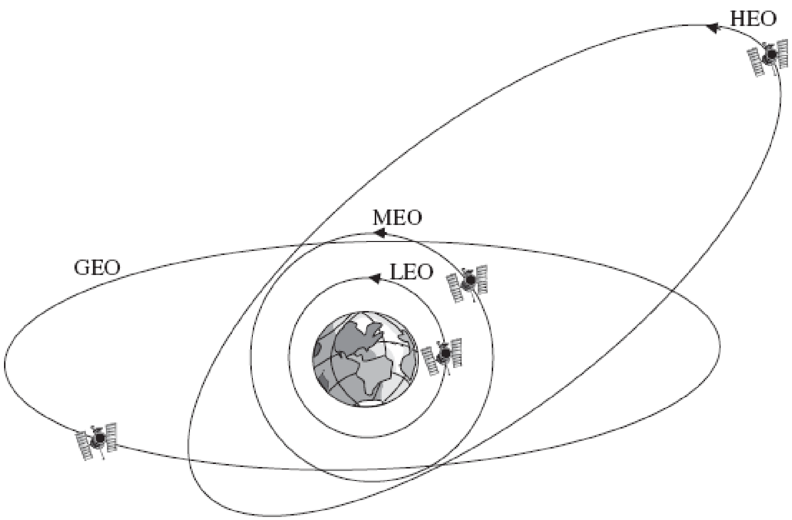
Návrh družicového spoje

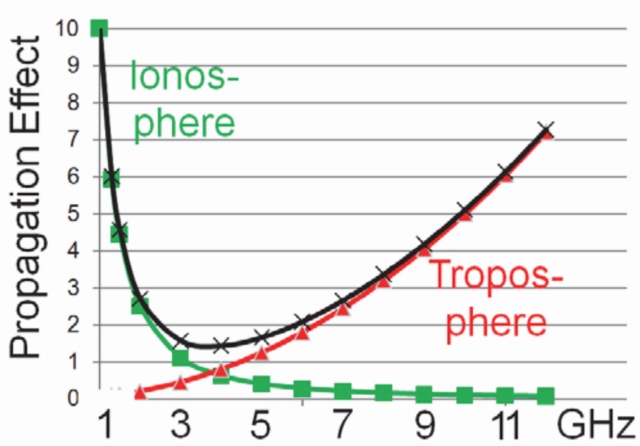
LETTER DESIGNATION FOR SATELLITE FREQUENCY BAND	FREQUENCY RANGE (GHZ)
L	1 -2
S	2 - 4
C	4 - 8
X	8 - 12 (8 - 12.5 in North America)
Ku	12 - 18 (12.5 - 18 in North America)
K	18 - 27 (18 - 25.5 in North America)
Ka	27 - 40 (26.5 - 40 in North America)
O	40 - 50
V	50 - 75



Číslo pásma	Mezinárodní zkratka	Frekvence	Vlnová délka	Český ekvivalent	Metrické označení
3	ULF	300 Hz – 3 kHz	1000 km-100 km	EDV, extrémně dlouhé v.	hkm, hektokilometrické,
4	VLF	3 kHz – 30 kHz	100 km-10 km	VDV, velmi dlouhé vlny	Mam, myriametrové v.
5	LF	30 kHz – 300 kHz	10 km-1 km	DV, dlouhé vlny	km, kilometrové vlny
6	MF	300 kHz – 3 MHz	1 km-100 m	SV, střední vlny	Hm, hektometrové v.
7	HF	3 MHz – 30 MHz	100 m-10 m	KV, krátké vlny	Dm, dekametrové v.
8	VHF	30 MHz – 300 MHz	10 m-1 m	VKV, velmi krátké vlny	m, metrové vlny
9	UHF	300 MHz – 3 GHz	1 m-10 cm	UKV, ultra krátké vlny	dm, decimetrové vlny
10	SHF	3 GHz – 30 GHz	10 cm-1 cm	SKV, super krátké vlny	cm, centimetrové vlny
11	EHF	30 GHz- 300 GHz	1 cm-1 mm	EKV, extrémně krátké vlny	mm, milimetrové vlny

Vlivy šíření na družicové služby

- Okolí pozemního terminálu (environment)
  - Zastínění (shadowing, blockage)
  - Vícecestné šíření (multipath)
- Troposféra
  - Útlum atmosférickými plyny (gas attenuation)
  - Útlum srážkami (rain attenuation)
  - Útlum oblaky (cloud attenuation)
  - Scintilace (scintillation)
  - Depolarizace (XPD reduction)
  - Zpoždění (delay)
- Ionosféra
  - Scintilace (scintillation)
  - Zpoždění (delay)
  - Faradayova rotace (Faraday rotation)



Převzato od Bertram Arbesser-Rastburg

Pevný družicový spoj – základní aspekty šíření vln

- Jasná obloha
  - Útlum atmosférickými plyny (γ se mění s výškou, f > 20 GHz)
  - Troposférická refrakce - zanedbatelný vliv pro elevace > 10° a f < 10 GHz
    - Pomalé úniky vlivem změn N ve velkém měřítku
    - Rychlé úniky (scintilace) vlivem změn N ve malém měřítku
    - Vícecestné šíření - zanedbatelné pro elevace > 5°
    - Vychylování paprsku – řádově max 0.1 °
    - Snížení zisku na velkých parabolách vlivem kolísání fáze
    - Divergence anténního svazku (ve vertikálním směru je lom paprsku na spodním/horním okraji svazku odlišný) - zanedbatelné pro elevace > 5°
  - Vliv okolí pozemního terminálu (přídavné ztráty, šum)
- Zatažená obloha
  - Oblaka - ztráty, depolarizace (ledové krystaly), f > 10 GHz
  - Srážky - ztráty, rozptyl, depolarizace, f > 5 GHz
- Ionosféra (výrazný vliv pod 4 GHz, zanedbatelný nad 10 GHz)

Výkonová bilance – kvalita spojení

- Poměr výkon nosné a spektrální šumové hustoty
  Carrier-to-Noise Spectral Density Ratio

$$\frac{C}{N_0}$$

  - C (W) - výkon nosné = přijatý výkon P_R
  - N_0 (W/Hz)- spektrální šumová hustota
  - $N = kTB$ (W) - výkon šumu
  - B (Hz) - šumová šířka pásma
  - $k = 1{,}38 \cdot 10^{-23}$ J/K - Boltzmannova konstanta
  - T (K) – teplota

$$N_0 = \frac{N}{B} = kT$$

- Energie na jeden bit / spektrální šumová hustota
  - f_b (1/s) = bitová rychlost

$$\frac{E_b}{N_0} = \frac{E_b}{N_0}\frac{f_b}{f_b} = \frac{C}{N_0 f_b}$$

$$\frac{C}{N_0} = \frac{E_b f_b}{N_0} = \frac{E_b f_b}{\boldsymbol{T_s}}$$

Rádiový šum, šumová teplota

- vyzařování černého tělesa

$$N = kTB$$

- ekvivalentní šumové teploty (*equivalent noise temperature*)

$$T_{ekv} = \frac{N}{kB}$$

- jasová teplota (*brightness temperature*) objektu

$$N = kT_j B = \varepsilon kTB \qquad T_j = \varepsilon T$$

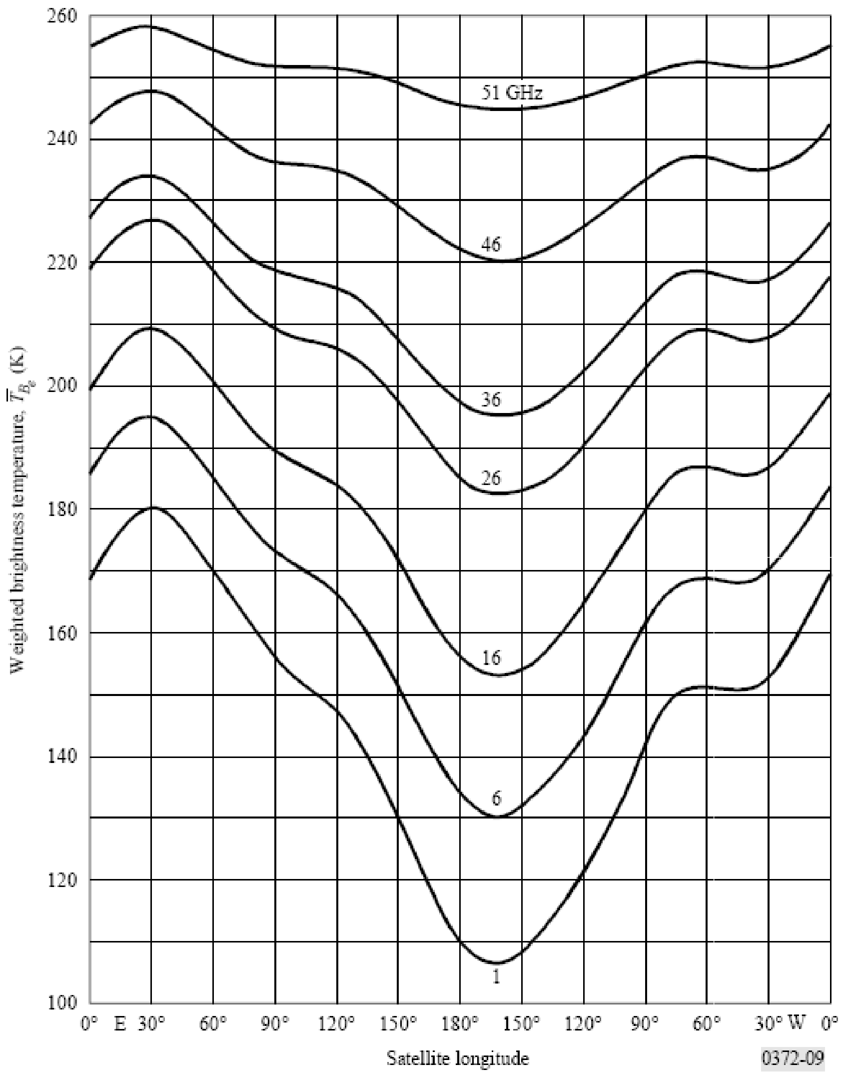
- šumová teploty antény

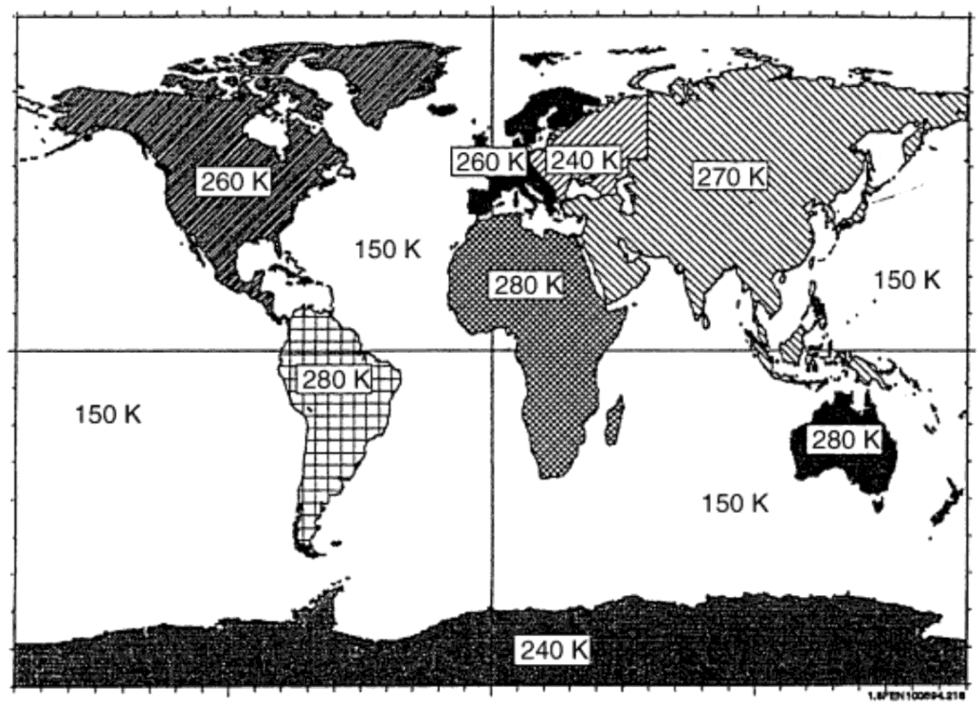
$$T_\mathrm{A} = \frac{\int_0^{2\pi}\int_0^{\pi} T_\mathrm{j}(\vartheta,\varphi) G(\vartheta,\varphi) \sin\vartheta \,\mathrm{d}\vartheta \,\mathrm{d}\varphi}{\int_0^{2\pi}\int_0^{\pi} G(\vartheta,\varphi) \sin\vartheta \,\mathrm{d}\vartheta \,\mathrm{d}\varphi}$$

Šumová teploty antény – na družici (uplink)

FIGURE 9

Weighted brightness temperature of the Earth as a function of longitude viewed from geostationary orbit at frequencies between 1 and 51 GHz





Převzato: ESA/EUTELSAT model of the Earth’s brightness temperature at Ku band (12 – 18 GHz) podle Maral, Bousquet

Šumová teploty antény – na Zemi (downlink)

- jasová teplota (*brightness temperature*) objektu

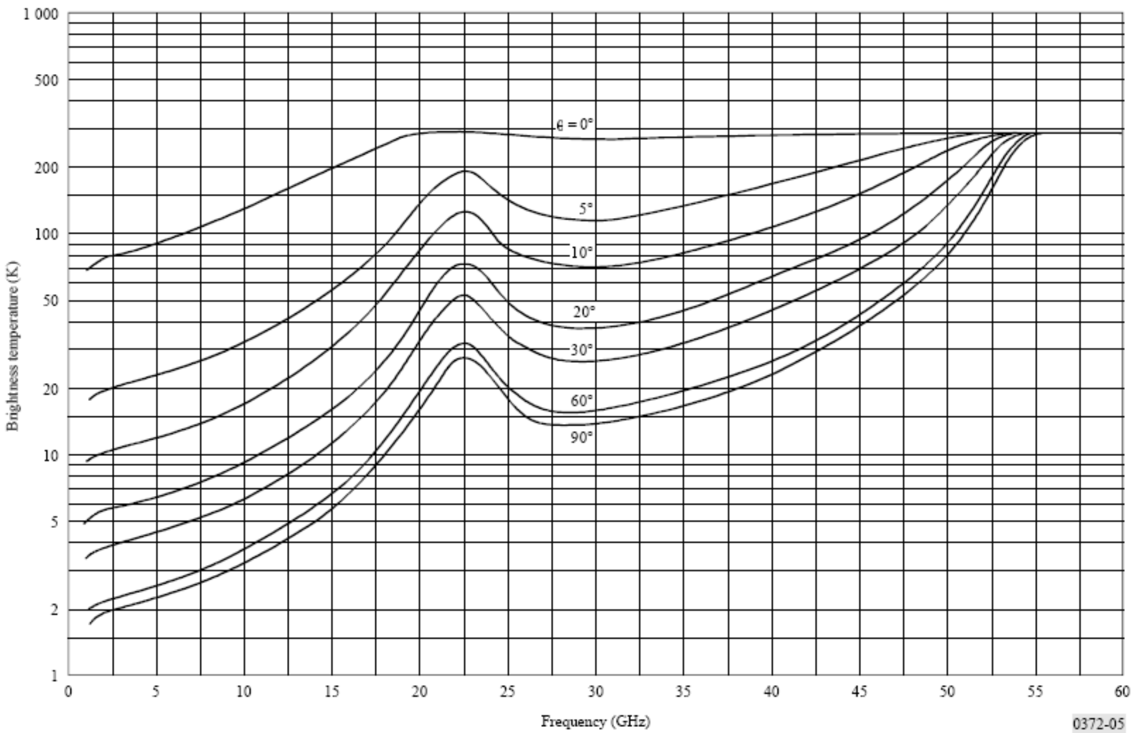
$$N = kT_j B = \varepsilon kTB \qquad T_j = \varepsilon T$$

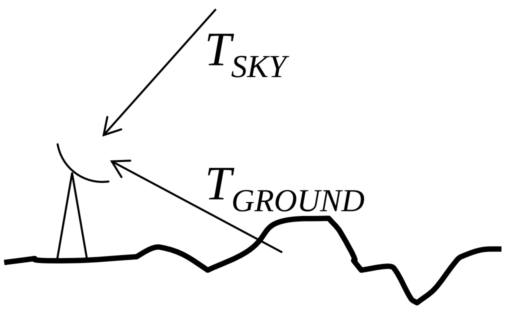
- šumová teploty antény

$$T_\mathrm{A} = \frac{\int_0^{2\pi}\int_0^{\pi} T_\mathrm{j}(\vartheta,\varphi)\, G(\vartheta,\varphi)\sin\vartheta\,\mathrm{d}\vartheta\,\mathrm{d}\varphi}{\int_0^{2\pi}\int_0^{\pi} G(\vartheta,\varphi)\sin\vartheta\,\mathrm{d}\vartheta\,\mathrm{d}\varphi}$$

FIGURE 5

Brightness temperature for clear air for 7.5 g/m³ of water vapour concentration (expansion of abscissa scale of Fig. 4); θ is the elevation angle





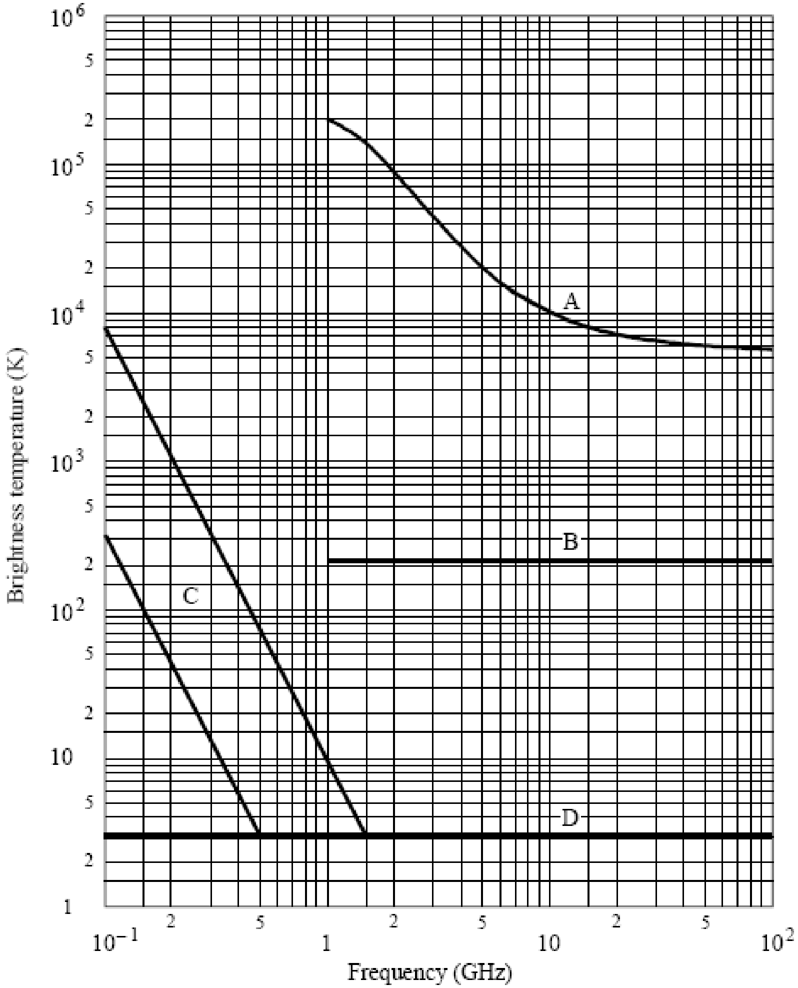
$$T_A = T_{SKY} + T_{GROUND}$$

$$T_{GROUND} \approx 10 \div 290\,\mathrm{K}$$

(dle elevace a smer.char.)

Šumová teploty antény

FIGURE 12
Extra-terrestrial noise sources



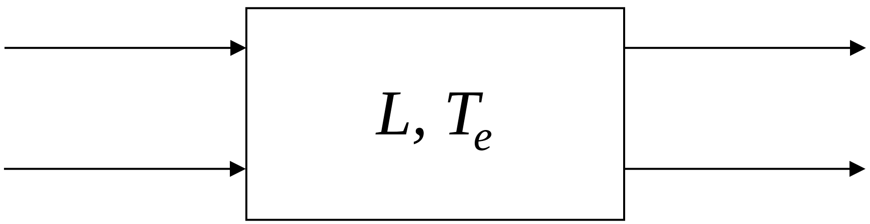
A: quiet Sun } diameter ~ 0.5°
B: Moon } diameter ~ 0.5°
C: range of galactic noise
D: cosmic background

0372-12

$$T_{\mathrm{A}} = \frac{\int_0^{2\pi}\int_0^{\pi} T_{\mathrm{j}}(\vartheta,\varphi)\,G(\vartheta,\varphi)\sin\vartheta\,\mathrm{d}\vartheta\,\mathrm{d}\varphi}{\int_0^{2\pi}\int_0^{\pi} G(\vartheta,\varphi)\sin\vartheta\,\mathrm{d}\vartheta\,\mathrm{d}\varphi}$$

Pasivní atenuátor s útlumem *L* (*L* = 1 / *G*)

$$kT_0B = \frac{k\left(T_0 + T_e\right)B}{L} \qquad T_e = T_0\left(L-1\right)$$



$$T_{in} \qquad T_{out} = \frac{T_{in} + T_e}{L}$$

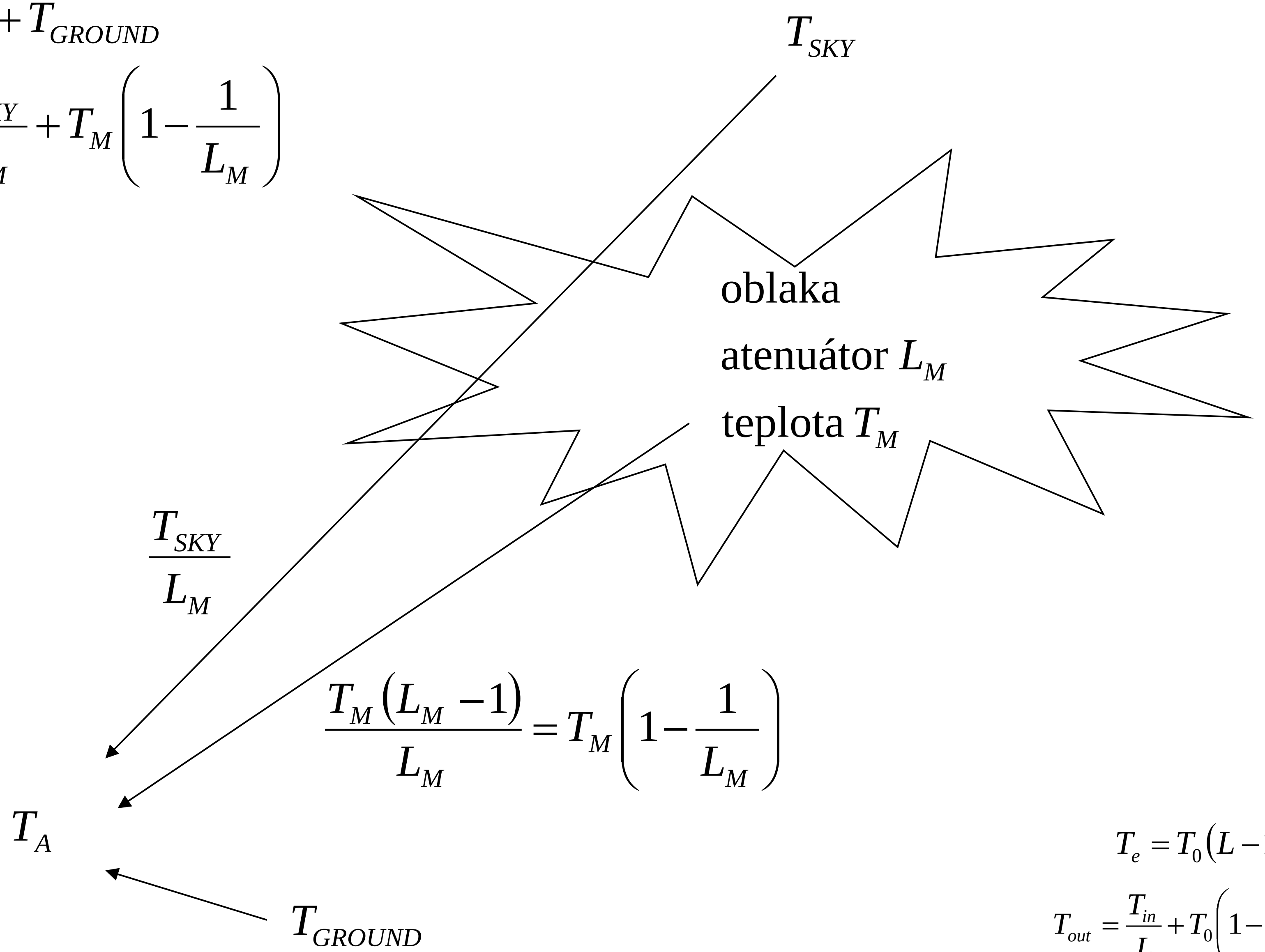
$$T_{out} = \frac{T_{in} + T_e}{L} = \frac{T_{in}}{L} + \frac{T_0\left(L-1\right)}{L} = \frac{T_{in}}{L} + T_0\left(1 - \frac{1}{L}\right)$$

$$T_0 = 290\ \mathrm{K}\ \text{(obvyklá volba)}$$

Šumová teploty antény – zatažená obloha

$$T_A = T'_{SKY} + T_{GROUND}$$

$$T'_{SKY} = \frac{T_{SKY}}{L_M} + T_M\left(1 - \frac{1}{L_M}\right)$$



$$\frac{T_M(L_M - 1)}{L_M} = T_M\left(1 - \frac{1}{L_M}\right)$$

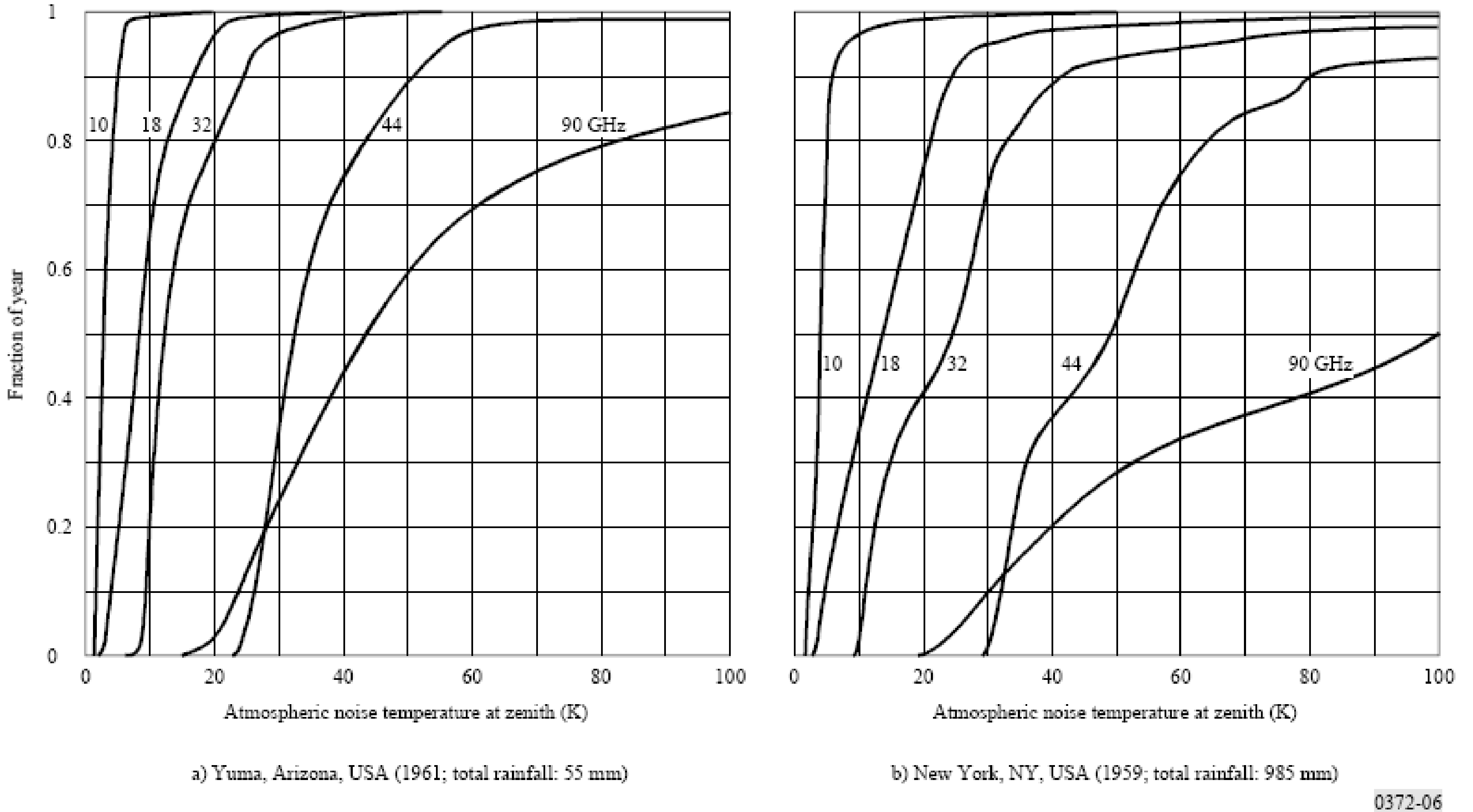
$$T_e = T_0(L - 1)$$

$$T_{out} = \frac{T_{in}}{L} + T_0\left(1 - \frac{1}{L}\right)$$

Šumová teploty antény – T'_{SKY}

FIGURE 6

Fraction of the time the zenith sky noise (brightness) temperature is equal to or less than the abscissa value for a typical year



Šumová teploty antény –příklad

$$T_A = T'_{SKY} + T_{GROUND}$$

$$T'_{SKY} = \frac{T_{SKY}}{L_M} + T_M\left(1 - \frac{1}{L_M}\right)$$

$$T_{SKY} = 5\,\mathrm{K}$$

---

bezúnikový stav

$$L_M = 0\,\mathrm{dB}$$

$$T'_{SKY} = T_{SKY}$$

---

ztráty 10 (10 dB)

$$T_M = 260 \div 280\,\mathrm{K}$$

(dest 260 K, oblaka 280 K)

$$T'_{SKY} = \frac{5}{10} + 260\left(1 - \frac{1}{10}\right) = 252{,}5\,\mathrm{K}$$

---

ztráty 2 (3 dB)

$$T'_{SKY} = \frac{5}{2} + 273\left(1 - \frac{1}{2}\right) = 139\,\mathrm{K}$$

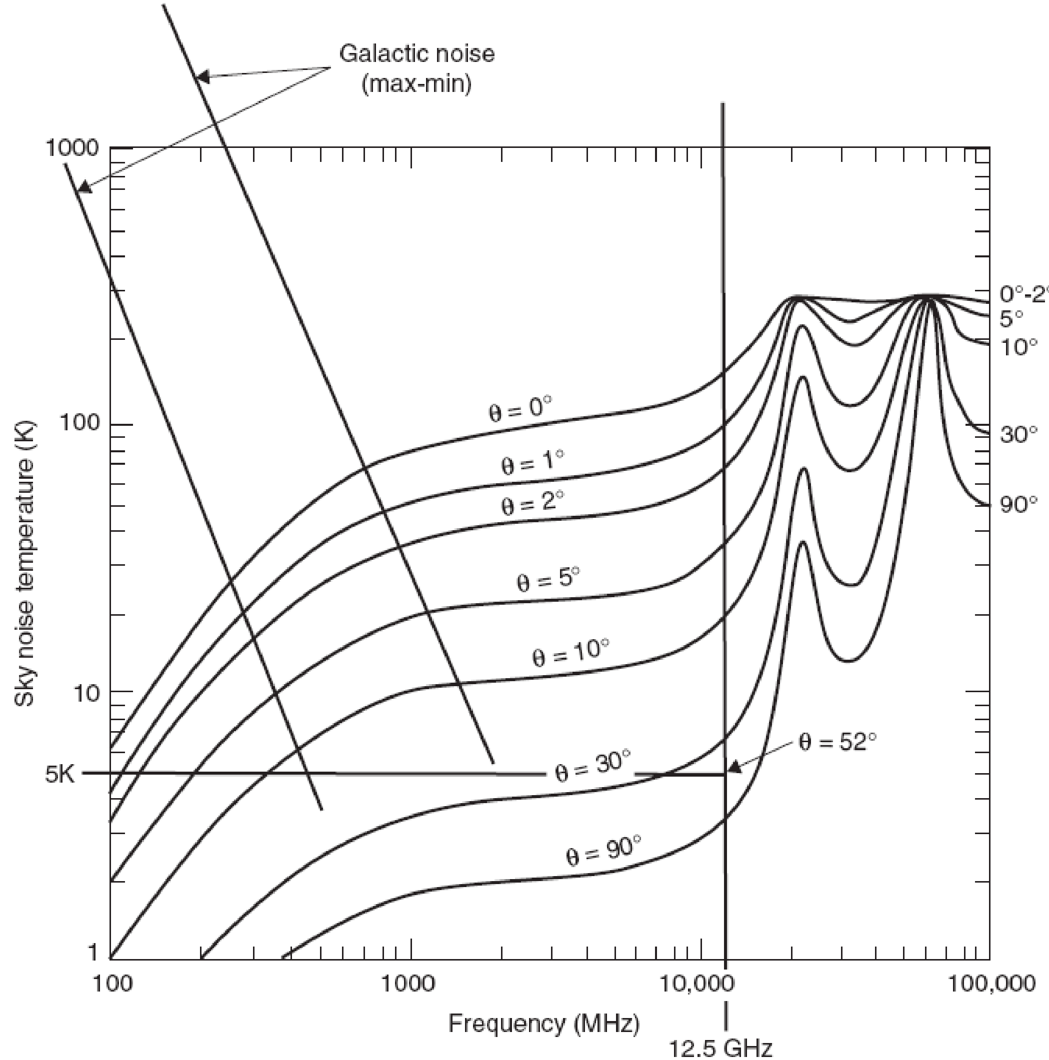
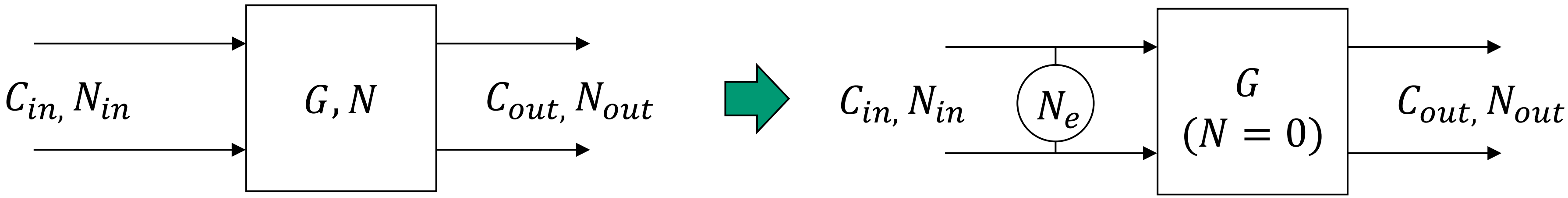


Figure 11.8 Sky noise temperature versus frequency for different elevation angles. (Figure 71.3 from Ref. 18, courtesy of CRC Press.)

Seybold J.S., Introduction to RF Propagation, Wiley, 2005

Šumový činitel / *noise factor*



$$CNR_{in} = \frac{C_{in}}{kT_{in}B} \qquad CNR_{out} = \frac{C_{in}G}{k(T_{in} + T_e)BG} \qquad N_e = \frac{N}{G} = kT_eB$$

$$F = \frac{CNR_{in}}{CNR_{out}} = \frac{C_{in}}{N_{in}} \frac{(N_{in} + N_e)G}{C_{in}G} = \frac{N_{in} + N_e}{N_{in}} = 1 + \frac{N_e}{N_{in}} = 1 + \frac{kT_eB}{kT_{in}B} = 1 + \frac{T_e}{T_{in}}$$

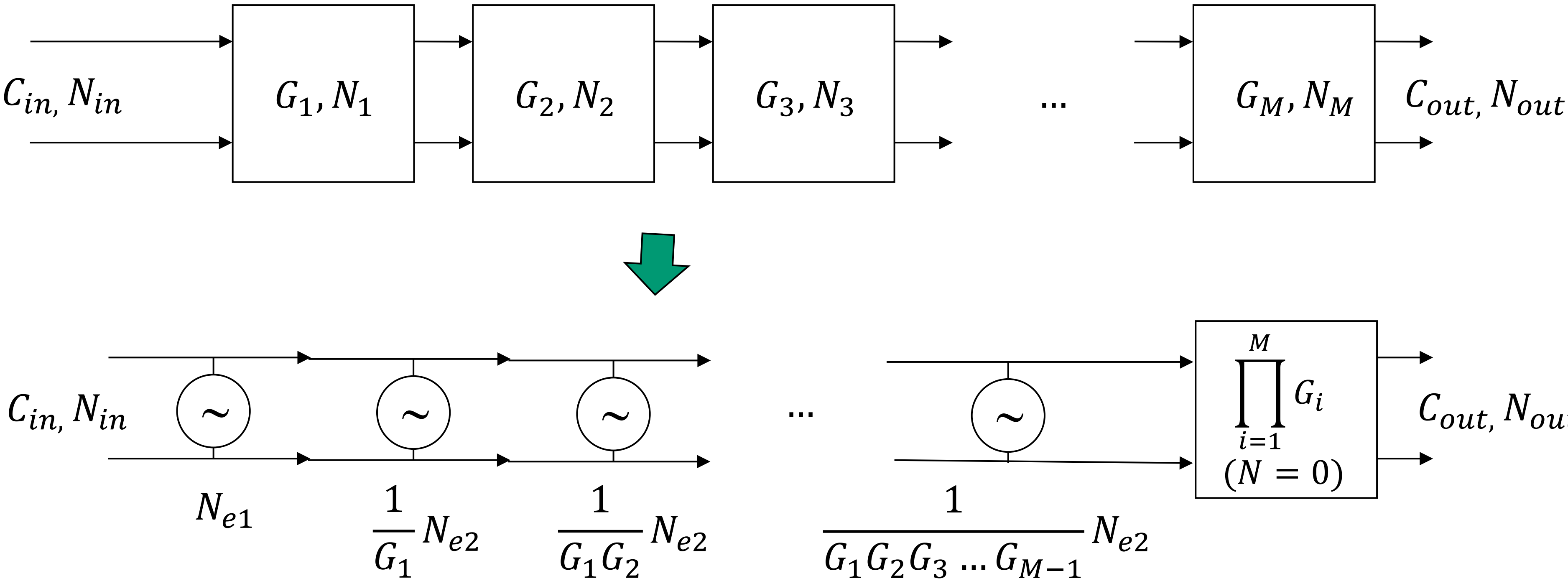
Jako reference pokojová teplota $T_{in} = T_0 = 290$ K $\qquad T_e = T_0(F - 1)$

šumové číslo / *noise figure*: $NF = 10 \log F$ (dB)

Pro atenuátor $L = 1/G$:

$$T_e = T_0(L - 1) \qquad F = 1 + \frac{T_e}{T_0} = 1 + \frac{(L-1)T_0}{T_0} = L$$

Kaskádní řazení *M* dvojbranů



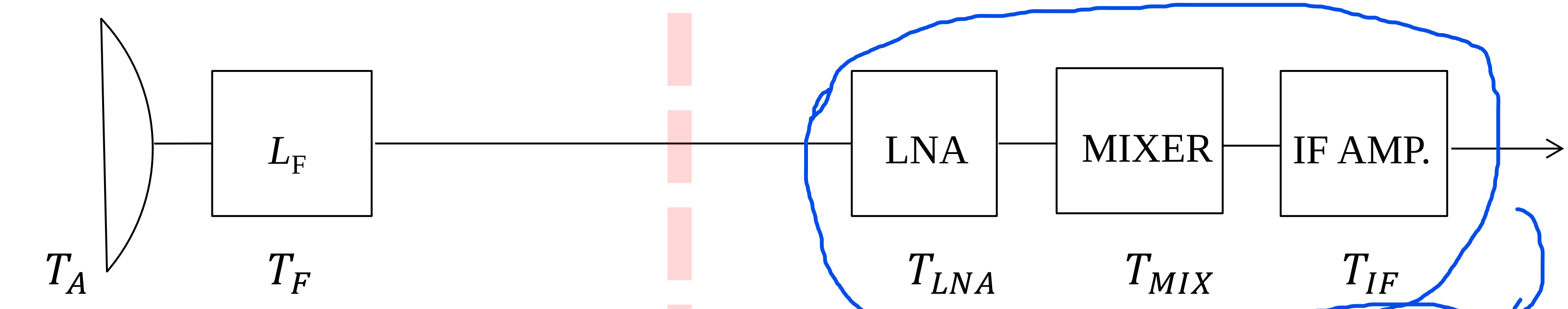
$$N_c = \frac{N_1}{G_1} + \frac{N_2}{G_1 G_2} + \cdots + \frac{N_M}{G_1 G_2 \dots G_M} = N_{e1} + \frac{N_{e2}}{G_1} + \frac{N_{e3}}{G_1 G_2} + \cdots + \frac{N_{eM}}{G_1 G_2 \dots G_{M-1}}$$

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots + \frac{T_{eM}}{G_1 G_2 \dots G_{M-1}}$$

$$F = 1 + \frac{T_e}{T_o} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{T_{eM} - 1}{G_1 G_2 \dots G_{M-1}}$$

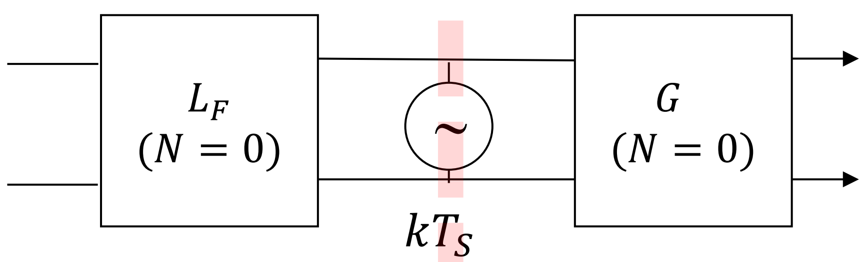
$$\boxed{\begin{array}{c} F_1, G_1, N_1 \\ \text{LNA} \end{array}}$$

Družicový přijímač, Ekvivalentní šumová teplota systému



$$k[T_A + T_F(L_F - 1)]$$

$$k\left[T_{LNA} + \frac{1}{G_{LNA}}T_{MIX} + \frac{1}{G_{LNA}G_{MIX}}T_{IF}\right] \cong kT_{LNA}$$



$$T_S = \frac{1}{L_F}[T_A + T_F(L_F - 1)] + T_{LNA} = \frac{T_A}{L_F} + T_F\left(1 - \frac{1}{L_F}\right) + T_{LNA}$$

Příklad

- Přijímač $F = 8$ (9 dB)
- $B = 30$ kHz
- $T_0 = 300$ K
- $T_A = 290$ K
- Celkový šum na vstupu?

$$N_c = kT_0B + kT_eB = kT_0BF$$

$$F = 1 + \frac{T_e}{T_0}$$

- $T_e = (F - 1)\ T_0 = (8 - 1)300 = 2100$ K
- $T_s = T_A + T_e = 290 + 2100 = 2390$ K
- $N_c = (1 + \mathrm{T}_s / T_0)\ k\ T_0\ B =$
  $= (1 + 2390/300) \cdot 1{,}38 \cdot 10^{-23} \cdot 300 \cdot 30000$
  $= 1{,}1 \cdot 10^{-15}$ W (-119,5 dBm)

Výkonová bilance družicového spoje

- Poměr výkon nosné / spektrální šumová hustota

$$\frac{C}{N_0} = \frac{P_R}{kT_S} = \frac{P_T G_T G_R}{L_{F,T} L_{mis,T} \; L_{F,R} L_{mis,R} \; L_{FSL} L_{atm} \; kT_S}$$

$$\frac{C}{N_0} = EIRP \frac{G_R}{T_S} \frac{1}{L_{F,T} L_{mis,T} \; L_{F,R} L_{mis,R} \; L_{FSL} L_{atm} \; k}$$

  - Vysílač: $EIRP = P_T G_T$, roste s frekvencí a velikostí antény, resp. ziskem G_T a výkonem vysílače P_T; klesá s útlumem napaječe $L_{F,T}$, vychýlením antény (*misalignment loss*) $L_{mis,T}$, příp. dalšími sys. ztrátami
  - Přijímač: roste s poměrem G_R / T_S, tj. s frekvencí a velikostí antény resp. ziskem G_R a klesajícím šumovým číslem LNA; klesá s útlumem napaječe $L_{F,R}$, vychýlením antény (*misalignment loss*) $L_{mis,R}$, příp. dalšími sys. ztrátami
  - Šíření: ztráty volným prostorem L_{FSL}, atmosférické ztráty L_{atm} (plyny, srážky, oblaka, …)

Jakostní číslo přijímače G/T (Figure of Merit)

- Šumová teplota systému v K
  - ref. rovina konektoru přijímače

$$T_S = \frac{T_A}{L_F} + T_F\left(1 - \frac{1}{L_F}\right) + T_R$$

  - šumová teplota antény T_A
  - napáječ (kabel/vlnovod…), teplota T_F, útlum L_F
  - přijímač, ekvivalentní š. teplota T_R

- Jakostní číslo přijímacího řetězce v dB(K^{-1})
  - Poměr mezi ziskem antény G_R a ekv. šum. teplotou systému T_S
  - Zisk antény je třeba přepočítat na ref. rovinu konektoru přijímače (G_R/L_F)

$$\frac{G}{T} = 10\log\left(\frac{G_R}{L_F}\frac{1}{T_S}\right)$$

Výkonová bilance

- Výkon nosné C (W), EIRP = $P_T \,.\, G_T$, Spektrální výkonová hustota šumu N_0 (W/Hz)
- Boltzmannova k. k = 1,38 . 10^{-23} J/K, Ekvivalentní šumová teplota systému T_S (K)
- Výkon šumu $N = kTB$ (W), Šumová šířka pásma B (Hz)
- Poměr výkon nosné / spektrální šumová hustota

$$\frac{C}{N_0} = EIRP\,\frac{1}{L}\,G_R\,\frac{1}{kT_s} = \frac{EIRP}{L}\,\frac{G_R}{T_s}\,\frac{1}{k}$$

$$\left(\frac{C}{N_0}\right) = EIRP - L + \left(\frac{G_R}{T_s}\right) + 228{,}6 \quad \left(\mathrm{dB(Hz), dBW, dB, dB(K^{-1}), dB(J/K)}\right)$$

- Poměr nosná / šum

$$\frac{C}{N} = \frac{C}{N_0 B} \qquad \left(\frac{C}{N}\right) = EIRP - L + \left(\frac{G_R}{T_s}\right) + 228{,}6 - 10\log B$$

- Energie na jeden bit / spektrální šumová hustota

$$\frac{E_b}{N_0} = \frac{C}{N_0}\,\frac{1}{f_b} \qquad \left(\frac{E_b}{N_0}\right) = EIRP - L + \left(\frac{G_R}{T_s}\right) + 228{,}6 - 10\log f_b$$

bitová rychlost f_b (1/s)

Příklad

A. Inputs		
Satellite longitude	Degrees	119.0
Earth station latitude and longitude (lat/long)	Degrees	38.90/77.01
Earth station altitude above mean sea level	Km	0.01
Satellite e.i.r.p. in the direction of the DBS earth station	DBW	52.6
Operating frequency	GHz	12.45
Required operating threshold	DB	6.1
Receiver noise bandwidth	MHz	24.0
Earth station antenna diameter	M	0.45
Earth station antenna pointing loss towards the satellite	DB	0.5
Clear-sky earth station antenna system noise temperature	Kelvin	85.0
Atmospheric absorption	DB	0.2
C/I for other assignments in the BSS Plan	DB	20.0
Clear-sky feeder link C/(N+I)	DB	26.2
Boltzman’s constant	DB	228.6

B. Calculate		
Distance from GSO satellite to earth station	Km	38,825
Earth station antenna elevation angle	Degrees	27.6
Free space path loss	DB	206.1
Earth station antenna gain	DBi	33.83
$G = 10\log\left(\frac{4\pi}{\lambda^2} 0{,}55\pi 0{,}255^2\right)$		
Clear-sky earth station antenna G/T	DB	14.5
$\frac{G_R}{T} = 10\log\left(\frac{10^{3{,}383}}{85}\right)$		
Clear-sky carrier-to-thermal noise ratio	DB	15.1
$\left(\frac{C}{N}\right) = EIRP - L_0 + \left(\frac{G_R}{T_s}\right) + 228{,}6 - 10\log B = 52{,}6 - 0{,}5 - 206{,}1 - 0{,}2 + 14{,}5 + 228{,}6 - 10\log\left(24\cdot 10^6\right)$		
Clear-sky carrier-to-thermal noise plus interference ratio	DB	13.6
$\frac{C}{N + I_1 + I_2} = \frac{1}{\frac{N}{C} + \frac{I_1}{C} + \frac{I_2}{C}} = \frac{1}{\frac{1}{10^{1{,}51}} + \frac{1}{10^2} + \frac{1}{10^{2{,}62}}}$		
Clear-sky link margin	DB	7.5
13,6 – 6,1 = 7,5 dB		
Rain margin	DB	4.09
1. C klesne o ztráty deštěm 2. déšť zvýší šumovou teplotu antény (tj. dále klesne C/N)	$\left(\frac{C}{N+I}\right) - L_{rain} - \Delta\left(\frac{G_R}{T_S}\right)\left(L_{rain}\right) = 6{,}1$	
Satellite link unavailability due to rain (výpočet z P.618)	%	0.0647 340 min./rok
Calculated satellite link availability	%	99.9353

RECOMMENDATION ITU-R P.618-8

Propagation data and prediction methods required for the design of Earth-space telecommunication systems

(Question ITU-R 206/3)

(1986-1990-1992-1994-1995-1997-1999-2001-2003)

The ITU Radiocommunication Assembly,

considering

a) that for the proper planning of Earth-space systems it is necessary to have appropriate propagation data and prediction techniques;

b) that methods have been developed that allow the prediction of the most important propagation parameters needed in planning Earth-space systems;

c) that as far as possible, these methods have been tested against available data and have been shown to yield an accuracy that is both compatible with the natural variability of propagation phenomena and adequate for most present applications in system planning,

recommends

1 that the methods for predicting the propagation parameters set out in Annex 1 be adopted for planning Earth-space radiocommunication systems, in the respective ranges of validity indicated in Annex 1.

NOTE 1 – Supplementary information related to the planning of broadcasting-satellite systems as well as maritime, land, and aeronautical mobile-satellite systems, may be found in Recommendations ITU-R P.679, ITU-R P.680, ITU-R P.681 and ITU-R P.682, respectively.

2.5 Estimation of total attenuation due to multiple sources of simultaneously occurring atmospheric attenuation

For systems operating at frequencies above about 18 GHz, and especially those operating with low elevation angles and/or margins, the effect of multiple sources of simultaneously occurring atmospheric attenuation must be considered.

Total attenuation (dB) represents the combined effect of rain, gas, clouds and scintillation and requires one or more of the following input parameters:

$A_R(p)$: attenuation due to rain for a fixed probability (dB), as estimated by A_p in equation (8)

$A_C(p)$: attenuation due to clouds for a fixed probability (dB), as estimated by Recommendation ITU-R P.840

$A_G(p)$: gaseous attenuation due to water vapour and oxygen for a fixed probability (dB), as estimated by Recommendation ITU-R P.676

$A_S(p)$: attenuation due to tropospheric scintillation for a fixed probability (dB), as estimated by equation (27)

where p is the probability of the attenuation being exceeded in the range 50% to 0.001%.

Gaseous attenuation as a function of percentage of time can be calculated using § 2.2 of Annex 2 of Recommendation ITU-R P.676 if local meteorological data at the required time percentage are available. In the absence of local data at the required time percentage, the mean gaseous attenuation should be calculated and used in equation (46).

A general method for calculating total attenuation for a given probability, $A_T(p)$, is given by:

$$A_T(p) = A_G(p) + \sqrt{\left(A_R(p) + A_C(p)\right)^2 + A_S^2(p)} \qquad (46)$$

where:

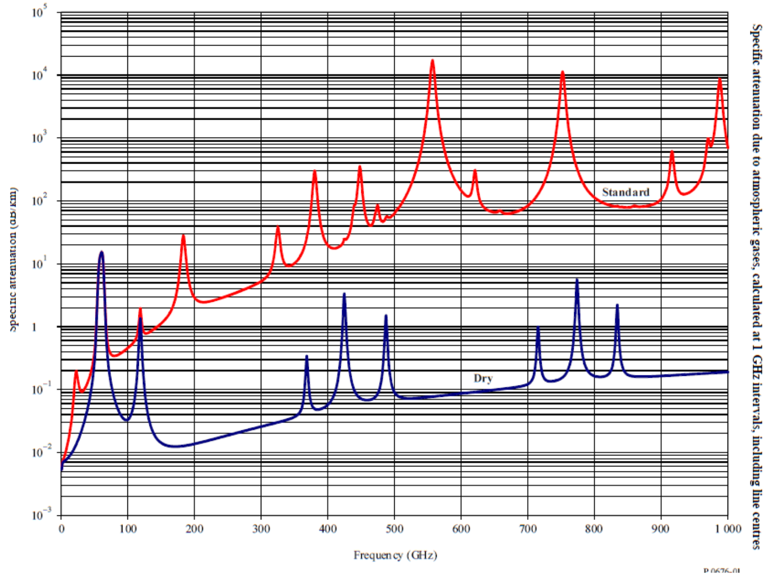
$$A_C(p) = A_C(1\%) \qquad \text{for } p < 1.0\% \qquad (47)$$

$$A_G(p) = A_G(1\%) \qquad \text{for } p < 1.0\% \qquad (48)$$

Equations (47) and (48) take account of the fact that a large part of the cloud attenuation and gaseous attenuation is already included in the rain attenuation prediction for time percentages below 1%.

Rec. ITU-R P.676-11 Attenuation by atmospheric gases

$$A = \gamma r_0 = (\gamma_o + \gamma_w) r_0 \qquad \text{dB}$$



The total slant path attenuation, $A(h, \varphi)$, from a station with altitude, h, and elevation angle, φ, can be calculated as follows when $\varphi \geq 0$:

$$A(h, \varphi) = \int_h^\infty \frac{\gamma(H)}{\sin \Phi} \, \mathrm{d}H \tag{11}$$

where the value of Φ can be determined as follows based on Snell's law in polar coordinates:

$$\Phi = \arccos\left(\frac{c}{(r+H) \times n(H)}\right) \tag{12}$$

where:

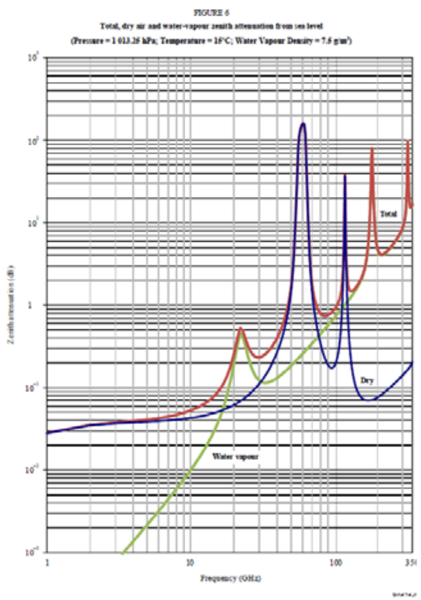
$$c = (r+h) \times n(h) \times \cos \varphi \tag{13}$$

where $n(h)$ is the atmospheric radio refractive index, calculated from pressure, temperature and water-vapour pressure along the path (see Recommendation ITU-R P.835) using equations (1) and (2) of Recommendation ITU-R P.453.

Rec. ITU-R P.676-11 Attenuation by atmospheric gases

Aproximate estimation for slant paths using equivalent heights

The total zenith attenuation is then:



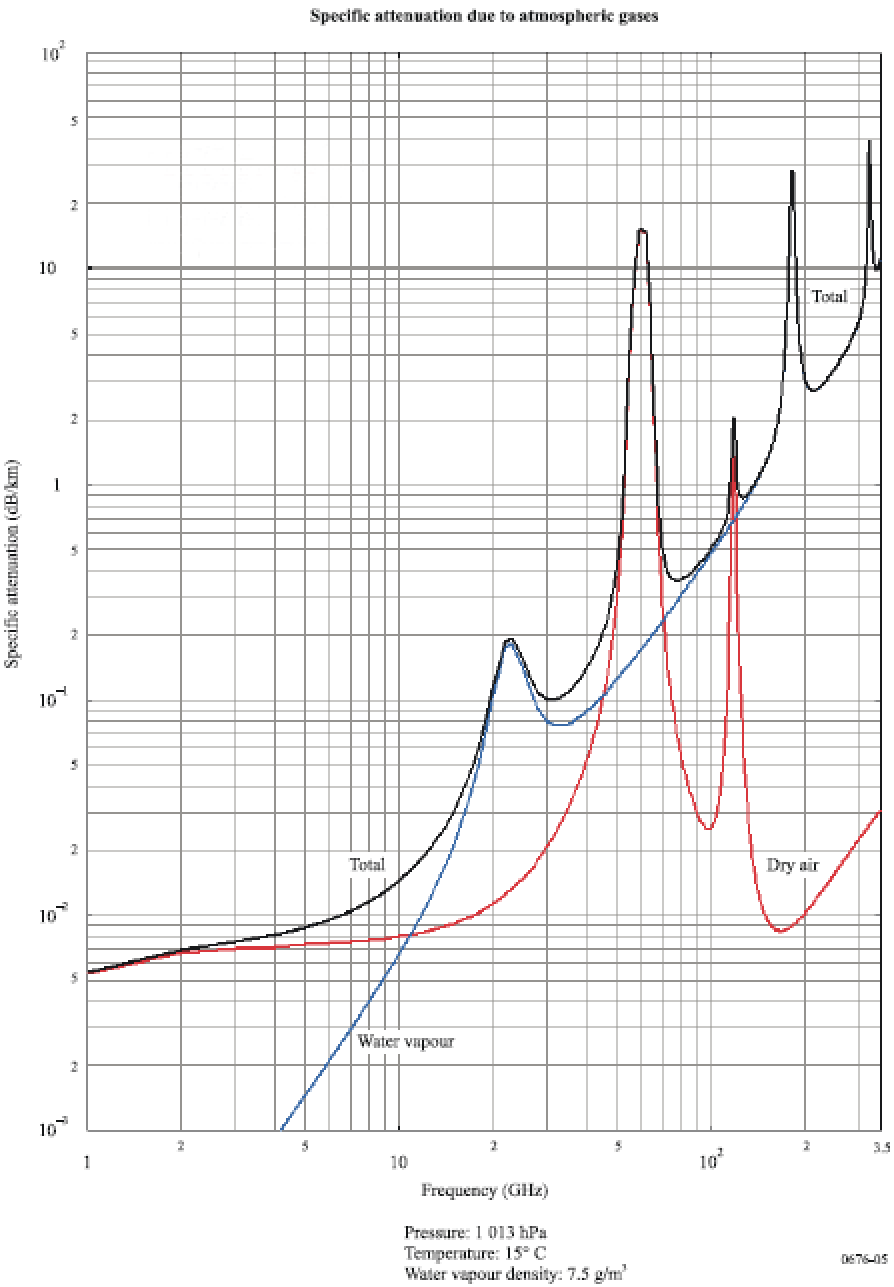
$$A = \gamma_o \, h_o + \gamma_w \, h_w \qquad \text{dB}$$

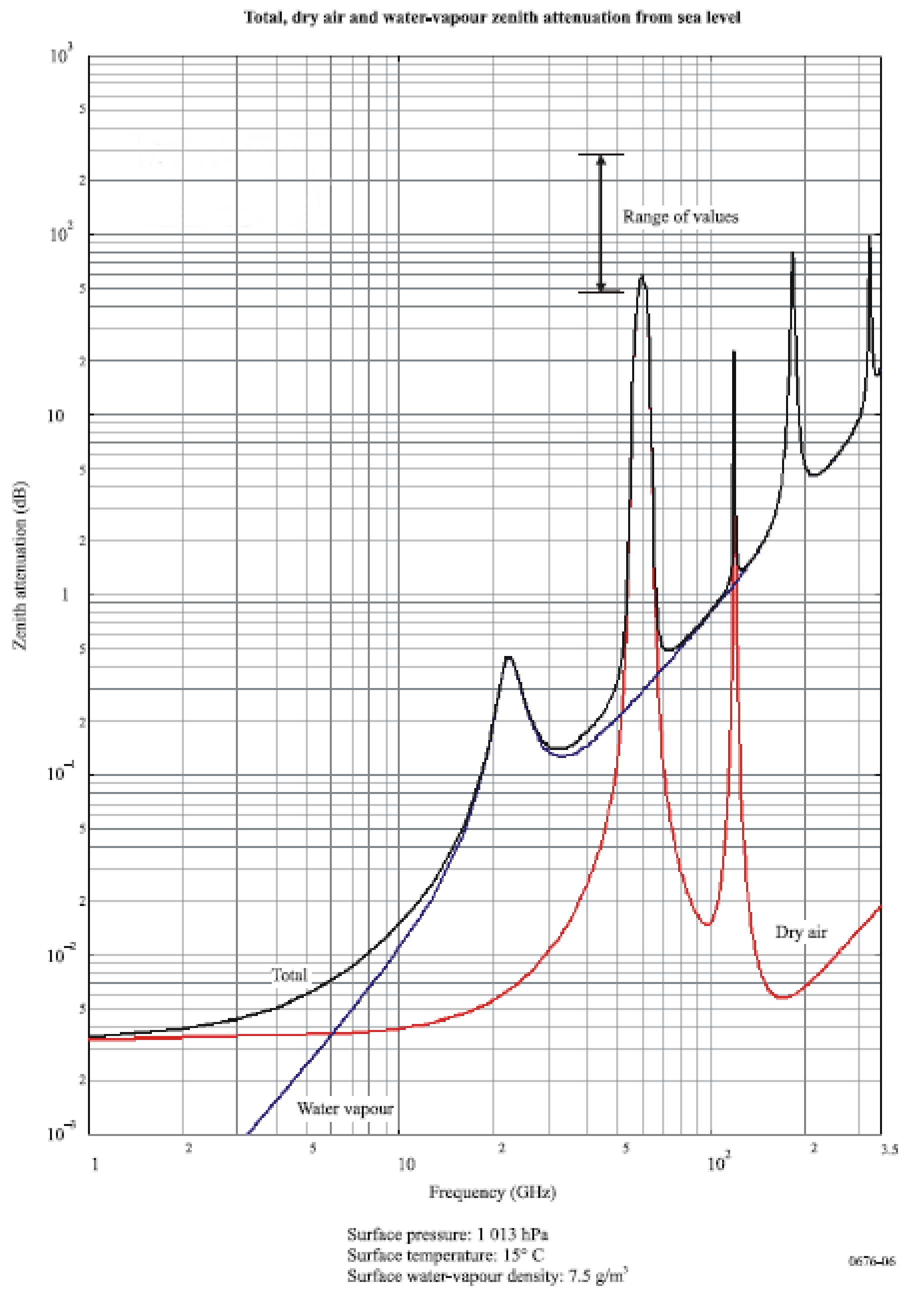
For an elevation angle, φ, between 5° and 90°, the path attenuation is obtained using the cosecant law, as follows:

For path attenuation based on surface meteorological data:

$$A = \frac{A_o + A_w}{\sin \varphi} \qquad \text{dB} \qquad (28)$$

where $A_o = h_o \, \gamma_o$ and $A_w = h_w \, \gamma_w$


Specific attenuation due to atmospheric gases
Specific attenuation (dB/km)
Total
Dry air
Water vapour
Frequency (GHz)
Pressure: 1 013 hPa
Temperature: 15° C
Water vapour density: 7.5 g/m3
0676-05


Total, dry air and water-vapour zenith attenuation from sea level
Zenith attenuation (dB)
Range of values
Total
Dry air
Water vapour
Frequency (GHz)
Surface pressure: 1 013 hPa
Surface temperature: 15° C
Surface water-vapour density: 7.5 g/m3
0676-06

Rec. ITU-R P.676-11 Attenuation by atmospheric gases

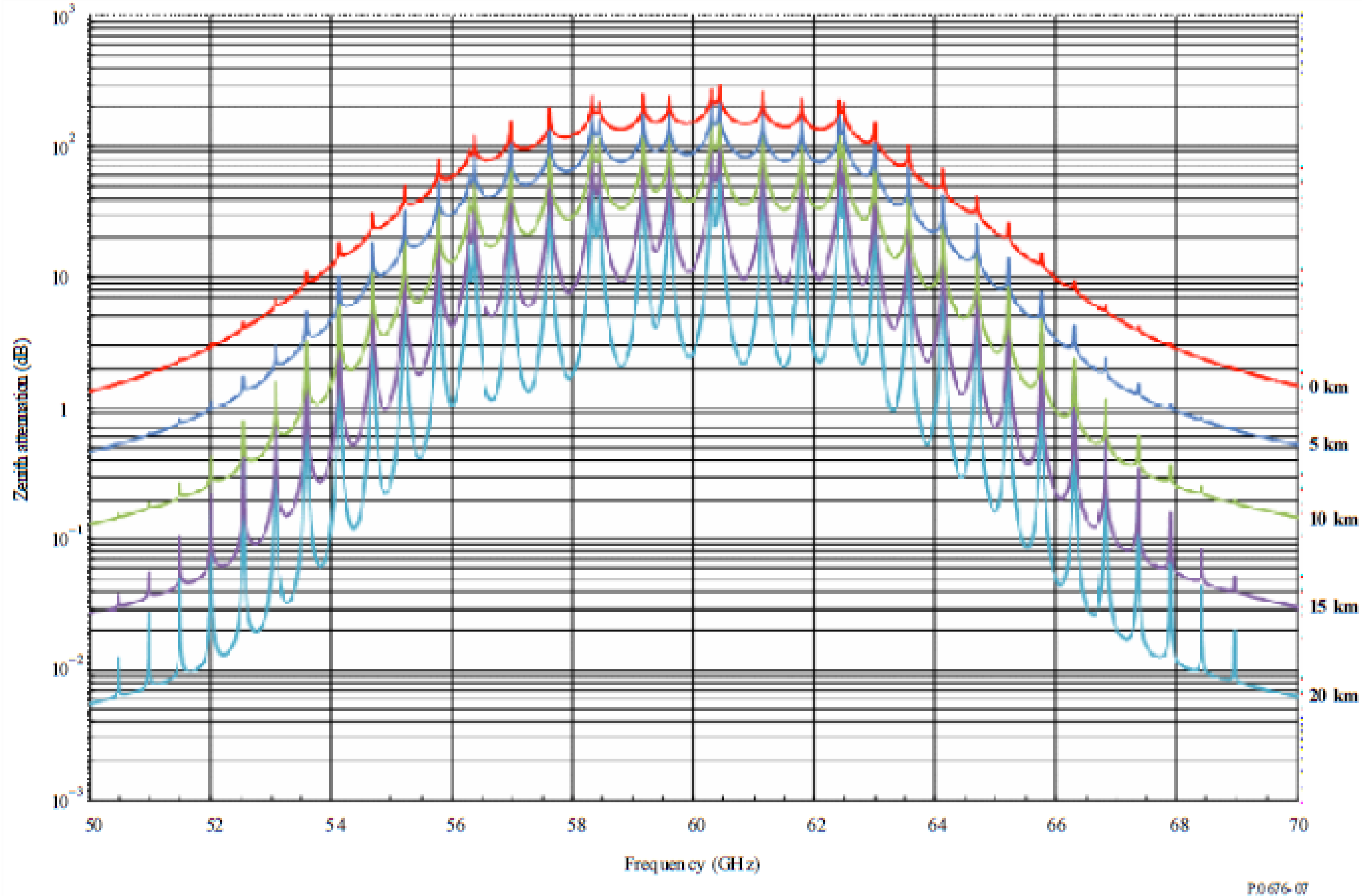
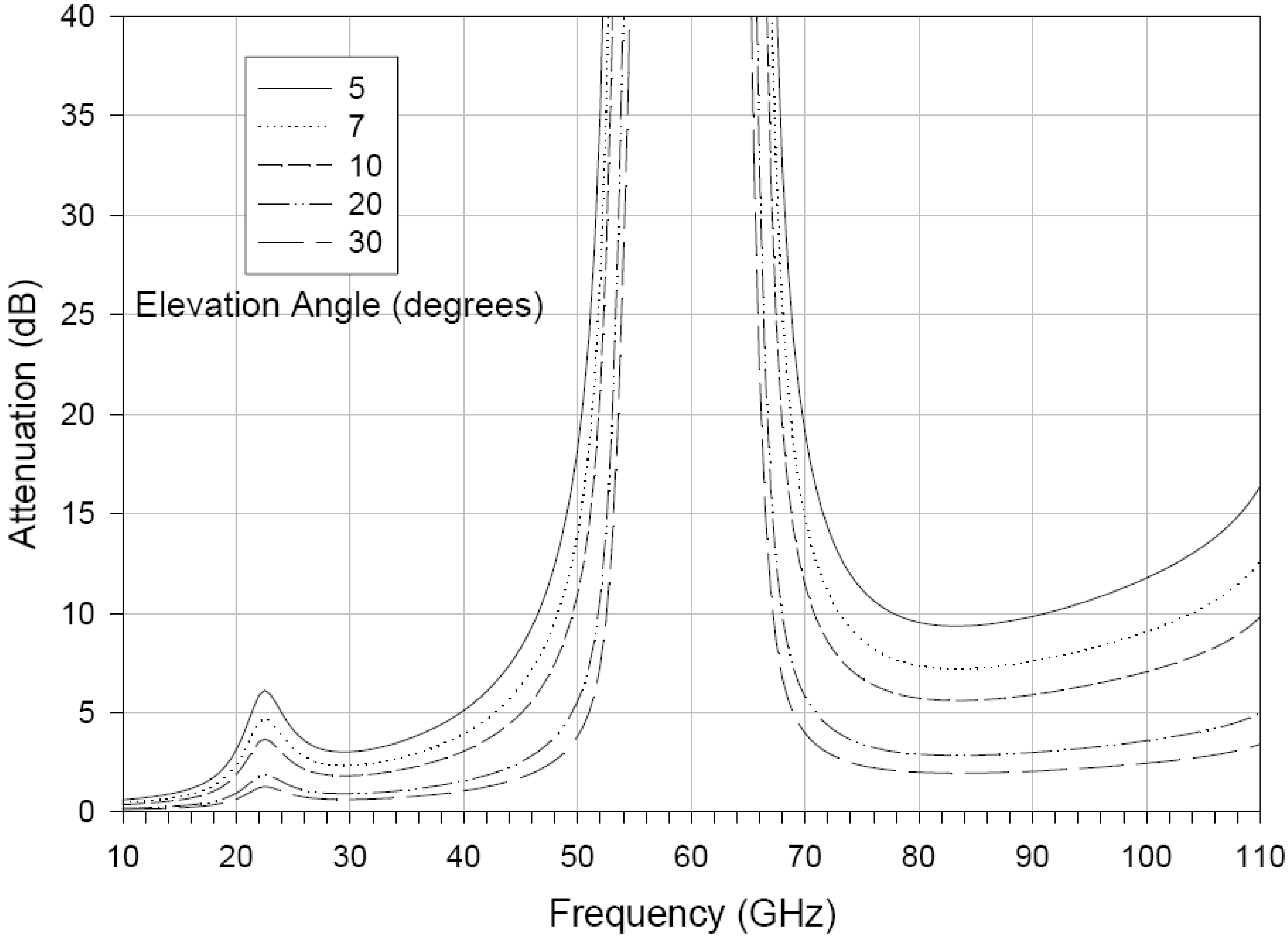


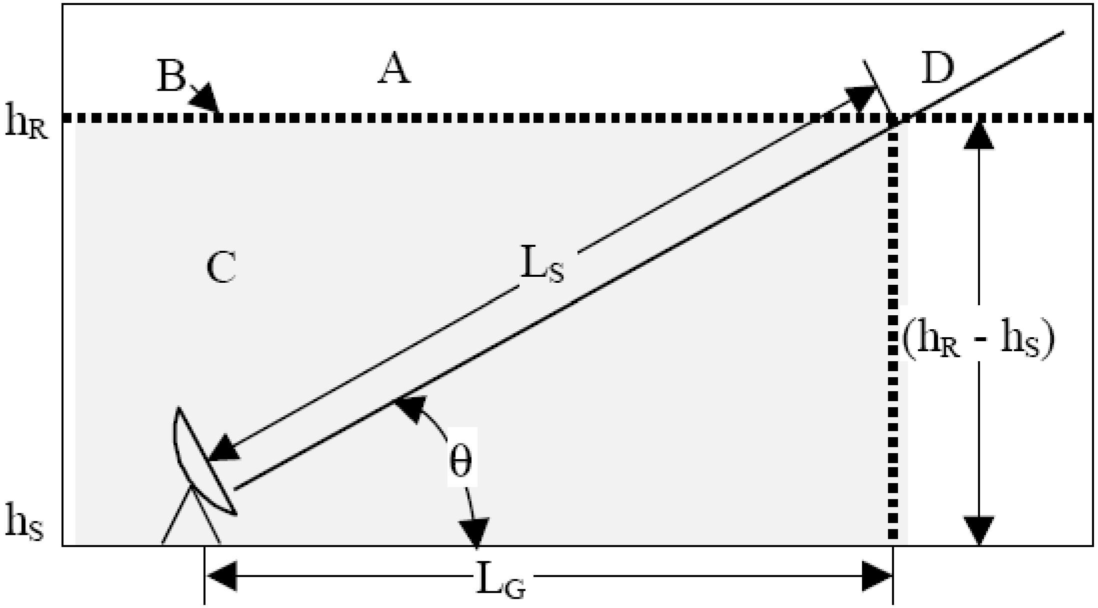
FIGURE 7

Zenith oxygen attenuation from the altitudes indicated, calculated at intervals of 10 MHz, including line centres (0 km, 5 km, 10 km, 15 km and 20 km)



Total path gaseous attenuation versus frequency for elevation angles from 5 to 30 degrees.
Location: Washington DC.

Družicový spoj (ITU-R P.618)



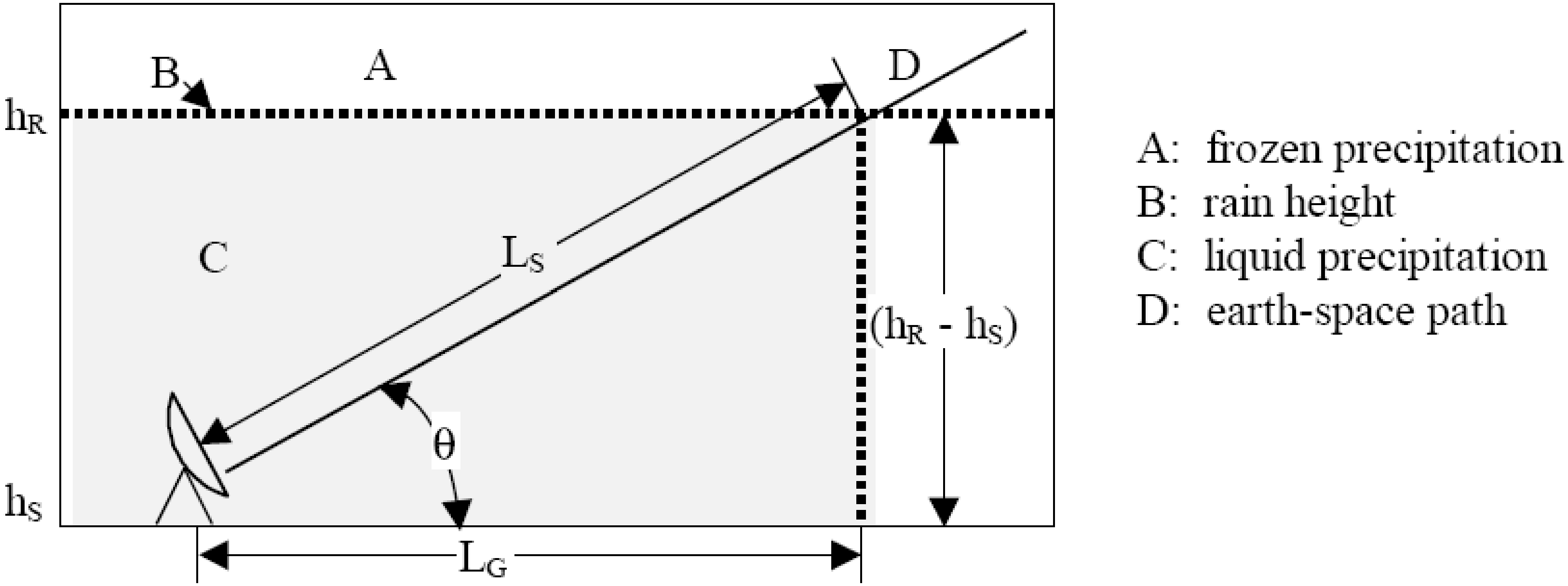
A: frozen precipitation
B: rain height
C: liquid precipitation
D: earth-space path

1/ h_R (výška nulové isotermy/hladina tání) jako funkce zeměpisné šířky φ

$$h_R(\varphi) = \begin{cases} 5 - 0.075(\varphi - 23) & \text{for} \quad \varphi > 23^\circ \\ 5 & \text{for} \quad -21^\circ \le \varphi \le 23^\circ \\ 5 + 0.1(\varphi + 21) & \text{for} \quad -71^\circ \le \varphi \le -21^\circ \\ 0 & \text{for} \quad \varphi < -71^\circ \end{cases}$$

Ippolito, L.J., Propagation Effects Handbook for Satellite Systems Design, NASA, Washington, D.C., 1999.

Družicový spoj (ITU-R P.618)



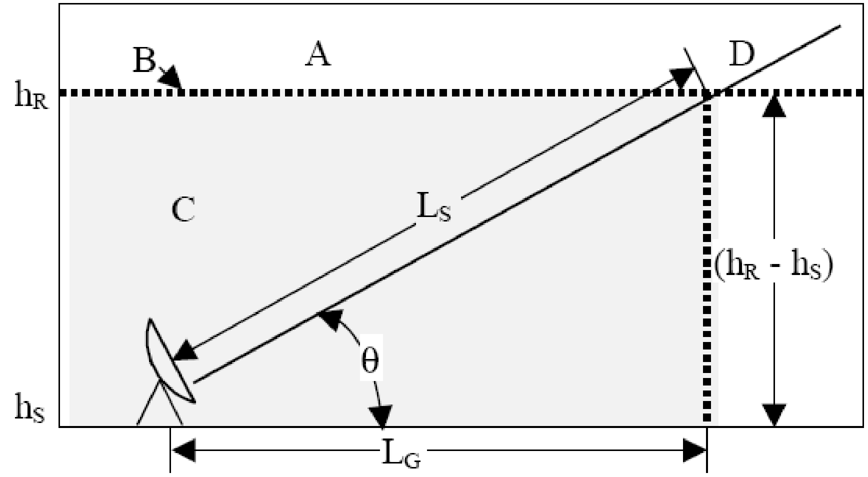
2/ délky L_S a L_G v km

$$L_S(\theta) = \begin{cases} \dfrac{(h_R - h_S)}{\sin\theta} & for \quad \theta \geq 5^\circ \\[2ex] \dfrac{2(h_R - h_S)}{\left[\sin^2\theta + \frac{2(h_R - h_S)}{R_e}\right]^{1/2} + \sin\theta} & for \quad \theta < 5^\circ \end{cases}$$

$$L_G = L_S \cos\theta$$

Družicový spoj (ITU-R P.618)

Dále jako pro pozemní spoj s d_{ef} = fce(L_G, L_s)



$$d_{ef} = \frac{L_S}{1 + \dfrac{L_G}{35\exp(-0{,}015 R_{0,01})}}$$

$$L_{0,01} = \gamma_R \cdot d_{ef} = k \cdot R_{0,01}{}^{\alpha} \cdot d_{ef}$$

Přepočet pro jiná procenta času p v rozsahu od 0,001 % do 1 % a zeměpisné šířky větší než 30° :

$$L_p = 0{,}12\, p^{-(0{,}546 + 0{,}043 \log p)} L_{0,01}$$

- Novější verze ITU-R P.618 má komplikovanější výpočet d_{ef}
- Mnoho jiných modelů, např. Crane Model, DAH Model, ExCell Model, Manningův model atd.

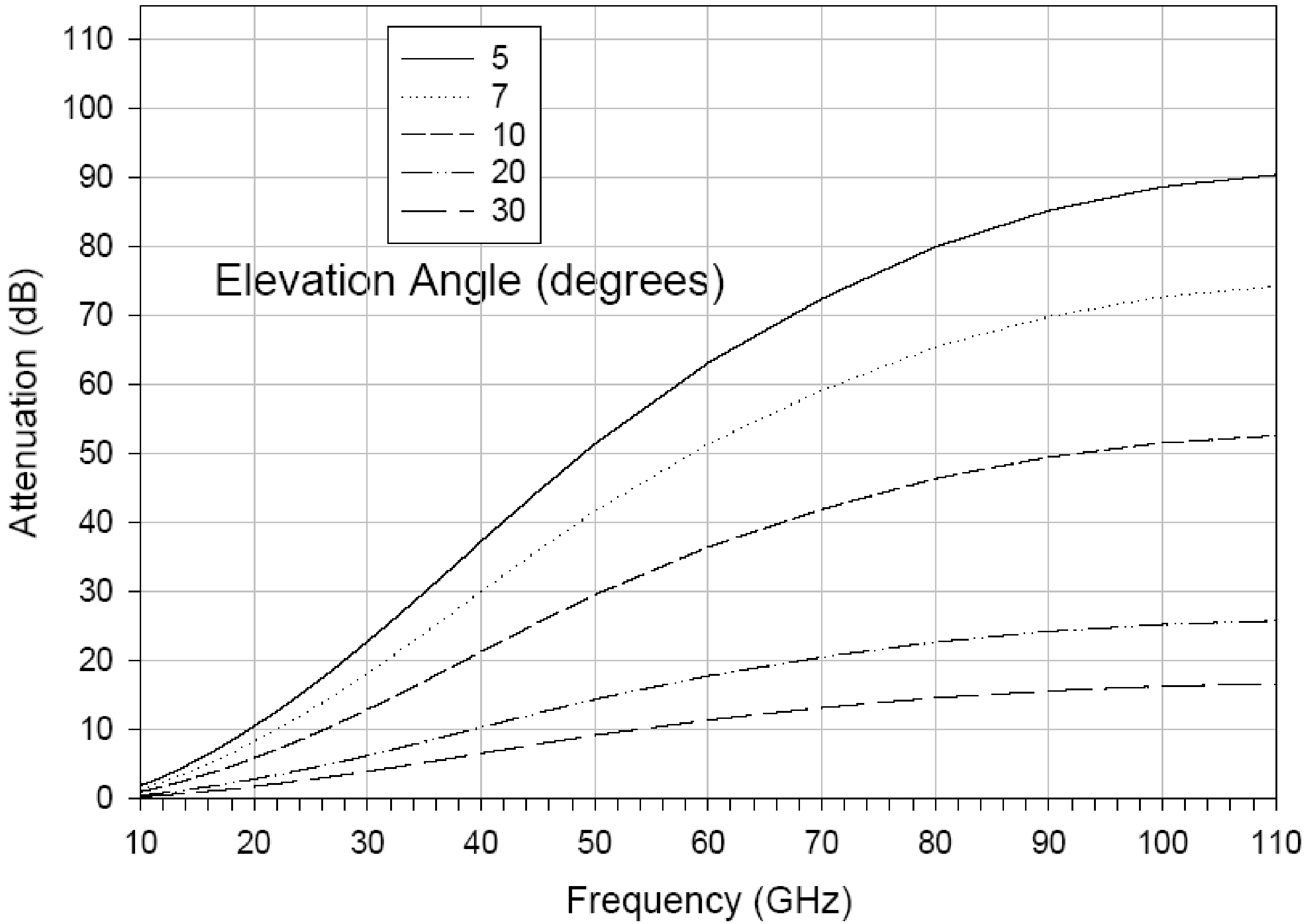


Exhibit1.3.3.2-2
Total path rain attenuation as a function of frequency and elevation angle
Location: Washington, DC
Availability: 99%

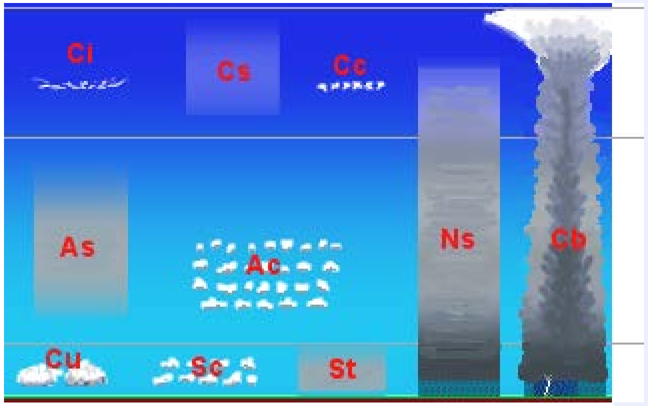
Ippolito, L.J., Propagation Effects Handbook for Satellite Systems Design, NASA, Washington, D.C., 1999.

Oblaka

- Oblak je viditelná soustava nepatrných částic vody nebo ledu
- Meteorologický atlas oblaků www.chmi.cz/meteo/om/mk/atlasobl/
- 2 kategorie: Stratus (Slohy), Cumulus (Kupy)

- 10 zákl. druhů
- Výskyt: oblaky vysokého, středního a nízkého patra; oblaky velkého vertikálního rozsahu.

Zkratka	Latinsky	Česky
St	Stratus	sloha
Ci	Cirrus	řasa
Cs	Cirrostratus	řasová sloha
Cc	Cirrocumulus	řasová kupa
Ac	Altocumulus	vyvýšená kupa
As	Altostratus	vyvýšená sloha
Sc	Stratocumulus	slohová kupa
Ns	Nimbostratus	dešťová sloha
Cu	Cumulus	kupa
Cb	Cumulonimbus	bouřkový oblak



Druhy	Tvary	Odrůdy	Zvláštnosti	Mateřské oblaky
Cirrus	fibratus	intortus	mamma	Cirrocumulus
	uncinus	radiatus		Altocumulus
	spissatus	vertebratus		Cumulonimbus
	castellanus	duplicatus		
	floccus			
Cirrocumulus	stratiformis	undulatus	virga	
	lenticularis	lacunosus	mamma	
	castellanus			
	floccus			
Cirrostratus	fibratus	duplicatus		Cirrocumulus
	nebulosus	undulatus		Cumulonimbus
Altocumulus	stratiformis	translucidus	virga	Cumulus
	lenticularis	perlucidus	mamma	Cumulonimbus
	castellanus	opacus		
	floccus	duplicatus		
		undulatus		
		radiatus		
		lacunosus		
Altostratus		translucidus	virga	Altocumulus
		opacus	praecipitatio	Cumulonimbus
		duplicatus	pannus	
		undulatus	mamma	
		radiatus		
Nimbostratus			praecipitatio	Cumulus
			virga	Cumulonimbus
			pannus	
Stratocumulus	stratiformis	translucidus	mamma	Altostratus
	lenticularis	perlucidus	virga	Nimbostratus
	castellanus	opacus	praecipitatio	Cumulus
		duplicatus		Cumulonimbus
		undulatus		
		radiatus		
		lacunosus		
Stratus	nebulosus	opacus	praecipitatio	Nimbostratus
	fractus	translucidus		Cumulus
		undulatus		Cumulonimbus
Cumulus	humilis	radiatus	pileus	Altocumulus
	mediocris		velum	Stratocumulus
	congestus		virga	
	fractus		praecipitatio	
			arcus	
			pannus	
			tuba	
Cumulonimbus	calvus		praecipitatio	Altocumulus
	capillatus		virga	Altostratus

Oblaka, mlha (*cloud, fog*)

- Malé kapičky *D* < 0,1 mm (dešťové kapky 0,1–10,0 mm); obsah vody může být v rozsahu 0,05 - 2 g/m^3

Cloud Type	Concentration *(no/cm^3)*	Liquid Water *(g/ m^3)*	Average Radius *(microns)*
Fair-weather cumulus	300	0.15	4.9
Stratocumulus	350	0.16	4.8
Stratus (over land)	464	0.27	5.2
Altostratus	450	0.46	6.2
Stratus (over water)	260	0.49	7.6
Cumulus congestus	2-7	0.67	9.2
Cumulonimbus	72	0.98	14.8
Nimbostratus	330	0.99	9.0

- Oblaka ve velkých výškách - krystalky ledu (zanedbatelný útlum, ale depolarizace)
- Mlha – přízemní oblaka – málo významná pro *f* < 100 GHz
  - 0,05 g/m3 - viditelnost cca 300 m
  - 0.5 g/m3 - viditelnost cca 50 m

ITU-R P.840
ATTENUATION DUE TO CLOUDS AND FOG

1 Introduction

For clouds or fog consisting entirely of small droplets, generally less than 0.01 cm, the Rayleigh approximation is valid for frequencies below 200 GHz and it is possible to express the attenuation in terms of the total water content per unit volume. Thus the specific attenuation within a cloud or fog can be written as:

$$\gamma_c = K_l \, M \qquad \text{dB/km} \tag{1}$$

where:

γ_c: specific attenuation (dB/km) within the cloud

K_l: specific attenuation coefficient ((dB/km)/(g/m^3))

M: liquid water density in the cloud or fog (g/m^3).

At frequencies of the order of 100 GHz and above, attenuation due to fog may be significant. The liquid water density in fog is typically about 0.05 g/m^3 for medium fog (visibility of the order of 300 m) and 0.5 g/m^3 for thick fog (visibility of the order of 50 m).

3 Cloud attenuation

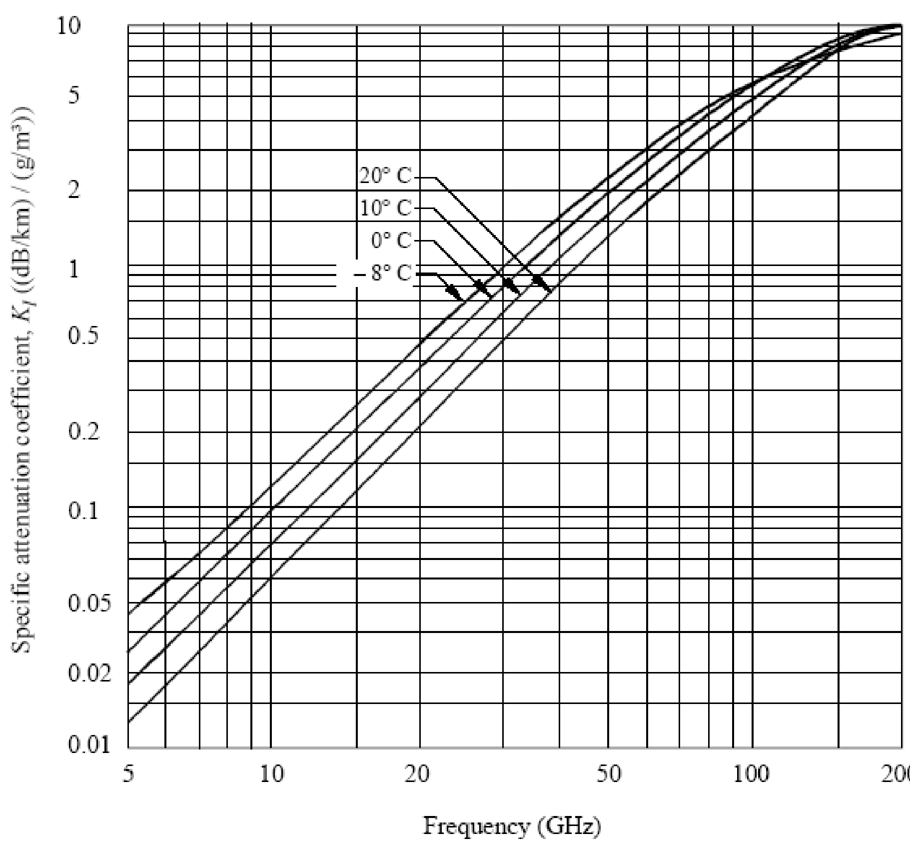
To obtain the attenuation due to clouds for a given probability value, the statistics of the total columnar content of liquid water L (kg/m^2) or, equivalently, mm of precipitable water for a given site must be known yielding:

$$A = \frac{L\, K_l}{\sin\theta} \qquad \text{dB} \qquad \text{for} \quad 90° \geq \theta \geq 5° \qquad (12)$$

where θ is the elevation angle and K_l is read from Fig. 1. Note that K_l is identical to the mass absorption coefficient a_L introduced in Recommendation ITU-R P.836, equation (1).

FIGURE 1

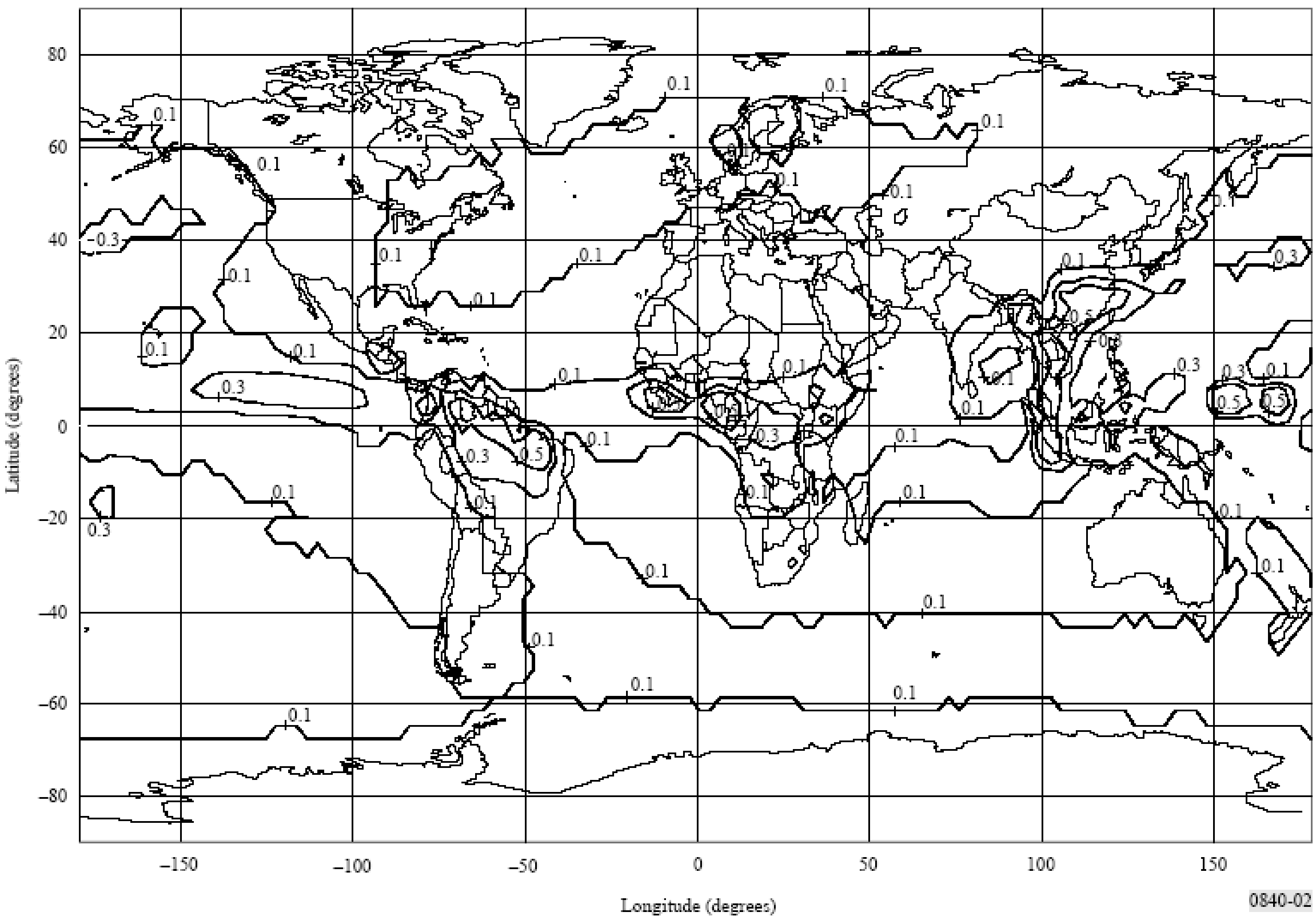
Specific attenuation by water droplets at various temperatures as function of frequency



0840-01

FIGURE 2

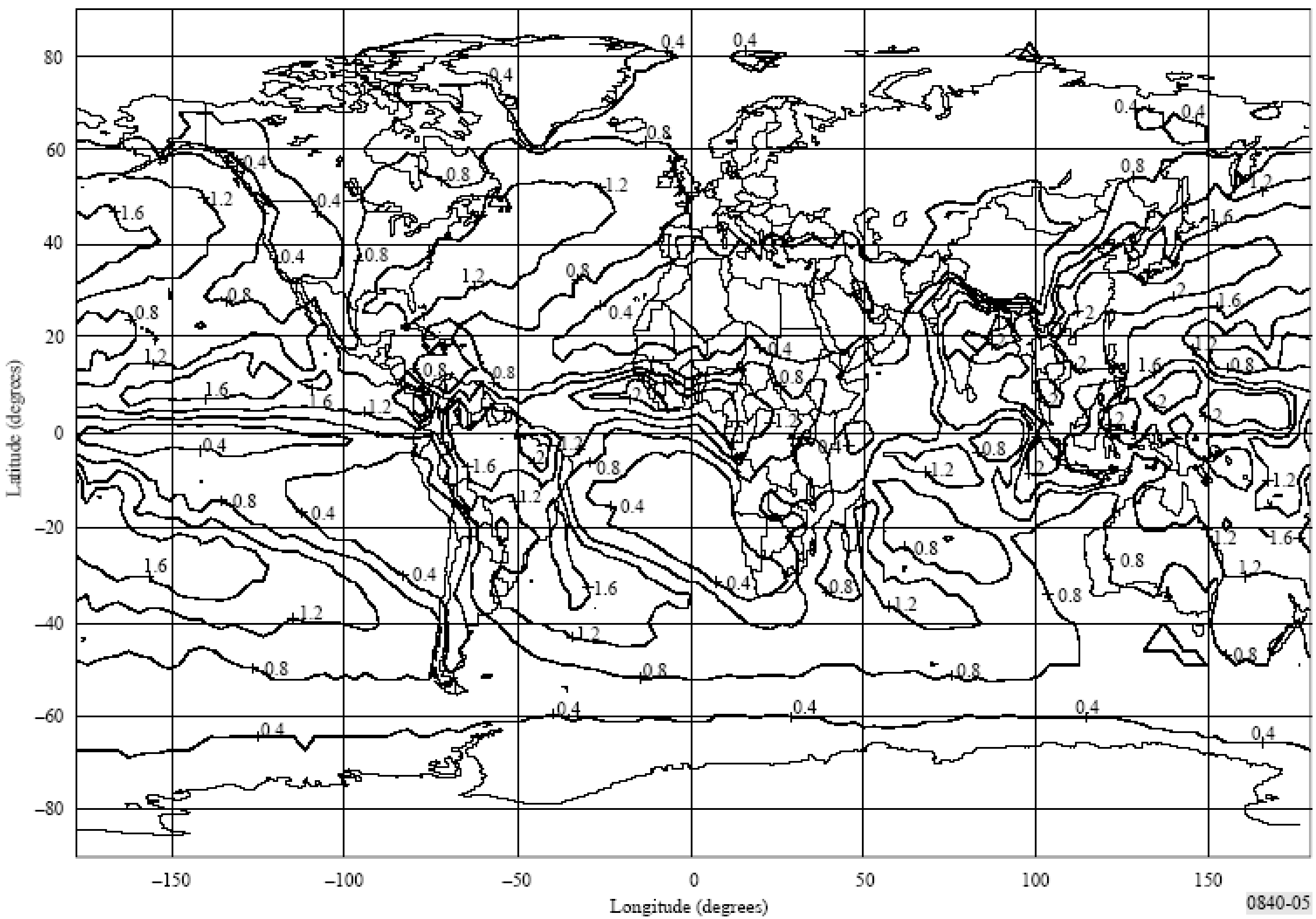
Normalized total columnar content of cloud liquid water (kg/m²) exceeded for 20% of the year



0840-02

FIGURE 5

Normalized total columnar content of cloud liquid water (kg/m²) exceeded for 1% of the year



Slobin Cloud Model (12 kategorií oblaků)

Cloud Type	Case No.	Liquid Water (g/m^3)	Lower Cloud		Upper Cloud	
			Base (km)	Thickness (km)	Base (km)	Thickness (km)
Light, Thin	2	0.2	1.0	0.2	--	--
Light	4	0.5	1.0	0.5	--	--
Medium	6	0.5	1.0	1.0	--	--
Heavy I	8	0.5	1.0	1.0	3.0	1.0
Heavy II	10	1.0	1.0	1.0	3.0	1.0
Very Heavy I	11	1.0	1.0	1.5	3.5	1.5
Very Heavy II	12	1.0	1.0	2.0	4.0	2.0

Frequency (GHz)	**Light Thin Cloud**	**Light Cloud**	**Medium Cloud**	**Heavy Clouds I**	**Heavy Clouds II**	**Very Heavy Clouds I**	**Very Heavy Clouds II**
6 / 4	<0.1 dB	<0.1 dB	<0.2 dB	<0.2 dB	<0.2 dB	<0.3 dB	<0.3 dB
14 / 12	0.1	0.15	0.2	0.3	0.45	0.6	0.9
17	0.2	0.22	0.3	0.45	0.7	1.0	1.4
20	0.25	0.3	0.4	0.6	0.9	1.4	1.8
30	0.3	0.4	0.5	1.0	1.7	2.7	3.9
42	0.7	0.9	1.2	2.1	3.5	5.5	7.9
50	1.5	1.9	2.3	3.6	5.7	8.4	11.7

Exhibit 2.2.2.3-2
Cloud Attenuation at Zenith (90° Elevation Angle) from the Slobin Model

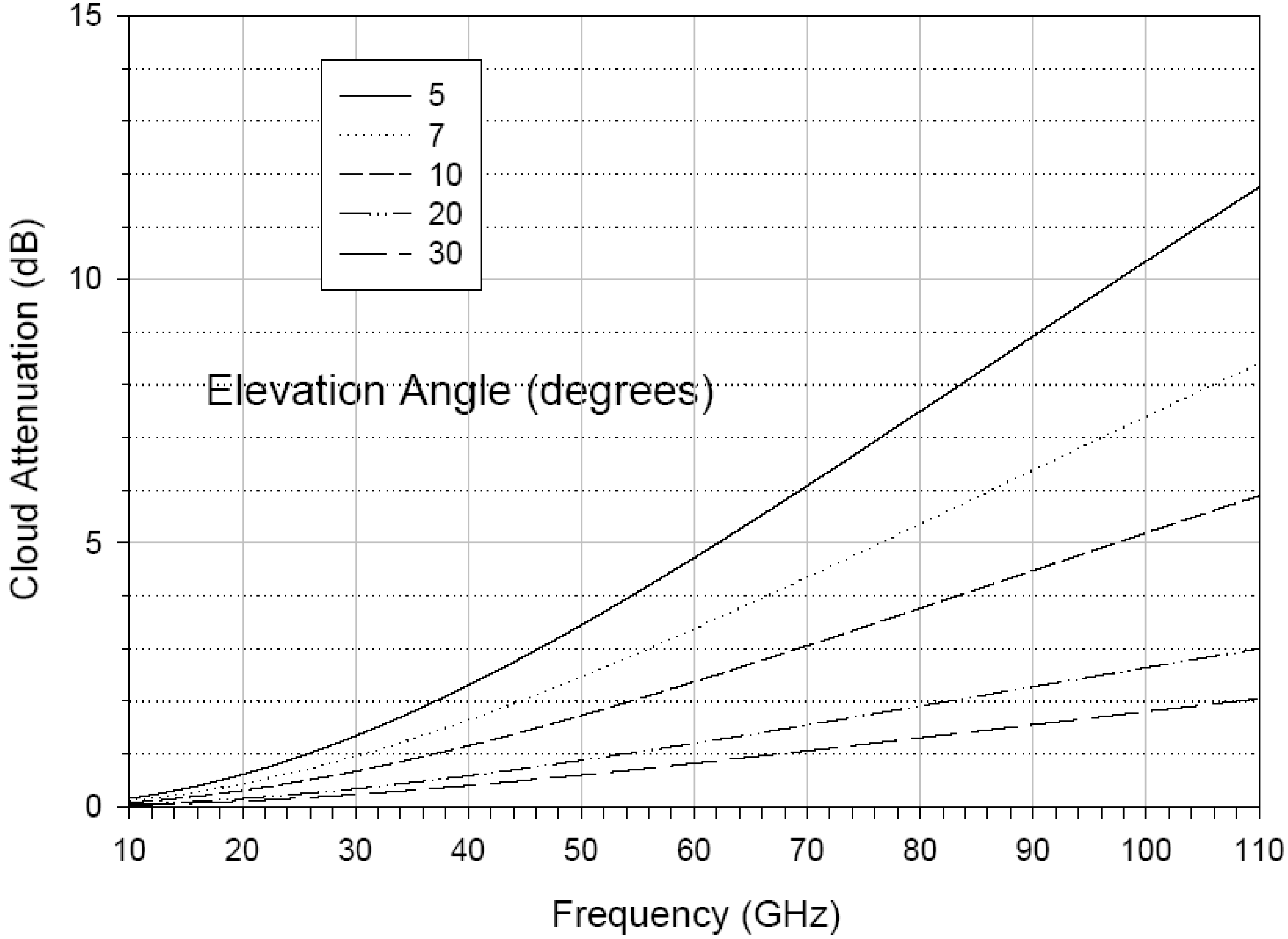
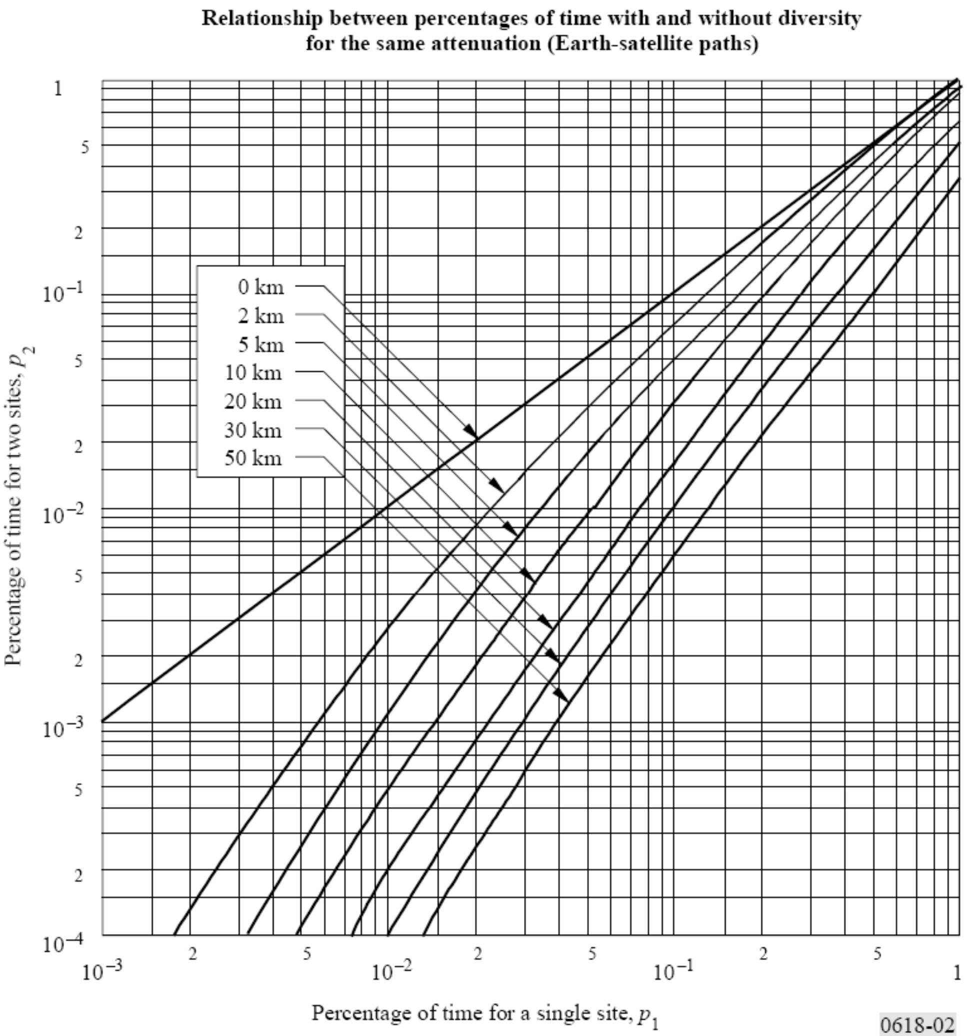


Exhibit 1.3.2-3
Total cloud attenuation as a function of frequency, for elevation angles from 5 to 30 degrees

Ippolito, L.J., Propagation Effects Handbook for Satellite Systems Design, NASA, Washington, D.C., 1999.

Trasová diverzita



2.2.4.1 Diversity improvement factor

The diversity improvement factor, I, is given by:

$$I = \frac{p_1}{p_2} = \frac{1}{(1+\beta^2)}\left(1 + \frac{100\,\beta^2}{p_1}\right) \approx 1 + \frac{100\,\beta^2}{p_1} \qquad (11)$$

where p_1 and p_2 are the respective single-site and diversity time percentages, and β is a parameter depending on link characteristics. The approximation on the right-hand side of equation (11) is acceptable since β^2 is generally small.

From a large number of measurements carried out in the 10-20 GHz band, and mainly between 11 GHz and 13.6 GHz, it has been found that the value of β^2 depends basically on the distance, d, between the stations, and only slightly on the angle of elevation and the frequency. It is found that β^2 can be expressed by the following empirical relationship:

$$\beta^2 = 10^{-4}\, d^{1.33} \qquad (12)$$

Figure 2 shows p_2 versus p_1 on the basis of equations (11) and (12).

2.2.4.2 Diversity gain

The diversity gain, G (dB), between pairs of sites is calculated with the empirical expression given below. Parameters required for the calculation of diversity gain are:

- d: separation (km) between the two sites
- A: path rain attenuation (dB) for a single site
- f: frequency (GHz)
- θ: path elevation angle (degrees)
- ψ: angle (degrees) made by the azimuth of the propagation path with respect to the baseline between sites, chosen such that $\psi \leq 90°$.

Step 1: Calculate the gain contributed by the spatial separation from:

$$G_d = a\,(1 - e^{-bd}) \qquad (13)$$

where:

$$a = 0.78\,A - 1.94\,(1 - e^{-0.11\,A})$$

$$b = 0.59\,(1 - e^{-0.1\,A})$$

Step 2: Calculate the frequency-dependent gain from:

$$G_f = e^{-0.025\,f} \qquad (14)$$

Step 3: Calculate the gain term dependent on elevation angle from:

$$G_\theta = 1 + 0.006\,\theta \qquad (15)$$

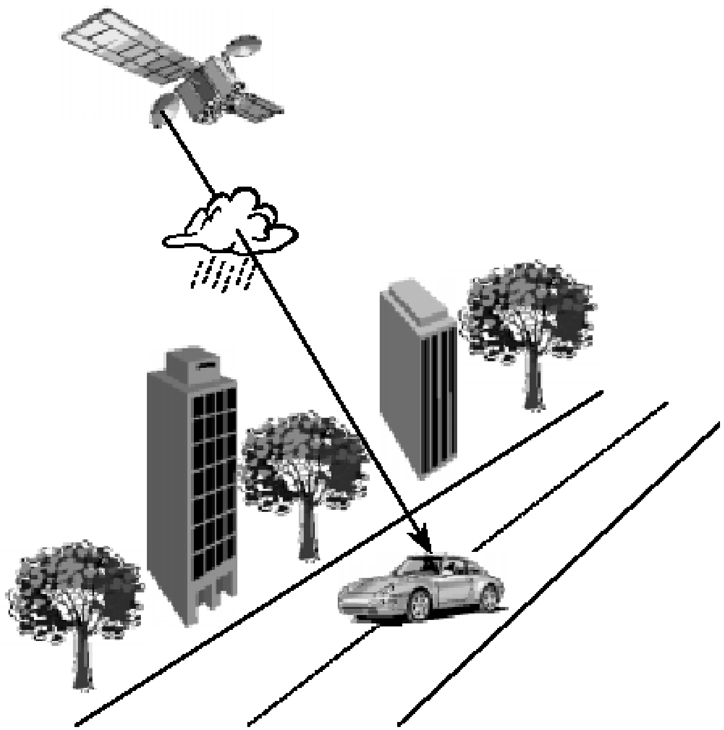
Step 4: Calculate the baseline-dependent term from the expression:

$$G_\psi = 1 + 0.002\,\psi \qquad (16)$$

Step 5: Compute the net diversity gain as the product:

$$G = G_d \cdot G_f \cdot G_\theta \cdot G_\psi \quad \text{dB} \qquad (17)$$

Družicová mobilní služba



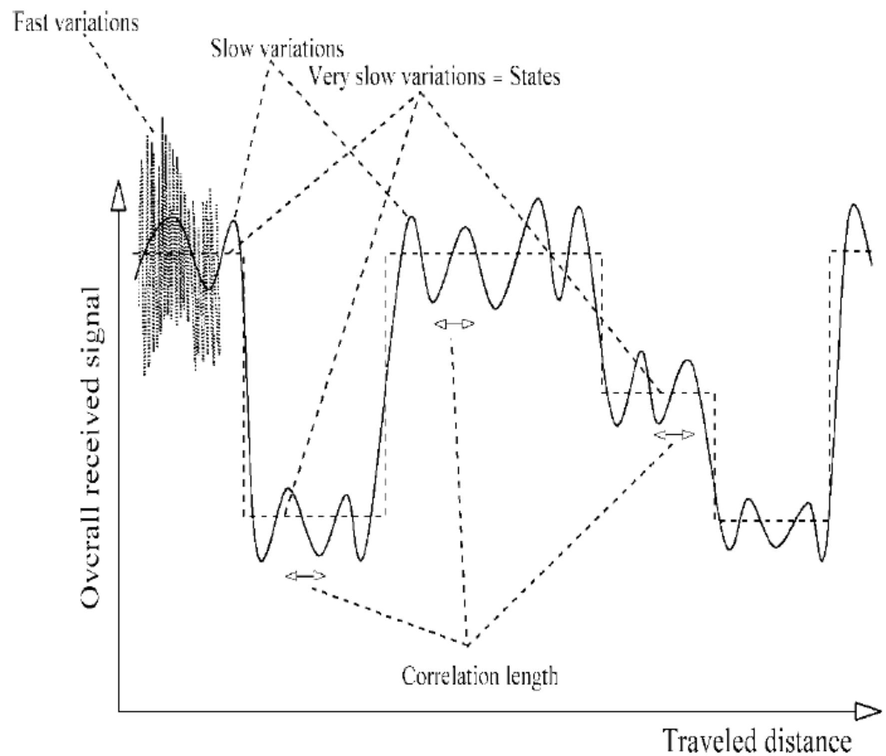
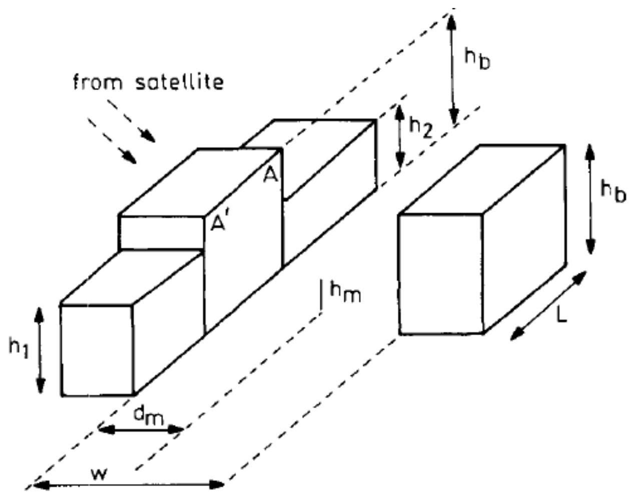
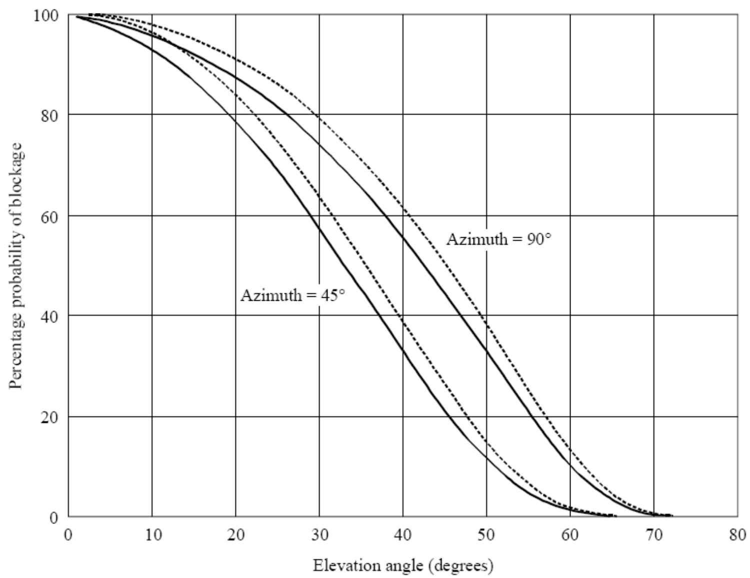


Fig. 3. Signal amplitude variations of a land Mobile Satellite scenario.

Roadside Shadowing Model



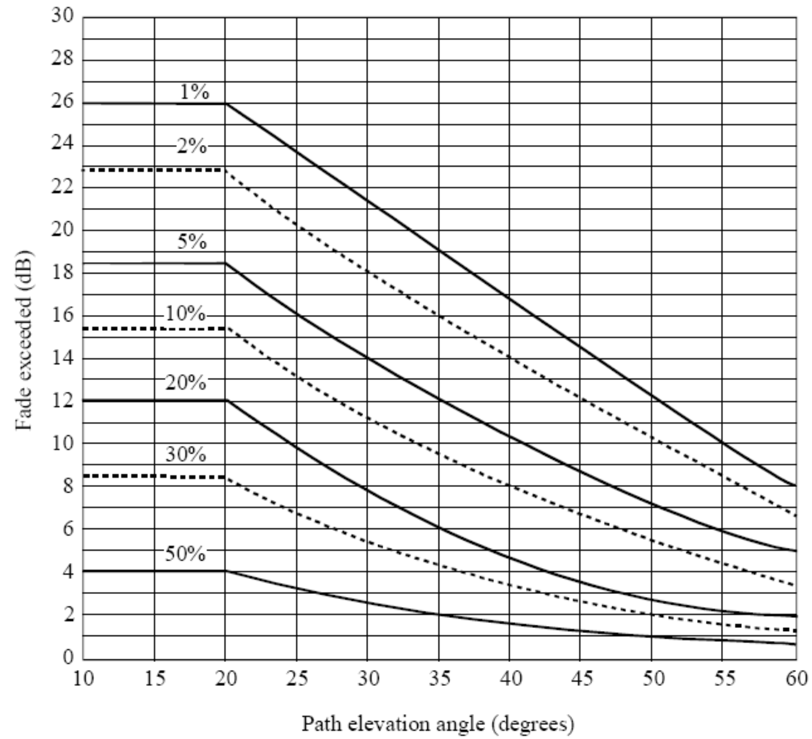
Examples of roadside building shadowing
(see text for parameter values)



- - - - - - Blockage assumed to occur at 0.7 Fresnel zone clearance
——— Blockage assumed to occur at zero Fresnel zone clearance

0681-04

Fading at 1.5 GHz due to roadside shadowing versus path elevation angle



0681-01

Definition of the propagation states are as follows:

State A: clear line-of-sight condition

State B: slightly shadowed condition (by trees and/or small obstacles such as utility poles)

State C: fully blocked condition (by large obstacles such as mountains and buildings).

The following parameters are required:

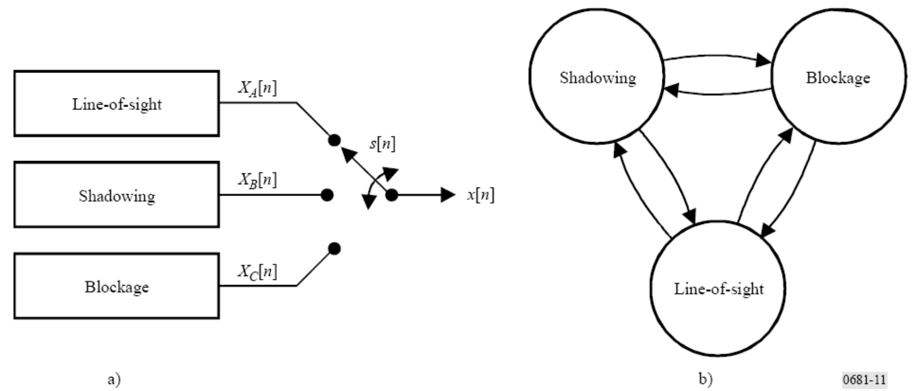
P_A, P_B and P_C: occurrence probability of States A, B and C

$M_{r,A}$, $M_{r,B}$ and $M_{r,C}$: mean multipath power in States A, B and C

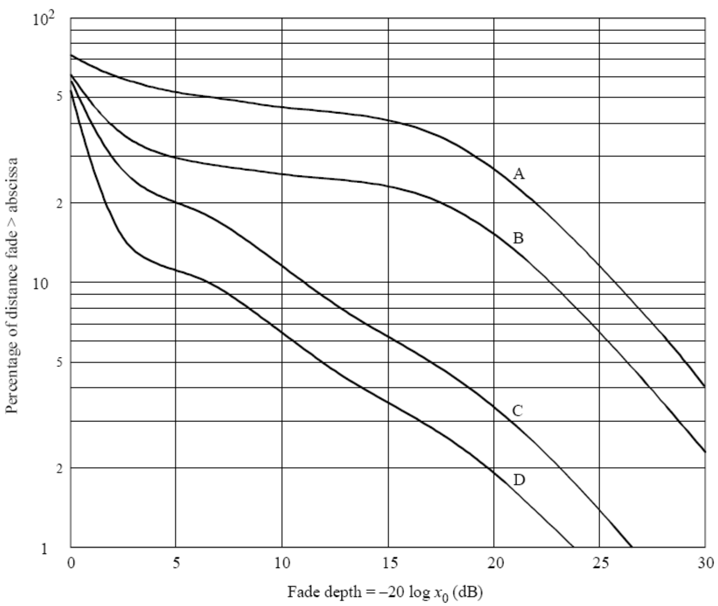
m and σ: mean and standard deviation of signal fading (dB) for the direct wave component in State B

θ: elevation angle (degrees).

Generation of the observed sequence a) and state transition diagram of a semi-Markov chain b)



Calculated examples of fading depth in urban and suburban areas at elevation angles of 30° and 45° (1.5-2.5 GHz; antenna gain ≤ 10 dBi)



Curves A: urban, 30°
B: urban, 45°
C: suburban, 30°
D: suburban, 45°

0681-12

Parameters for state duration distributions and state transition probabilities

	State A		State B		State C		Transition probabilities					
Environment	β	γ	α	σ	α	σ	$P_{A\to B}$	$P_{A\to C}$	$P_{B\to A}$	$P_{B\to C}$	$P_{C\to A}$	$P_{C\to B}$
Suburban (I)	0.88	0.61	1.73	1.11	2.62	0.98	1	0	0.65	0.35	0	1
Suburban (II)	0.83	0.66	1.89	0.93	3.28	1.04	1	0	0.65	0.35	0	1
Wooded	0.60	0.84	2.05	1.05	1.55	1.02	1	0	0.42	0.58	0	1

Based on comparison with fade and non-fade durations given in § 4.1, the state duration distributions are as follows:

The power-law distribution for State A duration is:

$$P_A(D \le d) = 1 - \beta d^{-\gamma} \tag{19}$$

where the parameters β and γ depend on the degree of optical shadowing and $d > \beta^{1/\gamma}$.

The duration distribution for States B and C is a log-normal model valid for $d \ge 0.1$ m:

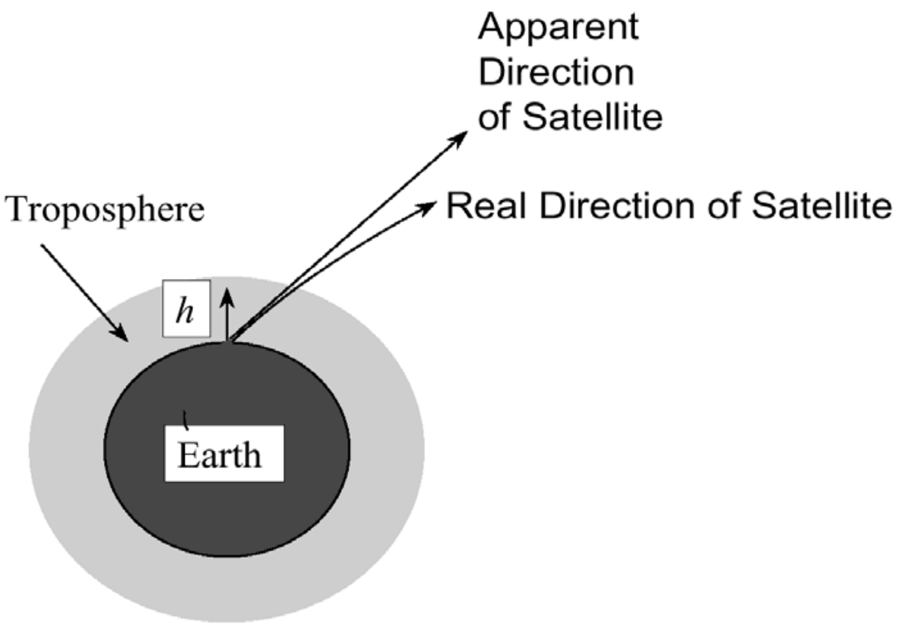
$$P_{B,C}(D \le d) = (1 + \mathrm{erf}[(\ln(d) - \ln(\alpha)) / \sqrt{2}\sigma]) / 2 \tag{20}$$

where σ is the standard deviation of $\ln(d)$, $\ln(\alpha)$ is the mean value of $\ln(d)$ and the erf is as defined in Recommendation ITU-R P.1057.

Vlivy šíření podle služby

- Pevný spoj, *Fixed SatCom Services*
  - Srážky
  - Oblaka
  - Diverzita
- Mobilní spoj, *Mobile Satellite Services*
  - Zastínění (Shadowing, blockage)
  - Vícecestné šíření
- Navigace, *Satellite Navigation Services*
  - Ionosféra
  - Troposféra

Troposférická refrakce a družicový spoj



Angular deviation values for propagation through the total atmosphere

Elevation angle, θ (degrees)	Average total angular deviation, Δθ (degrees)			
	Polar continental air	Temperate continental air	Temperate maritime air	Tropical maritime air
1	0.45	–	–	0.65
2	0.32	0.36	0.38	0.47
4	0.21	0.25	0.26	0.27
10	0.10	0.11	0.12	0.14
20		0.05	0.06	
30		0.03	0.04	

Rec. ITU-R P.834-5

Prodloužení délky vertikální dráhy vlny (Země-družice) vlivem troposféry

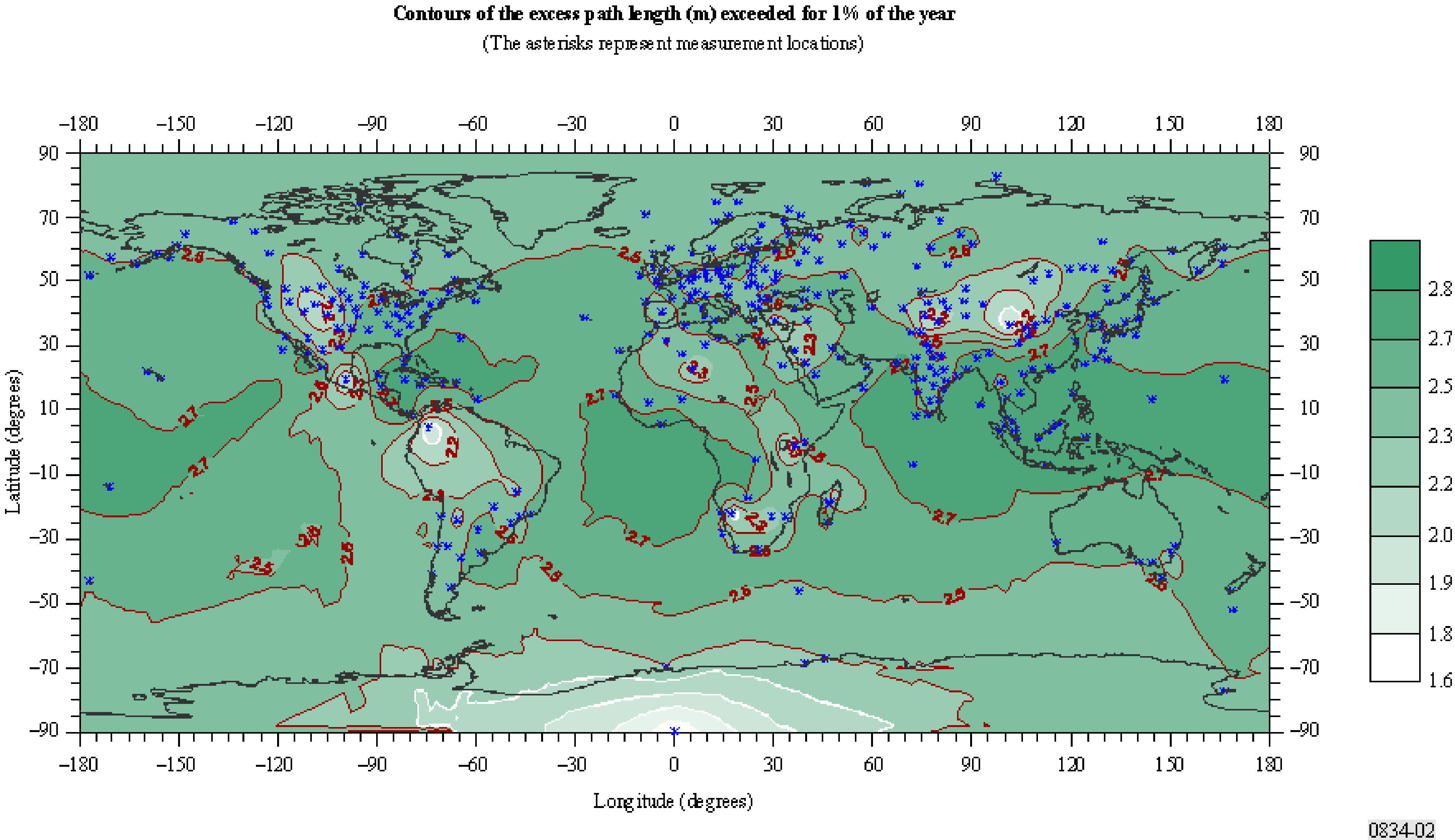
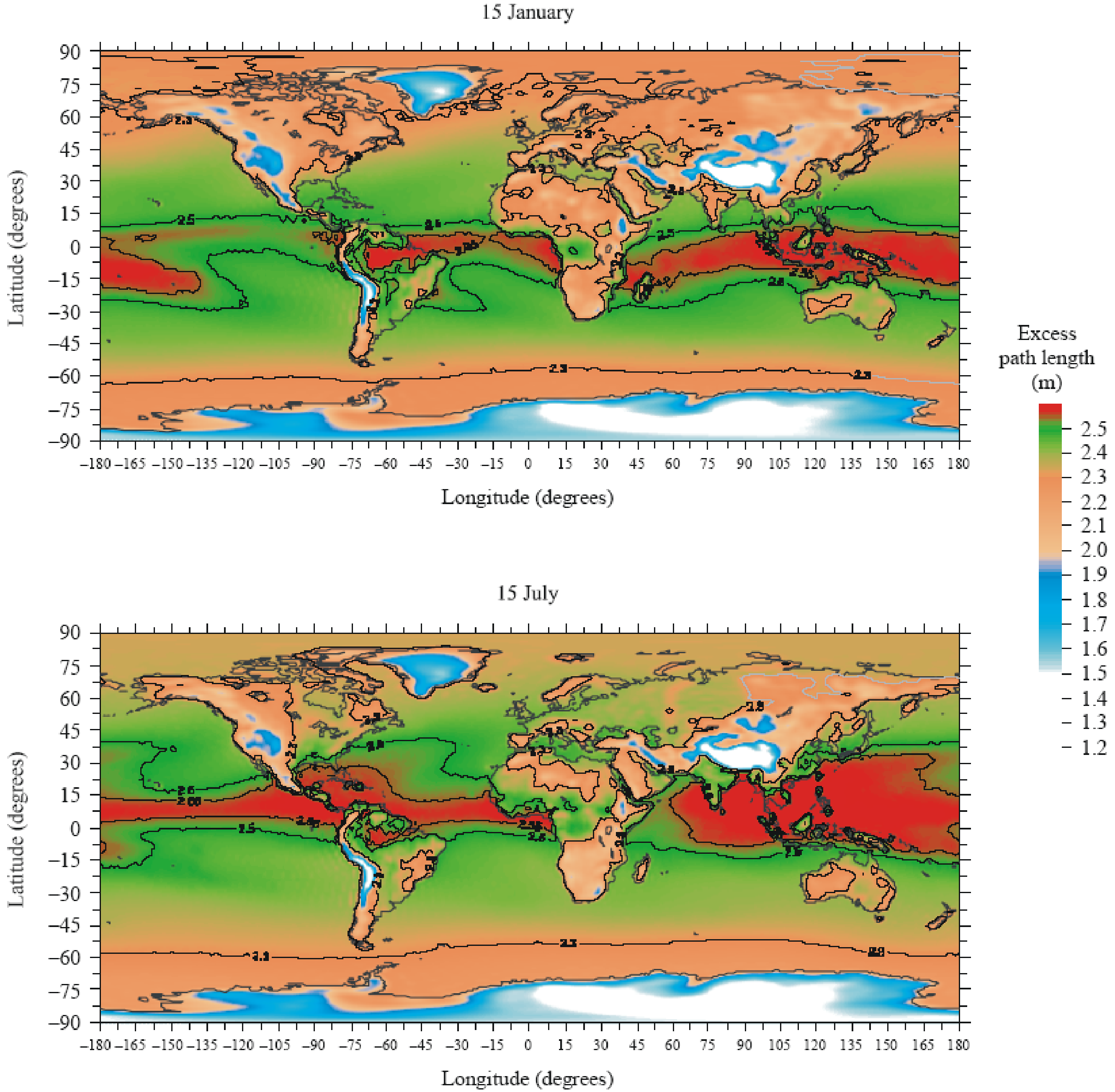


FIGURE 2

Maps of the average excess path delay at reference level in January and July



Vliv ionosféry na družicový spoje (dle ITU-R)

TABLE 1

Estimated* ionospheric effects for elevation angles of about 30° one-way traversal**

(derived from Recommendation ITU-R P.531)

Effect	Frequency dependence	0.1 GHz	0.25 GHz	0.5 GHz	1 GHz	3 GHz	10 GHz
Faraday rotation	$1/f^2$	30 rotations	4.8 rotations	1.2 rotations	108°	12°	1.1°
Propagation delay	$1/f^2$	25 μs	4 μs	1 μs	0.25 μs	0.028 μs	0.0025 μs
Refraction	$1/f^2$	< 1°	< 0.16°	< 2.4′	< 0.6′	< 4.2″	< 0.36″
Variation in the direction of arrival (r.m.s.)	$1/f^2$	20′	3.2′	48″	12″	1.32″	0.12″
Absorption (auroral and/or polar cap)	$\approx 1/f^2$	5 dB	0.8 dB	0.2 dB	0.05 dB	6×10^{-3} dB	5×10^{-4} dB
Absorption (mid-latitude)	$1/f^2$	< 1 dB	< 0.16 dB	< 0.04 dB	< 0.01 dB	< 0.001 dB	$< 1 \times 10^{-4}$ dB
Dispersion	$1/f^3$	0.4 ps/Hz	0.026 ps/Hz	0.0032 ps/Hz	0.0004 ps/Hz	1.5×10^{-5} ps/Hz	4×10^{-7} ps/Hz
Scintillation[(1)]	See Rec. ITU-R P.531	See Rec. ITU-R P.531	See Rec. ITU-R P.531	See Rec. ITU-R P.531	> 20 dB peak-to-peak	≈ 10 dB peak-to-peak	≈ 4 dB peak-to-peak

* This estimate is based on a TEC of 10^{18} electrons/m^2, which is a high value of TEC encountered at low latitudes in daytime with high solar activity

** Ionospheric effects above 10 GHz are negligible.

(1) Values observed near the geomagnetic equator during the early night-time hours (local time) at equinox under conditions of high sunspot number.

Pozn.: 0,1 μs = 30 m (GPS ~ 1,5 GHz)