is obtained by multiplying the rain by the mean path length. It is observed





7 Rainfall attenuation: with elevation angle.