LINK BUDGET CALCULATIONS

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PERFORMANCE

- characteristics of
  - TX station
  - RX station
- propagation
- noise, interference
- characteristics of satellite

NOISE

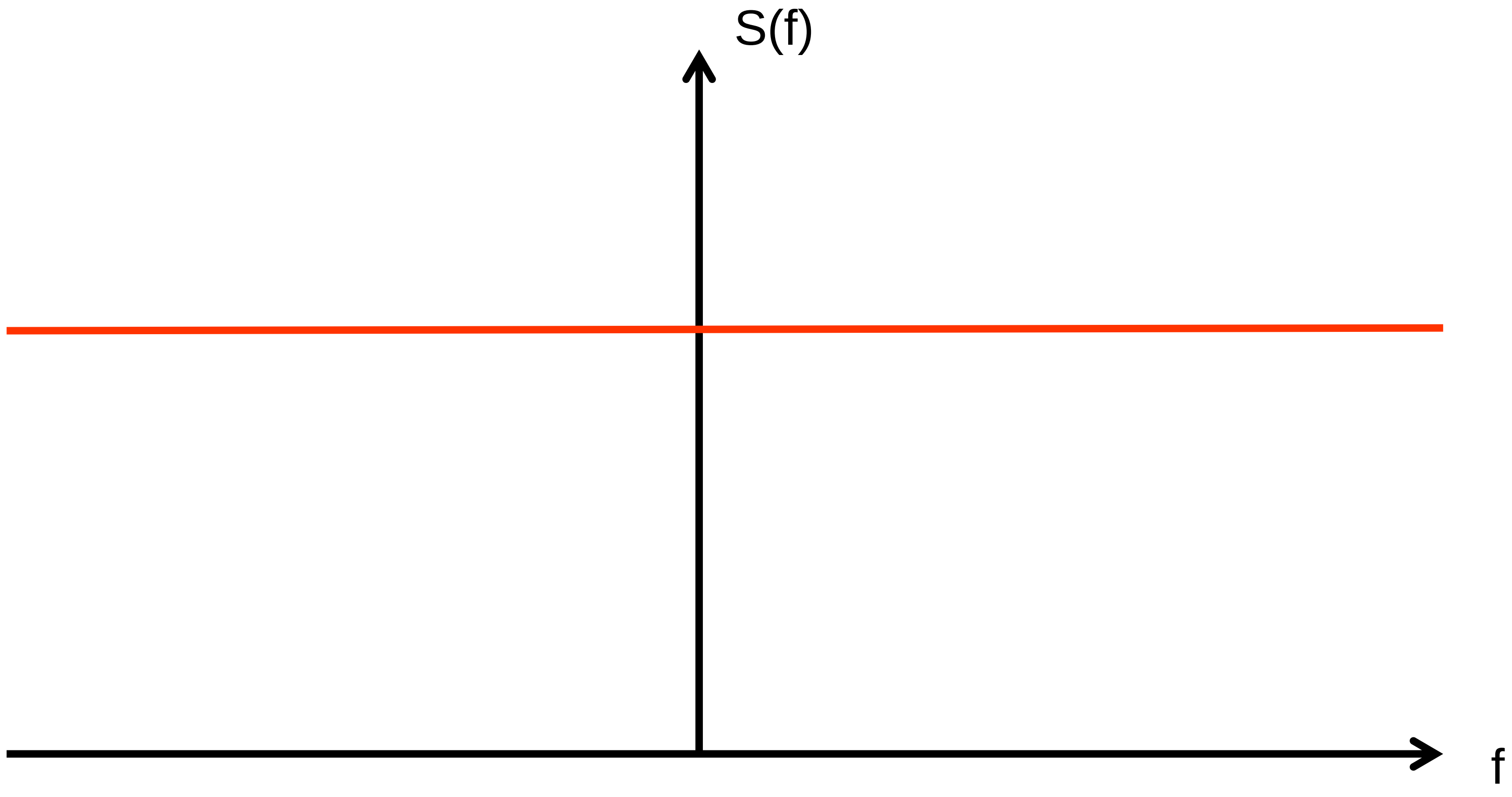
- noise voltage

$$\overline{u_n^{\,2}} = 4kTBR$$

k = 1.38 10^{-23} J/K, Boltzmann constant
B... noise bandwidth
R...resistance
T...absolute temperature

- independent of frequency, “white” noise

NOISE

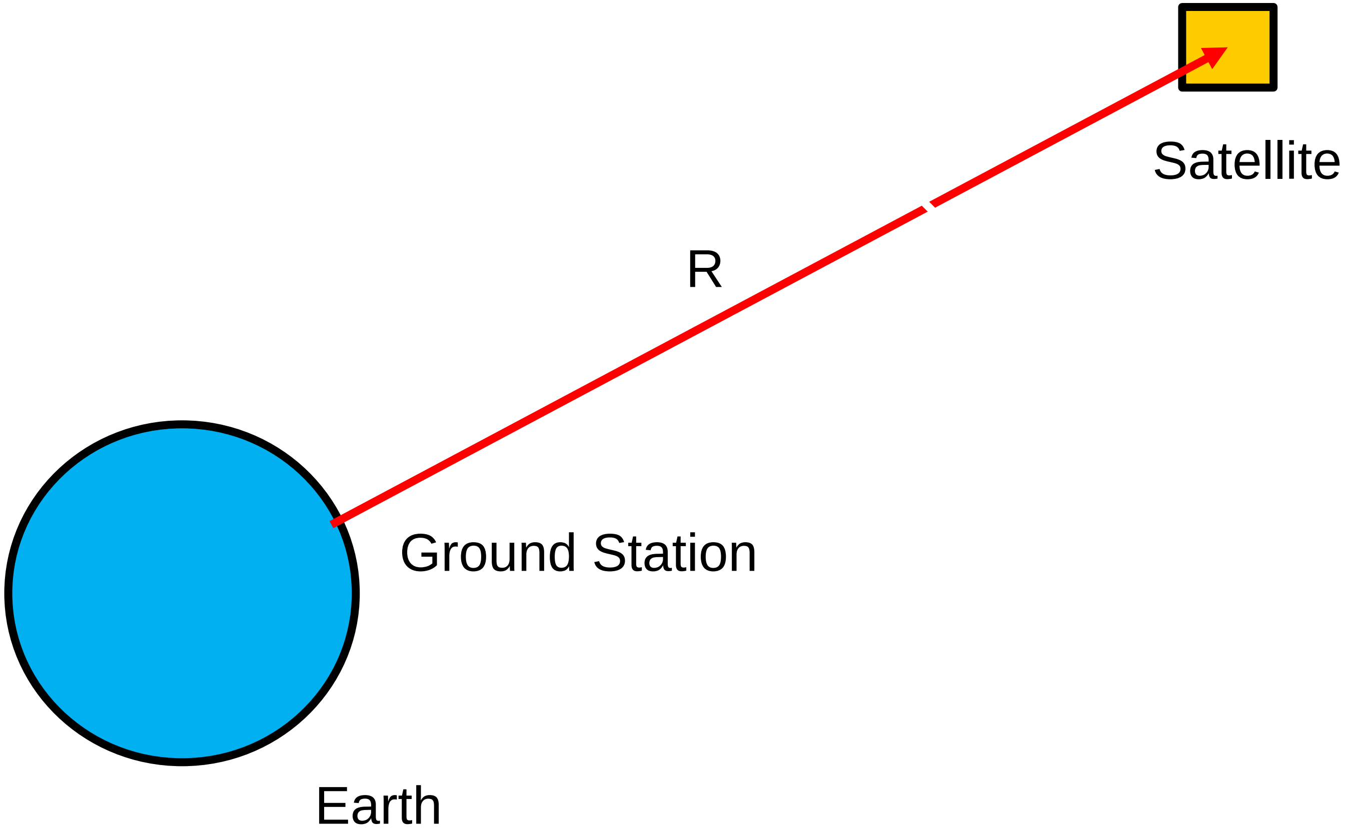


NOISE

- at very high frequencies thermal noise vanishes, only quantum noise remains
- Noise power

$$N = N_0 B = kTB$$

UPLINK
EARTH - SPACE



CARRIER POWER

- Inverse square law
- C…Carrier power (S…signal)
- P_T…transmit power
- A_{eff}... effective antenna aperture
- R...distance
- G_T...transmit antenna gain

$$C = \frac{P_T}{4\pi R^2} G_T A_{eff}$$

ANTENNA FORMULA

- effective aperture

$$A_{eff} = \frac{G\,\lambda^2}{4\pi} = \eta A$$

$$G = \eta \frac{4\pi}{\lambda^2} \frac{D^2 \pi}{4} = \eta \frac{\pi^2 D^2}{\lambda^2}$$

CARRIER POWER

$$C = \frac{P_T G_T}{4\pi R^2}\left(\frac{G_R \lambda^2}{4\pi}\right)$$

$$EIRP = P_T G_T$$

$$L_s = \left(\frac{4\pi R}{\lambda}\right)^2$$

free-space loss

CARRIER/NOISE RATIO

$$C = \frac{C}{N} N = \frac{C}{N} k T_s B$$

Signal/noise ratio

$$\frac{C}{N} = \frac{P_T G_T}{\left(4\pi R / \lambda\right)^2} \left(\frac{G_R}{T_s}\right) \frac{1}{kB}$$

Signal/noise density

$$\frac{C}{N_o} = \frac{P_T G_T}{\left(4\pi R / \lambda\right)^2} \left(\frac{G_R}{T_s}\right) \frac{1}{k}$$

FIGURE OF MERIT

- G/T [dB/K]
- important characteristic for
  - satellite
  - ground station

LINK BUDGET CALCULATION

- figures may vary widely
  - EIRP high
  - free-space loss very high
  - receive carrier power very low
- logarithmic representation advantageous

LOGARITHMIC REPRESENTATION

- Signal-to-noise ratio [dB]

$$\frac{C}{N} = 10\log(P_T) + 10\log(G_T) - 20\log\left(4\pi R/\lambda\right) + 10\log(G_R)$$

$$-10\log(T_s) - 10\log(k) - 10\log(B)$$

$$\frac{C}{N} = EIRP_{[dBW]} - L_{[dB]} + \left(G/T\right)_{[dB/K]} - k_{[dBJ/K]} - B_{[dBHz]}$$

C/N_o

- carrier power / noise density
- Normaliset to 1 Hz noise bandwidth

$$\frac{C}{N_o} = EIRP_{[dBW]} - L_{s[dB]} + (G/T)_{[dB/K]} - k_{[dBJ/K]}$$

C/T

- sometimes used in link budgets
- in [dBW/K]
- leaves out *k = -228.6 dB(J/K)*
- at the end of calculation B, k considered

$$\frac{C}{T} = EIRP_{[dBW]} - L_{s[dB]} + \left(G/T\right)_{[dB/K]}$$

E_b/N_o

- energy contrast ratio
- energy per bit / noise density
- r...rate of information rate (not necessarily channel rate)

$$\frac{E_b}{N_o} = \frac{C}{N}\frac{B}{r}$$

EXAMPLE (1)

- P = 10 W
- G = 18 dB

$$EIRP = 10\log(10) + 18 = 28dBW = 58dBm$$

Corresponds to 631 W!

EXAMPLE (2)

- free-space loss
- Distance: 1000 km
- f = 438 MHz, λ= 0.68 m

$$L_s = 10\log\left(\frac{4\pi R}{\lambda}\right)^2 = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 1E6}{0.68}\right) =$$

= 145.3 dB

EXAMPLE (3)

- free-space loss, distance = 1000 km
- f = 2.4 GHz, l = 0.125 m

$$L_s = 10\log\left(\frac{4\pi R}{\lambda}\right)^2 = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 1E6}{0.125}\right) =$$

= 160 dB

EXAMPLE (4)

- free-space loss, distance = 1000 km
- f = 8 GHz, l = 0.0375 m

$$L_s = 10\log\left(\frac{4\pi R}{\lambda}\right)^2 = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 1E6}{0.0375}\right) =$$

= 170.5 dB

EXAMPLE (5)

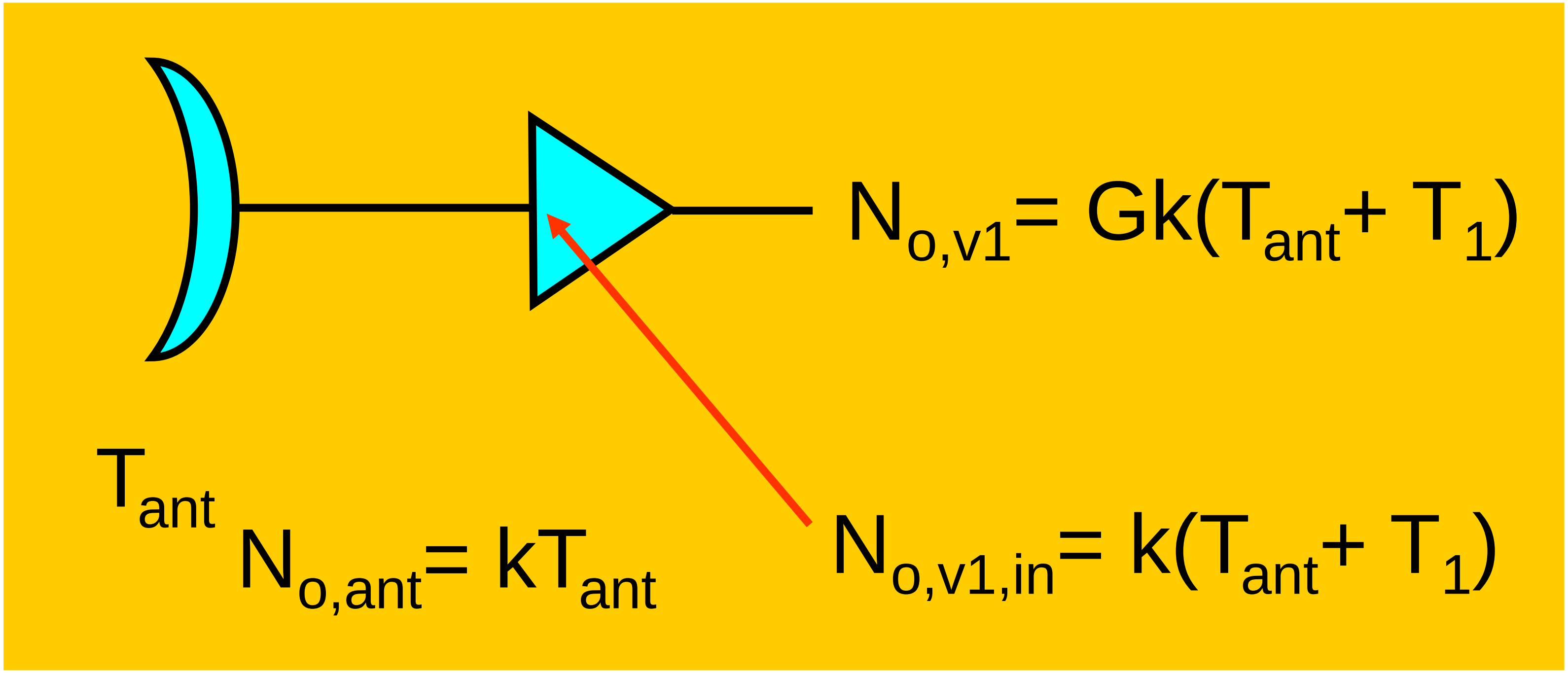
- free-space loss, distance = 1000 km
- f = 8 GHz, l = 0.0375 m

$$L_s = 10\log\left(\frac{4\pi R}{\lambda}\right)^2 = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 2E6}{0.0375}\right) =$$

= 176.5 dB

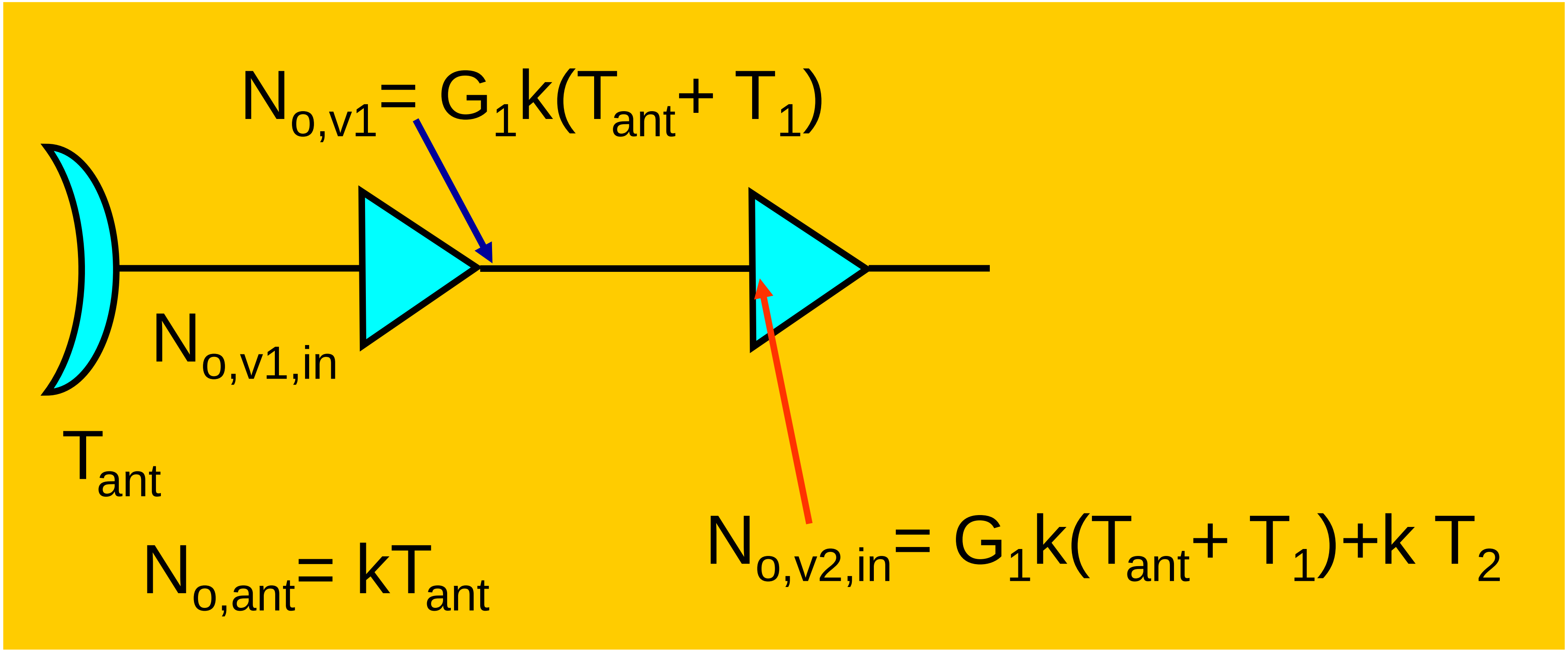
RECEIVER G/T

- amplifier and antenna



RECEIVER G/T

- cascaded amplifiers and antenna



SYSTEM NOISE TEMPERATURE

- referred to input of first stage

$$N_{o,v1,in} = k(T_{ant} + T_1 + T_2/G_1)$$

Friis formula

$$T_{sys} = T_{ant} + T_1 + T_2/G_1$$

$$T = (F - 1)T_o$$

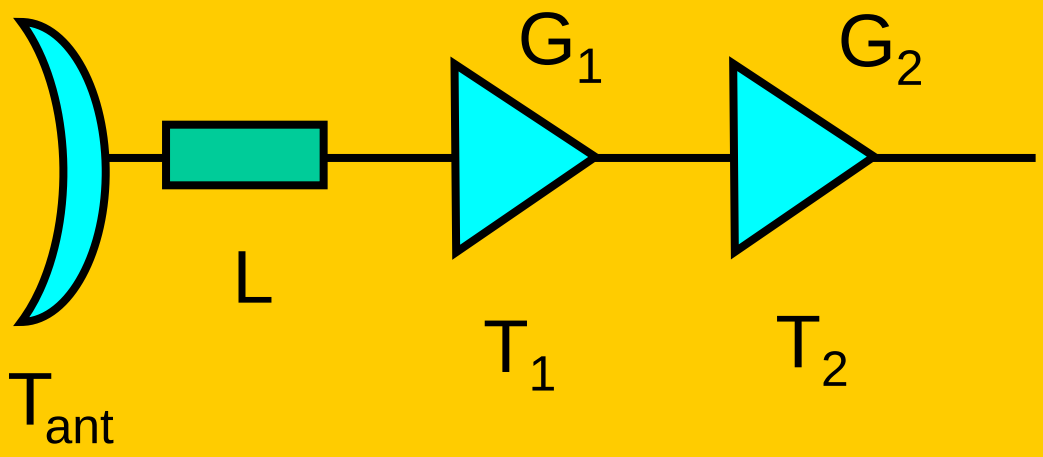
LOSSY SYSTEMS

- lossy lines (e.g. coaxial cables, waveguides)

- L = input power / output power = 1/G
- $T_e = T_{source}$ (L - 1)
- if network (resistor) at T_o : L = F,

  T=(F-1).290 = (L-1).290

RECEIVER WITH LOSSY LINES



$$T_{sys} = T_{ant} + T_L + L T_1 + \frac{L T_2}{G_1}$$

EXAMPLE A

- $T_{ant} = 150$ K
- $T_1 = 200$ K
- $G_1 = 25$ dB
- $F_2 = 8$ dB
- $G_2 = 40$ dB
- $L = 1$ dB

RESULT A

$$T_{sys} = T_{ant} + T_L + L T_1 + \frac{L T_2}{G_1}$$

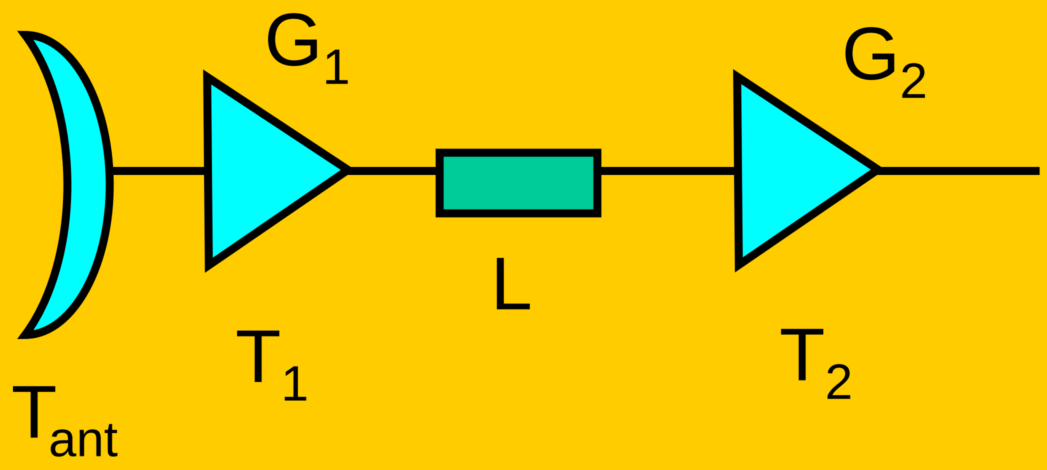
$$T_L = (F-1)290 = (L-1)290 = (10^{\frac{1}{10}} - 1)290 = 75K$$

$$T_2 = (F_2 - 1)290 = (10^{\frac{8}{10}} - 1)290 = 1539.8K$$

$$T_{sys} = 150 + 75 + 200.10^{\frac{1}{10}} + \frac{1.258.1539.8}{10^{\frac{25}{10}}}$$

$$T_{sys} = 483K$$

EXAMPLE B



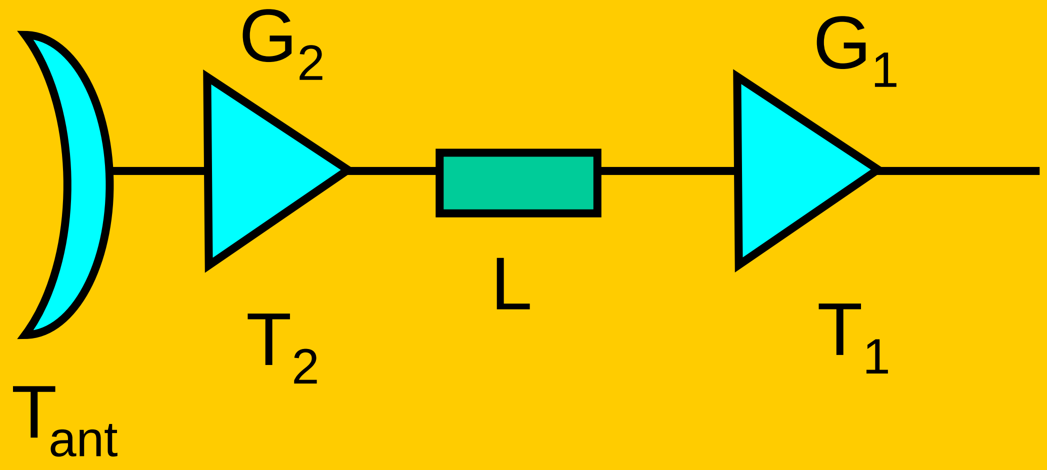
$$T_{sys} = T_{ant} + T_1 + \frac{T_L}{G_1} + \frac{L T_2}{G_1}$$

RESULT B

$$T_{sys} = 150 + 200 + \frac{75}{10^{\frac{25}{10}}} + \frac{1.258.1539.8}{10^{\frac{25}{10}}}$$

$$T_{sys} = 356K$$

EXAMPLE C



$$T_{sys} = T_{ant} + T_2 + \frac{T_L}{G_2} + \frac{L T_1}{G_2}$$

RESULT C

$$T_{sys} = 150 + 1539.8 + \frac{75}{10^{\frac{40}{10}}} + \frac{1.258.200}{10^{\frac{40}{10}}}$$

$$T_{sys} = 1670K$$

RESULT C

$$T_{sys} = 150 + 1539.8 + \frac{75}{10^{\frac{40}{10}}} + \frac{1.258.200}{10^{\frac{40}{10}}}$$

$$T_{sys} = 1670K$$

CONCLUSION

- Avoid losses in front of LNA
- Use LNA with lowest possible NF
- Use LNA with highest possible gain

SATELLITE ANTENNA NOISE TEMP.

- Noise from earth
- Noise captured from outer space
- Oceans radiate more noise than land masses
- Conservative figure: 290 K

G/T (spacecraft)

- Satellite antenna gain: 0 dB
- Tsys = 483 K (from example A)
- G/T = 0 – 10log(483) = - 26.8 dB/K

C/N

- f = 438 MHz
- G_T= 18 dB
- P = 10 W = 10 dBW
- R = 1000 km
- G/T = -26.8 dB/K
- B = 200 kHz = 10log(200000) = 53 dBHz

$$\frac{C}{N} = EIRP_{[dBW]} - L_{s[dB]} + \left(G/T\right)_{[dB/K]} - k_{[dBJ/K]} - B_{[dBHz]}$$

$$\frac{C}{N} = 28 - 145.3 - 26.8 - (-228.6) - 53 = 31.5dB$$

C/N$_o$

- normalized to 1 Hz noise bandwidth

$$\frac{C}{N_0} = 28 - 145.3 - 26.8 - (-228.6) = 84.5 dBHz$$

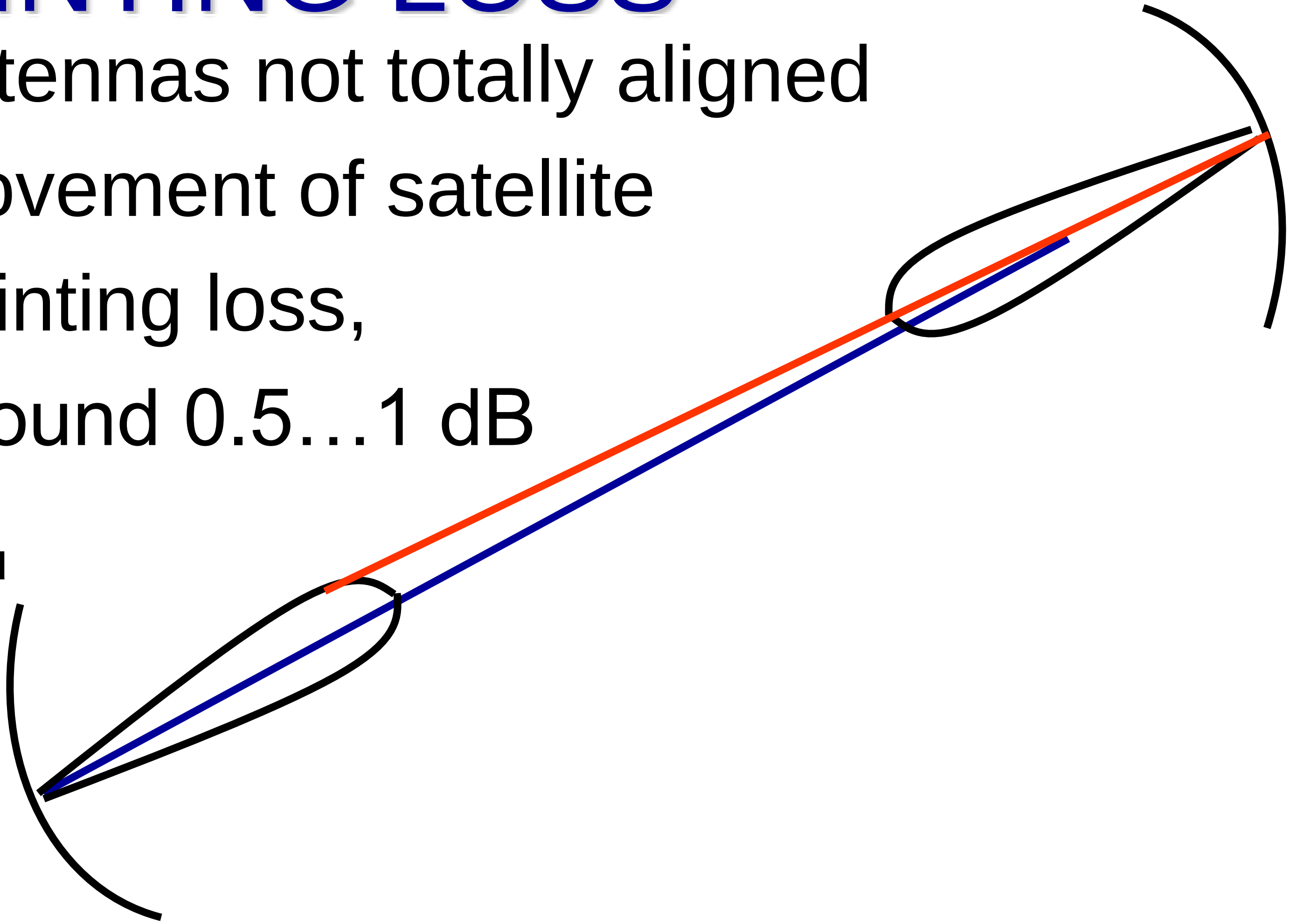
ADDITIONAL LOSSES

POLARIZATION LOSS

- If polarization plane of TX antenna and RX antenna are misaligned
- L_{pol}
- If TX and RX are circular: no loss

POINTING LOSS

- antennas not totally aligned
- movement of satellite
- pointing loss,
- Around 0.5…1 dB
- L_{pu}



ATMOSPHERIC ATTENUATION

- gaseous absorption in atmosphere
- attenuation by hydrometeors
- depending on rain rate, drop size, frequency
- L_{atu}

PROPAGATION EFFECTS

- Influence by troposphere
  - region up to 15 km
  - absorption
  - depolarization
- Influence by ionosphere
  - much less significant

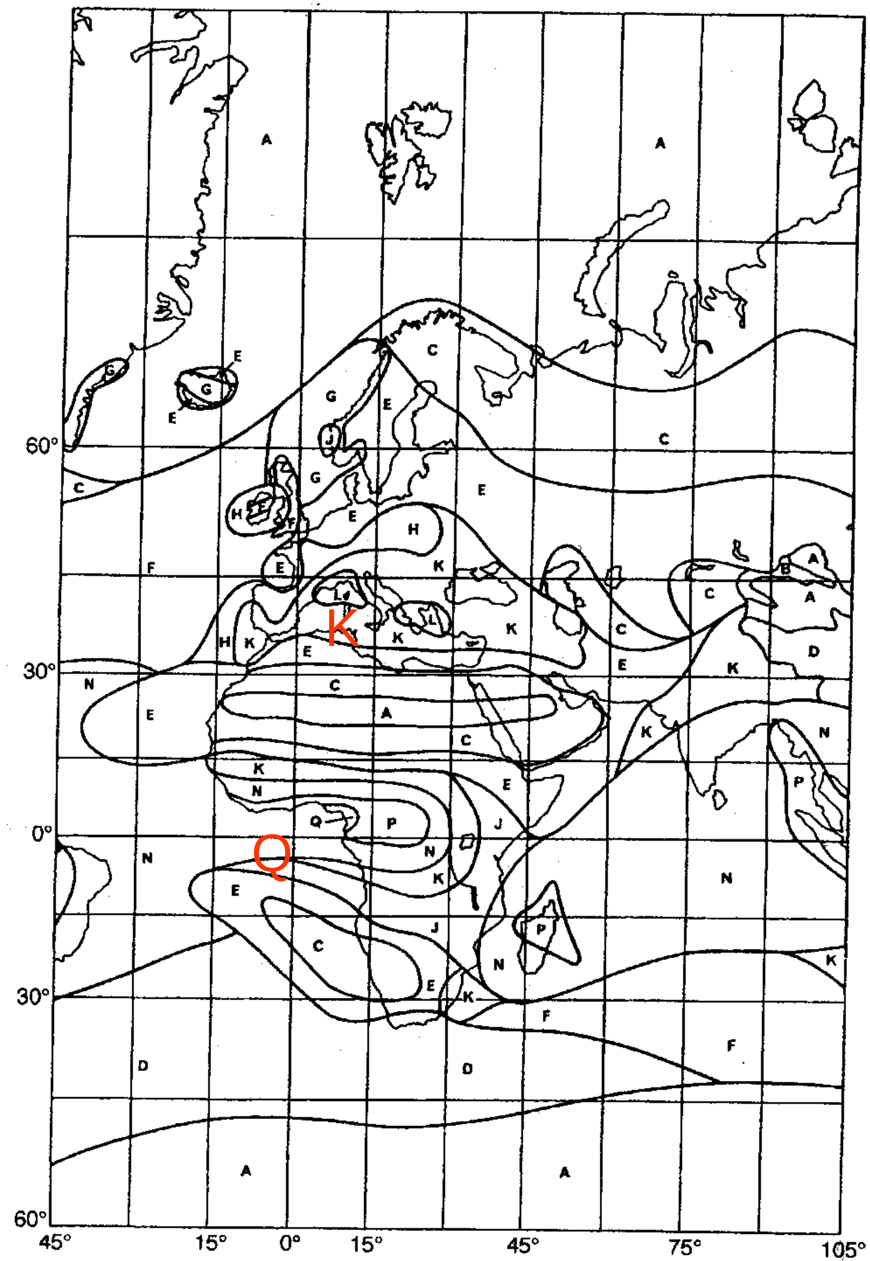
PRECIPITATION

- rain drop size important
- hail produces very significant attenuation
- wet snow
- dry snow less critical

PRECIPITATION

- Occurrence of precipitation defined by percentage of time during which a given intensity is exceeded
- Rain rate in mm/h
- Different climatic zones
- Measurements necessary for each zone

EUROPE
AFRICA



(b)

Figure 2.23 *(cont.)*

AMERICAS

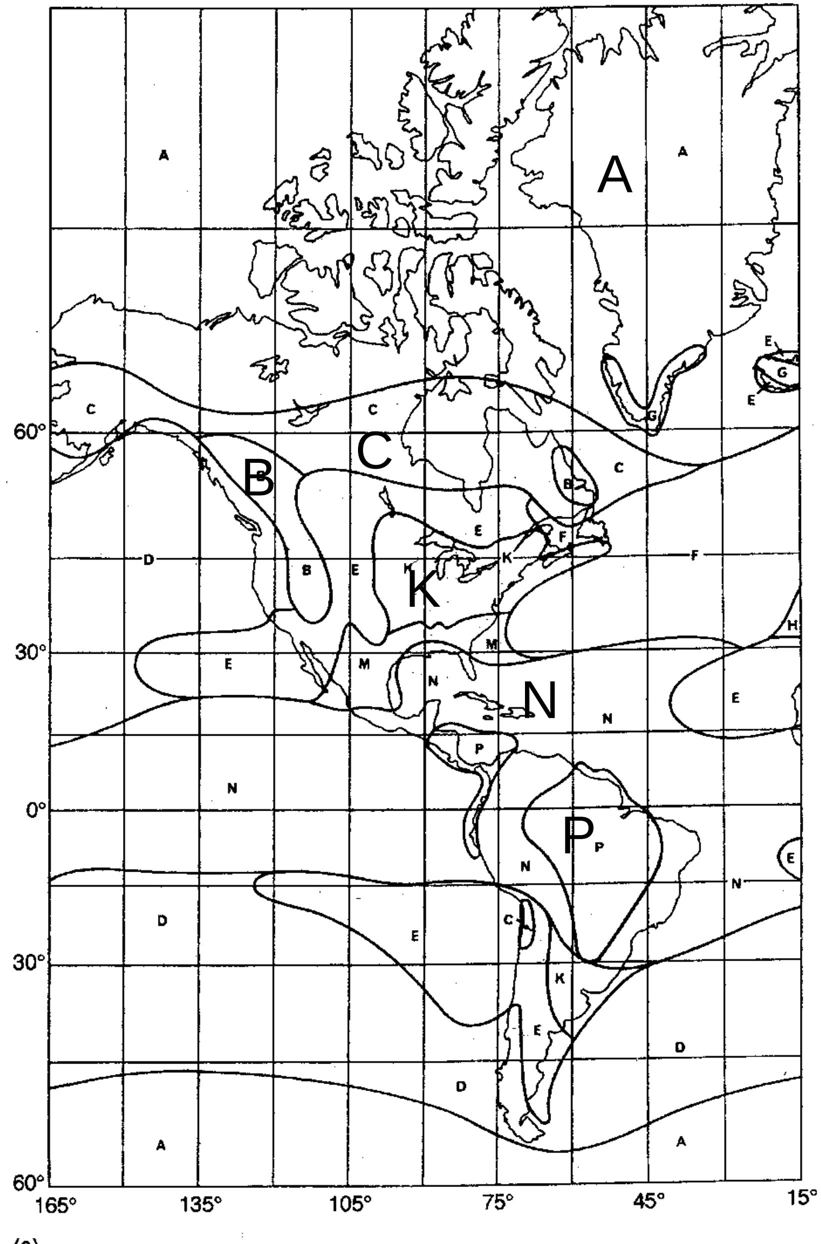
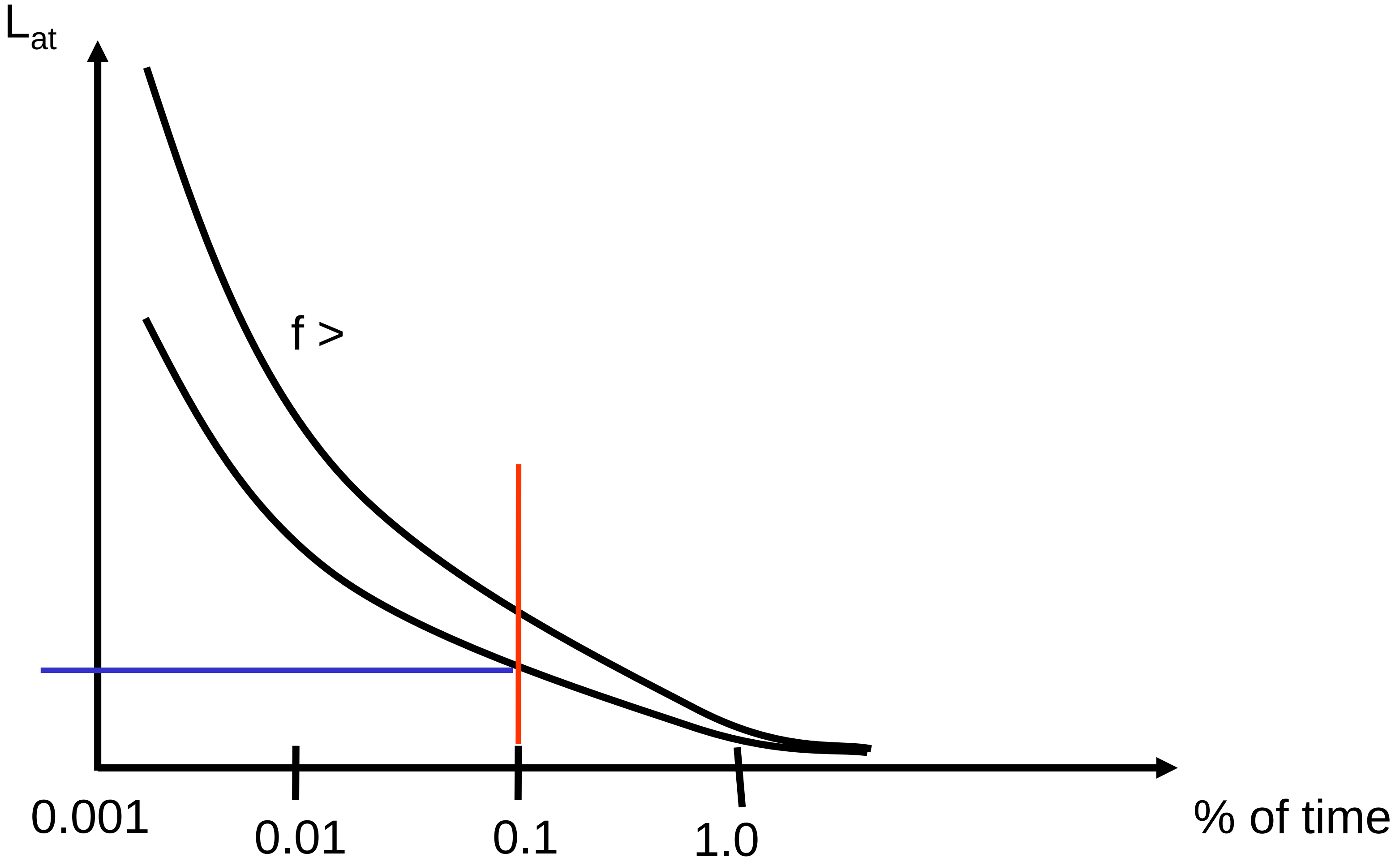


Figure 2.23 Climatic zones [Rec. ITU-R. PN837].

CUMULATIVE STATISTICS



CLEAR SKY ATTENUATION

- Depends on
  - frequency
  - elevation angle
  - atmosphere
    - pressure
    - temperature
    - water vapour content

IONOSPHERIC LOSSES

- Interaction between charged particles and electromagnetic wave
- Absorption, Faraday rotation, szintillation
- At microwave frequencies negligible
- Small effect at VHF/UHF

C/N at SATELLITE

$$\frac{C}{N} = EIRP - L_{su} - L_{pu} - L_{i} - L_{pol} - L_{atu} + \left(G/T\right) - k - B$$

EXAMPLE

- $f = 438$ MHz
- $G_T = 18$ dB
- $P = 10W = 10$ dBW
- $R = 1{,}000{,}000$ m
- $G/T = -26.8$ dB/K
- $L_{pol} = 1.5$ dB
- $L_i = 0.7$ dB
- $L_{pu} = 0.5$ dB
- $L_{atu} = 2$ dB
- $B = 200$ kHz

RESULT

$$\frac{C}{N} = EIRP - L_{su} - L_{pu} - L_{pol} - L_i - L_{atu} + \left(G/T\right) - k - B$$

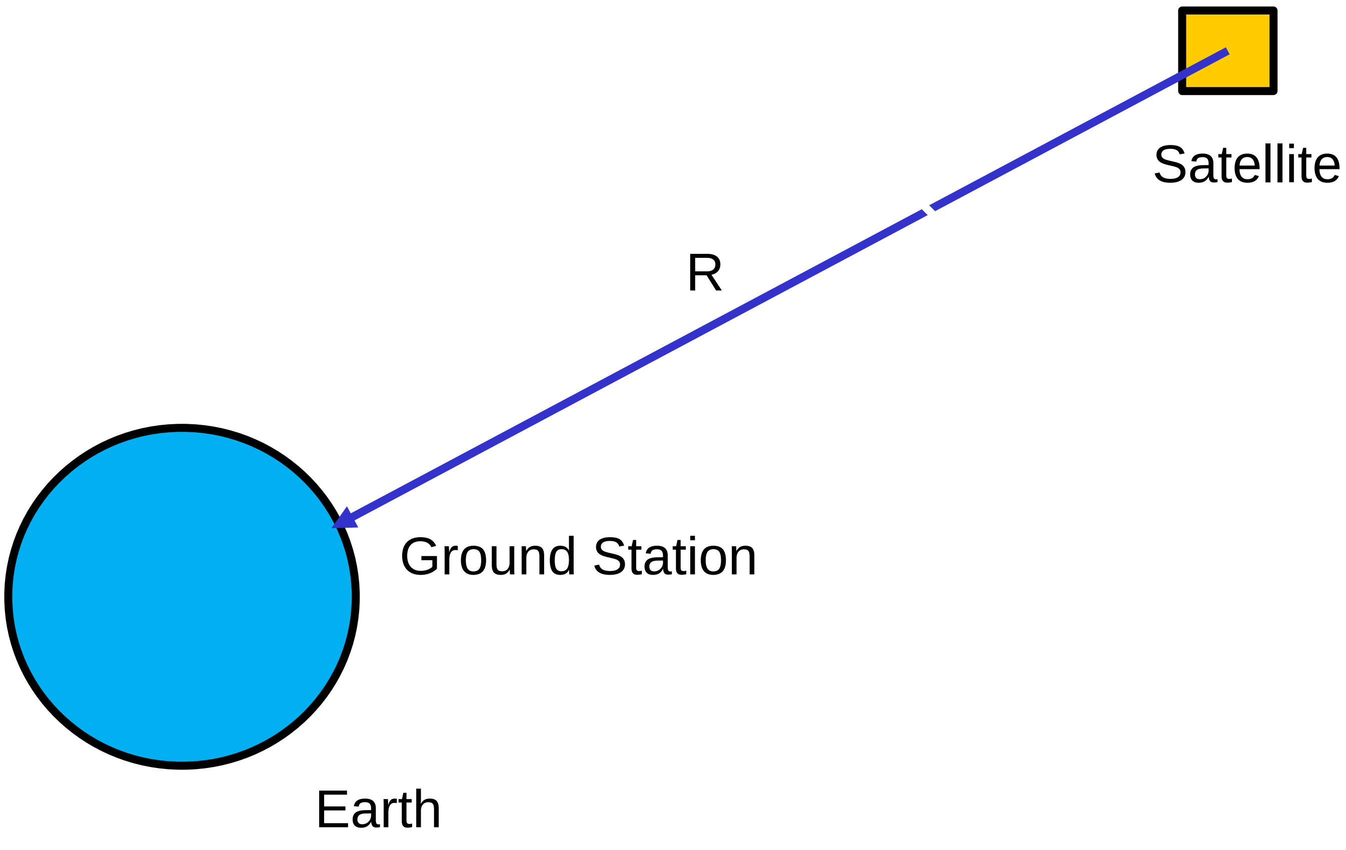
$$\frac{C}{N} = 28 - 145.3 - 0.5 - 1.5 - 0.7 - 2 - 26.8 + 228.6 - 53 = 26.5dB$$

P = 10 W

$$\frac{C}{N} = 18 - 145.3 - 0.5 - 1.5 - 0.7 - 2 - 26.8 + 228.6 - 53 = 16.5dB$$

P = 1 W

DOWNLINK
SPACE - EARTH



SATELLITE EIRP

- Maximum EIRP satellite: specified $EIRP_{sat}$
- EIRP due to drive level:

  $EIRP = EIRP_{sat} – B_{out}$ B_{out}…back-off

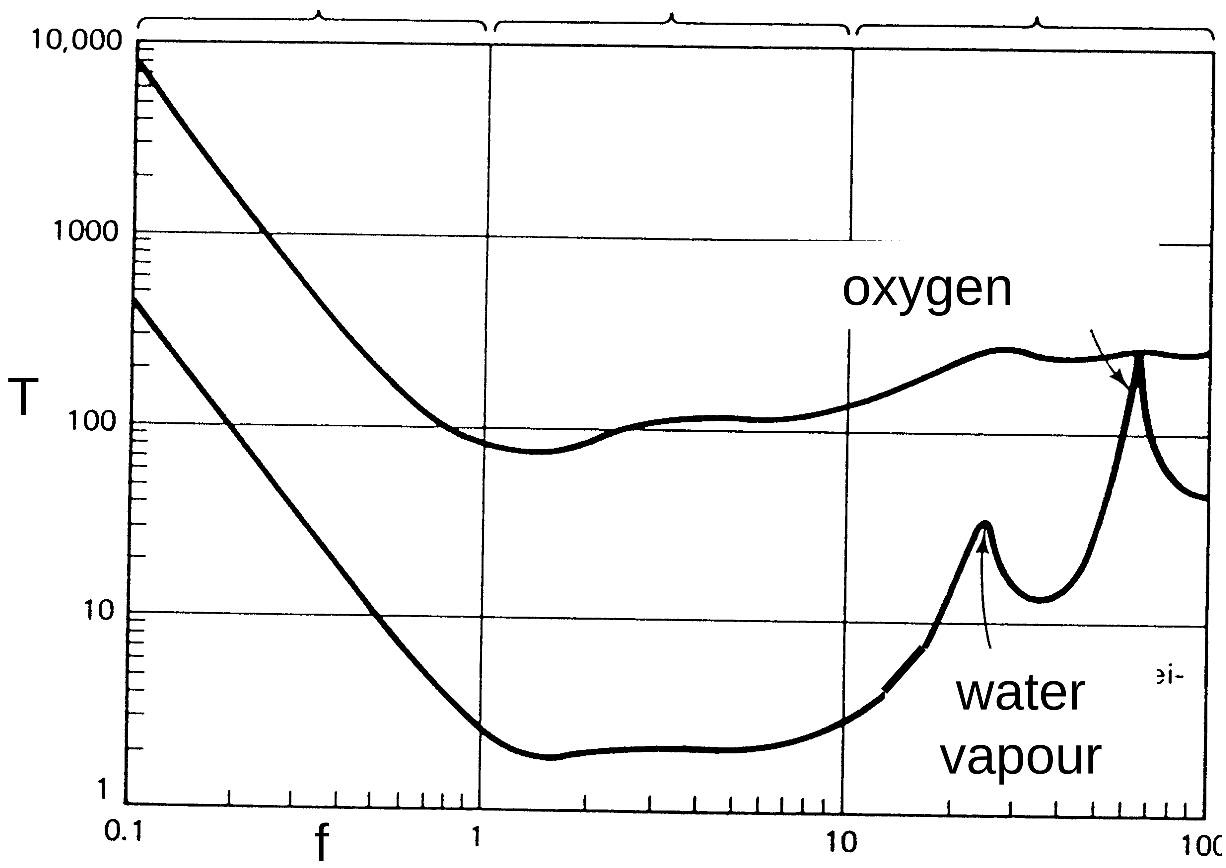
- Example:
- $EIRP_{sat}$ = -3 dBW (0.5 W into 0 dBi antenna)

  EIRP = = -3 – 1 = -4 dBW

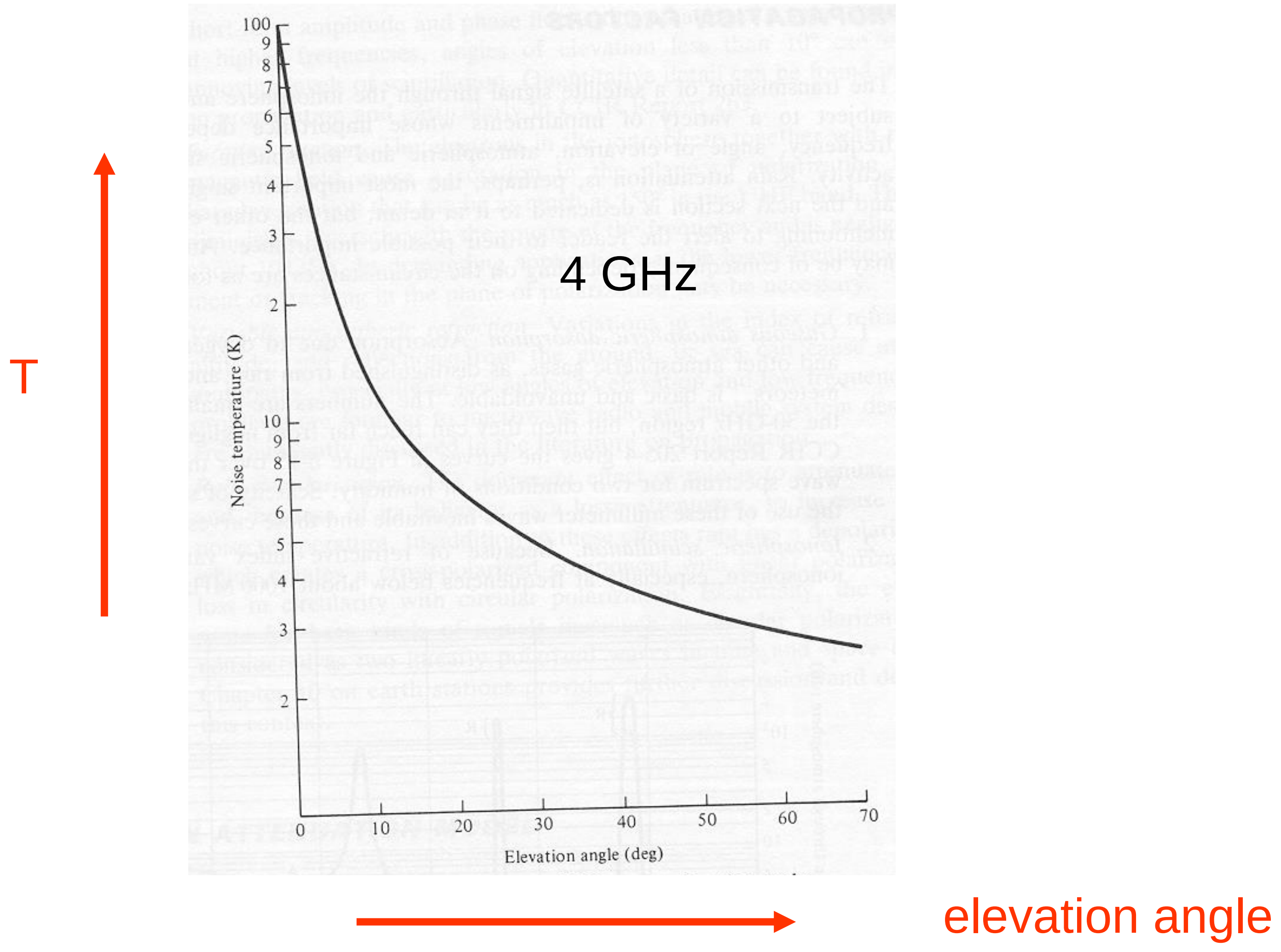
EARTH STATION ANTENNA

- noise from sky
- noise from earth
- above 2 GHz: dominant contribution from non-ionized region of atmosphere
- depends on elevation angle

ANTENNA NOISE



SKY NOISE TEMPERATURE



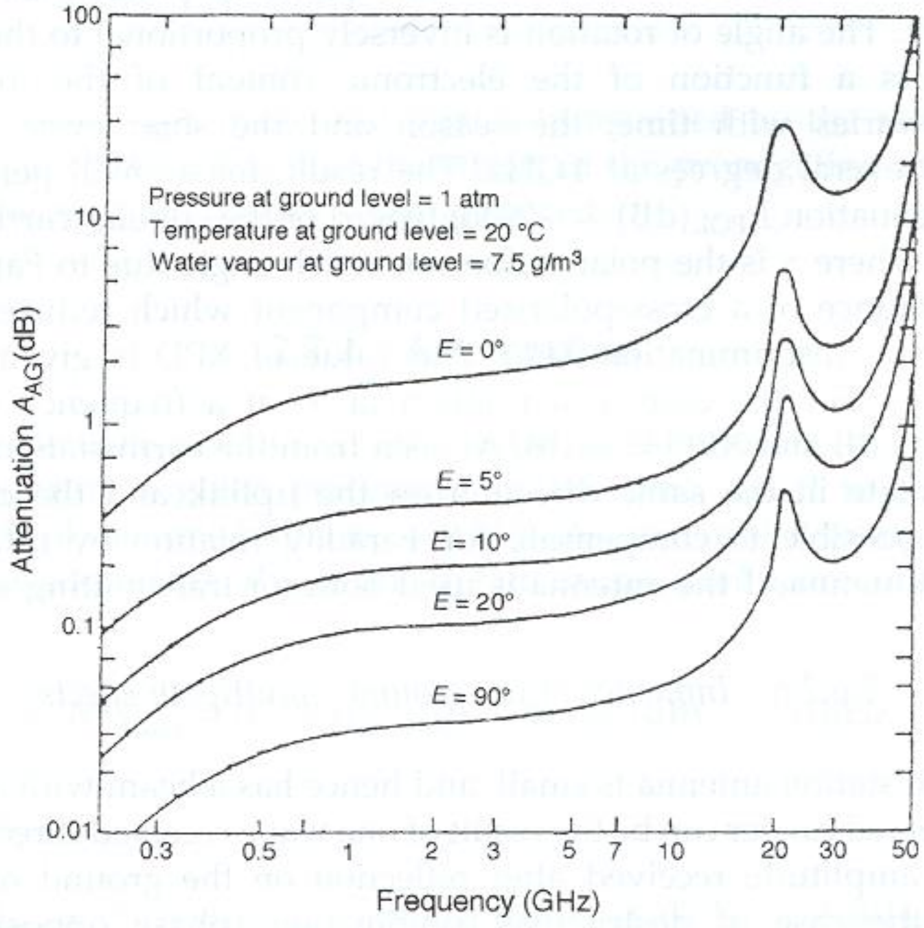
AVAILABILITY

- Percentage of time in which defined QoS is met
- e.g. bit error rate of 10^{-6} for 99.9 %
- Outage: percentage of time in which attenuation is too high to meet QoS
- e.g. 0.1 % = 8.76 hours /year
- 0.01 % = 53 minutes /year

AVAILABILITY

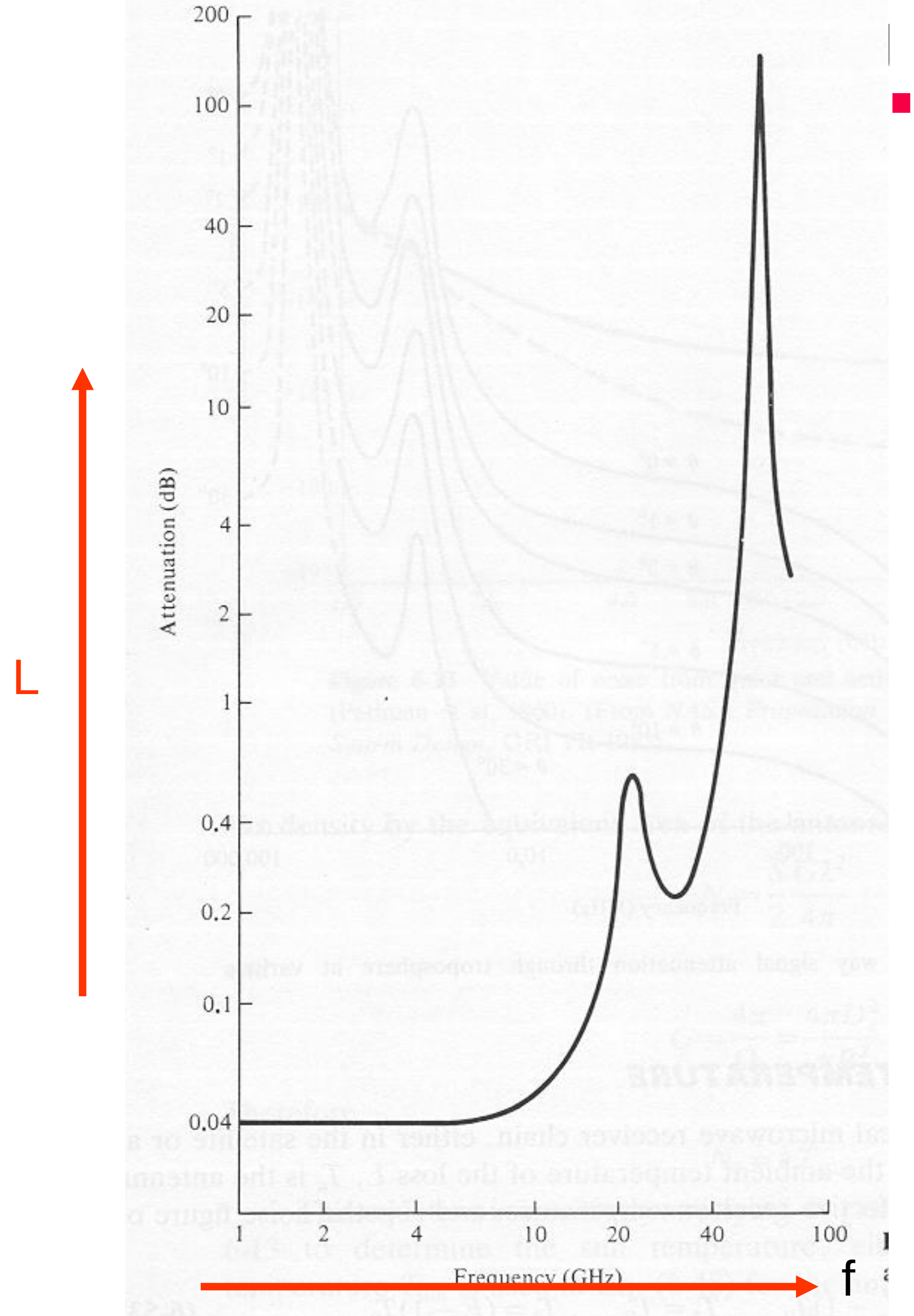
- directly related to precipitation time statistics

CLEAR SKY ATTENUATION



OXYGEN WATER VAPOUR ABSORPTION

at zenith



PROPAGATION MEASUEREMENTS

- Beacon receivers
- Radiometers
- Radar
- Rain gauge

INCREASE IN NOISE TEMPERATURE

- Atmosphere: “lossy line”
- T_m … medium temperature, 280 K
- to be added to overall noise temperature

$$T_{at} = (1 - \frac{1}{L_{at}}) T_m$$

ATMOSPHERIC ATTENUATION

- specific attenuation α in [dB/km]
- l… path length in
- R_p…rain rate

$$\alpha = a R_p^b$$

$$L_{at} = \alpha l$$

OVERALL NOISE TEMPERATURE

- Precipitation:

$$T_{sys} = T_{ant} + \left(1 - \frac{1}{L_{atd}}\right) T_m + T_{LNB} \cdot L_{atd}$$

EXAMPLE

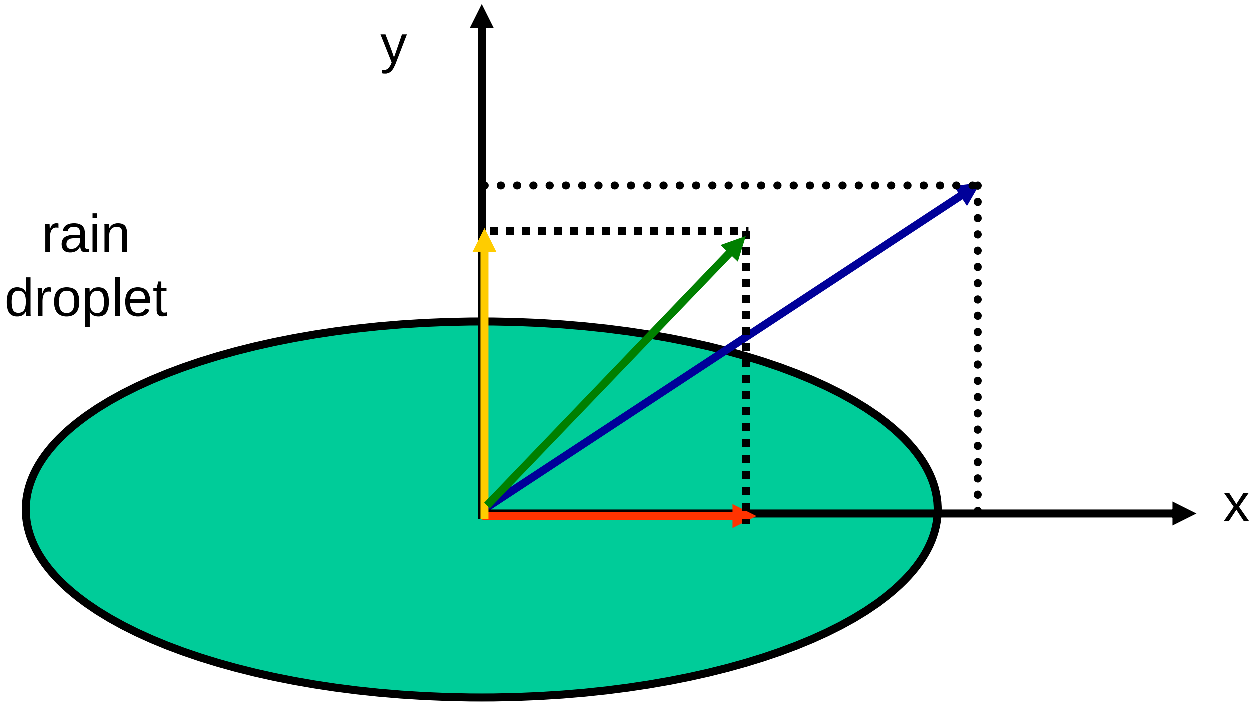
- L_{atd} = 2 dB = $10^{0.2}$ = 1.58
- T_{atm} = (1 - 1/1.58) 280 = 102.8 K

VARIATIONS

- can reach up to 1 dB/s at Ka-band
- slower at Ku-band
- any fade countermeasure technique must be able to cope with fluctuations

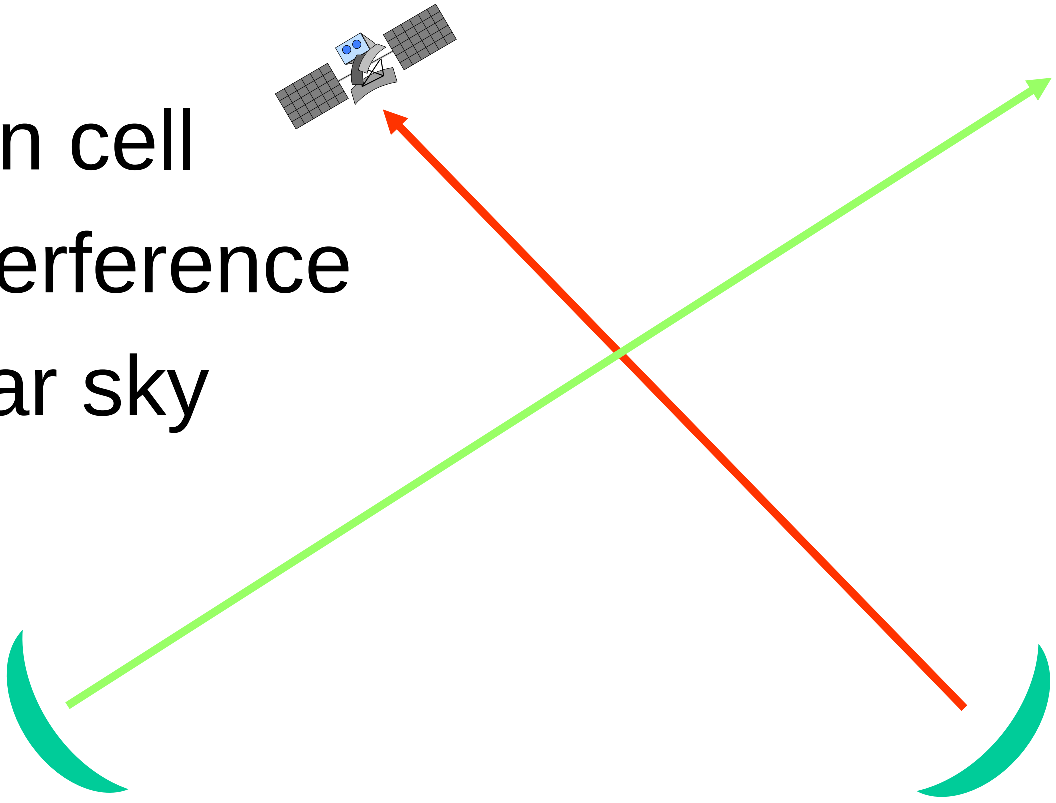
OTHER EFFECTS

DEPOLARIZATION



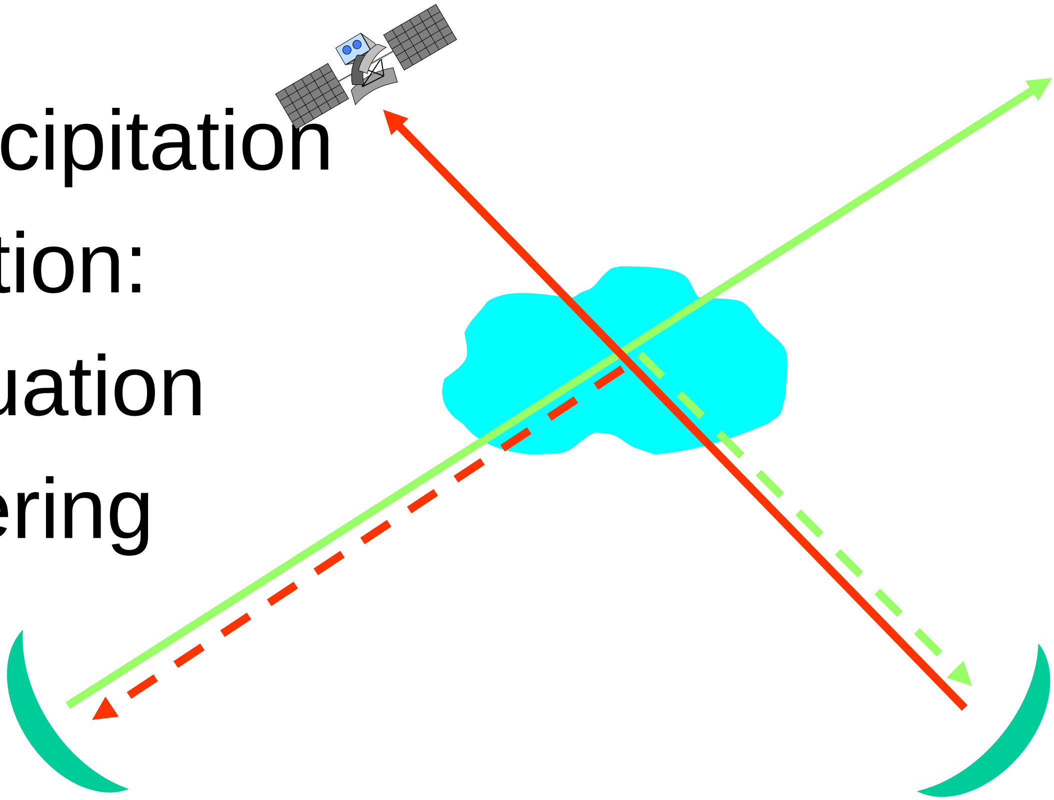
SCATTERING

- on rain cell
- no interference
  in clear sky



SCATTERING

- in precipitation condition:
- attenuation
- scattering



- interference

SCINTILLATIONS

- Variation of refraction index of atmosphere (troposphere and atmosphere)
- Refraction index of troposphere
  - decreases with altitude
  - independent of frequency

FARADAY ROTATION

- Ionosphere introduces a rotation of linearly polarized wave
  - inversely proportional to frequency
  - function of electronic content
- varies with time
- planes rotate in same direction for up - and downlink
- no compensation by rotating feed!

IONOSPHERIC EFFECTS

- can be neglected for normal satcom systems
- if exact propagation delay matters (GPS) ionospheric model and effects must be taken into account

C/N for DOWNLINK

$$\left(\frac{C}{N}\right)_d = EIRP_{sat} - L_{pol} - L_{sd} - L_{pd} - L_{atd} - L_i + \left(G/T\right)_e - k - B$$

$$(G/T)_e = G_R - 10\log(T_{sys})$$

EXAMPLE

- EIRP = -4 dBW
- Polarisation loss: 1.5 dB
- Pointing loss: 0.5 dB
- Ionospheric losses: 0.7 dB
- LNB noise temperature: 120 K
- Input loss: 1 dB
- Atmospheric attenuation: 2 dB

G/T Earth Station

- calculate system noise temperature

$$T_{RX} = T_L + L\,T_{LNA}$$

$$T_{RX} = 75 + 1.258 * 120 = 226K$$

$$T_{sys} = 50 + \left(1 - \frac{1}{10^{0.2}}\right)280 + (1.58) * 226 = 510.4K$$

$$G/T_e = 18 - 10\log(510.4) = -9.07\,dB/K$$

Gain of Parabolic Dish

$$G = 10\log\left(\eta\frac{\pi^2 D^2}{\lambda^2}\right) = 10\log\left(0.5\frac{\pi^2 2^2}{\left(\frac{3E8}{2E9}\right)^2}\right) = 30.28dB$$

C/N DOWNLINK

$$\left(\frac{C}{N}\right)_d = EIRP_{sat} - L'_{pol} - L_{sd} - L_{pd} - L_{atd} - L_i + (G/T)_e - k - B$$

$$L_s = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 1E6}{0.68}\right) = 145.3dB$$

$$\left(\frac{C}{N}\right)_d = -4 - 1.5 - 145.3 - 0.5 - 2 - 0,7 - 9.07 + 228.6 - 53 = 12.53dB$$

OVERALL C/N$_o$

- Composed of uplink and downlink

$$\left(\frac{C}{N}\right)^{-1} = \left(\frac{C}{N}\right)_u^{-1} + \left(\frac{C}{N}\right)_d^{-1}$$

$$\left(\frac{C}{N}\right) = \frac{1}{\left(\frac{C}{N}\right)_u^{-1} + \left(\frac{C}{N}\right)_d^{-1}}$$

EXAMPLE

- Overall C/N

$$\frac{C}{T} = 10\log\left(\frac{1}{10^{-(-26.5/10)} + 10^{-(-12.53/10)}}\right)$$

$$\frac{C}{N} = 12.34dB$$

INTERFERENCE

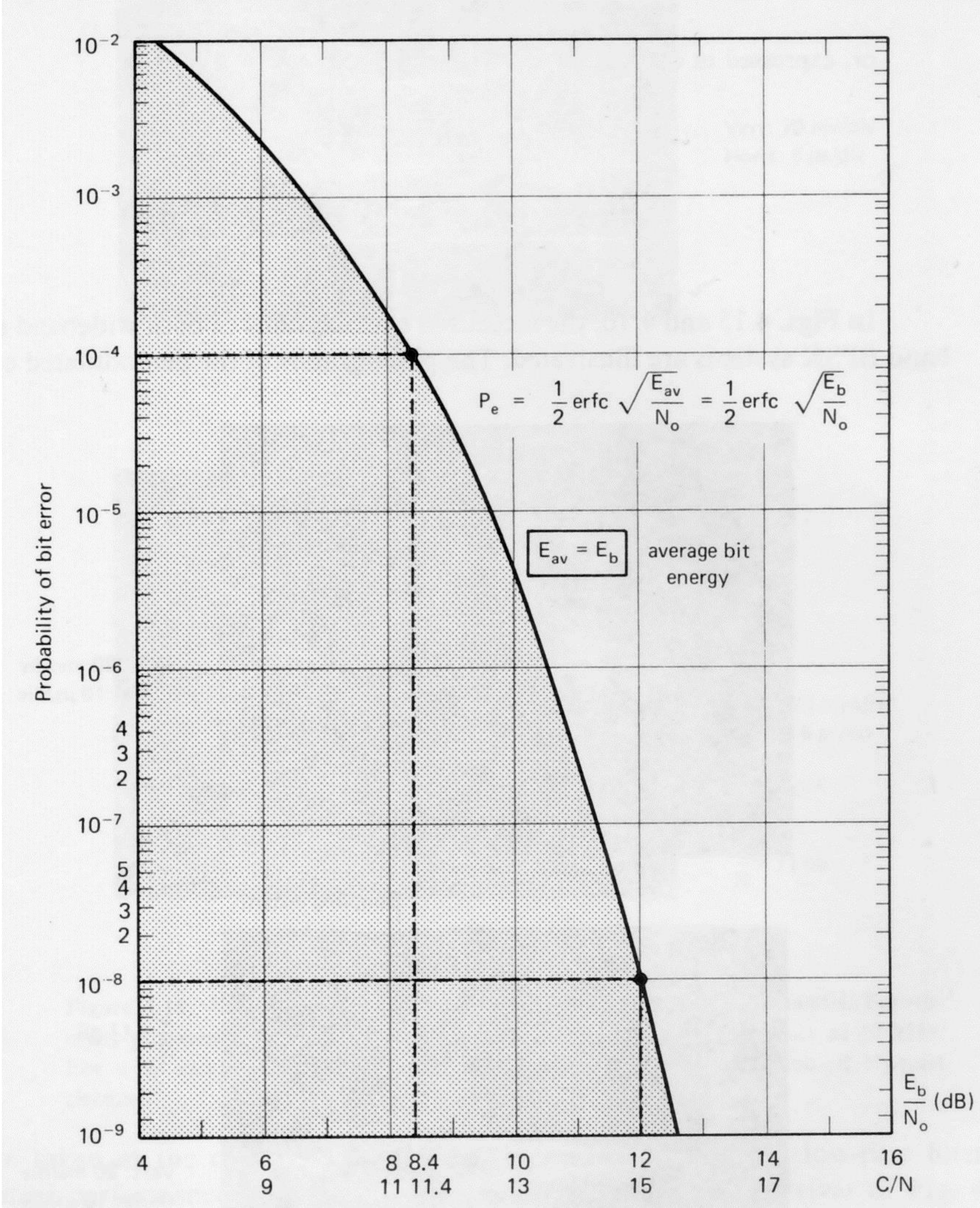
- Co-channel interference
- Adjacent channel interference

$$\left(\frac{C}{N}\right)^{-1} = \left(\frac{C}{N}\right)_u^{-1} + \left(\frac{C}{N}\right)_d^{-1} + \left(\frac{C}{I}\right)^{-1}$$

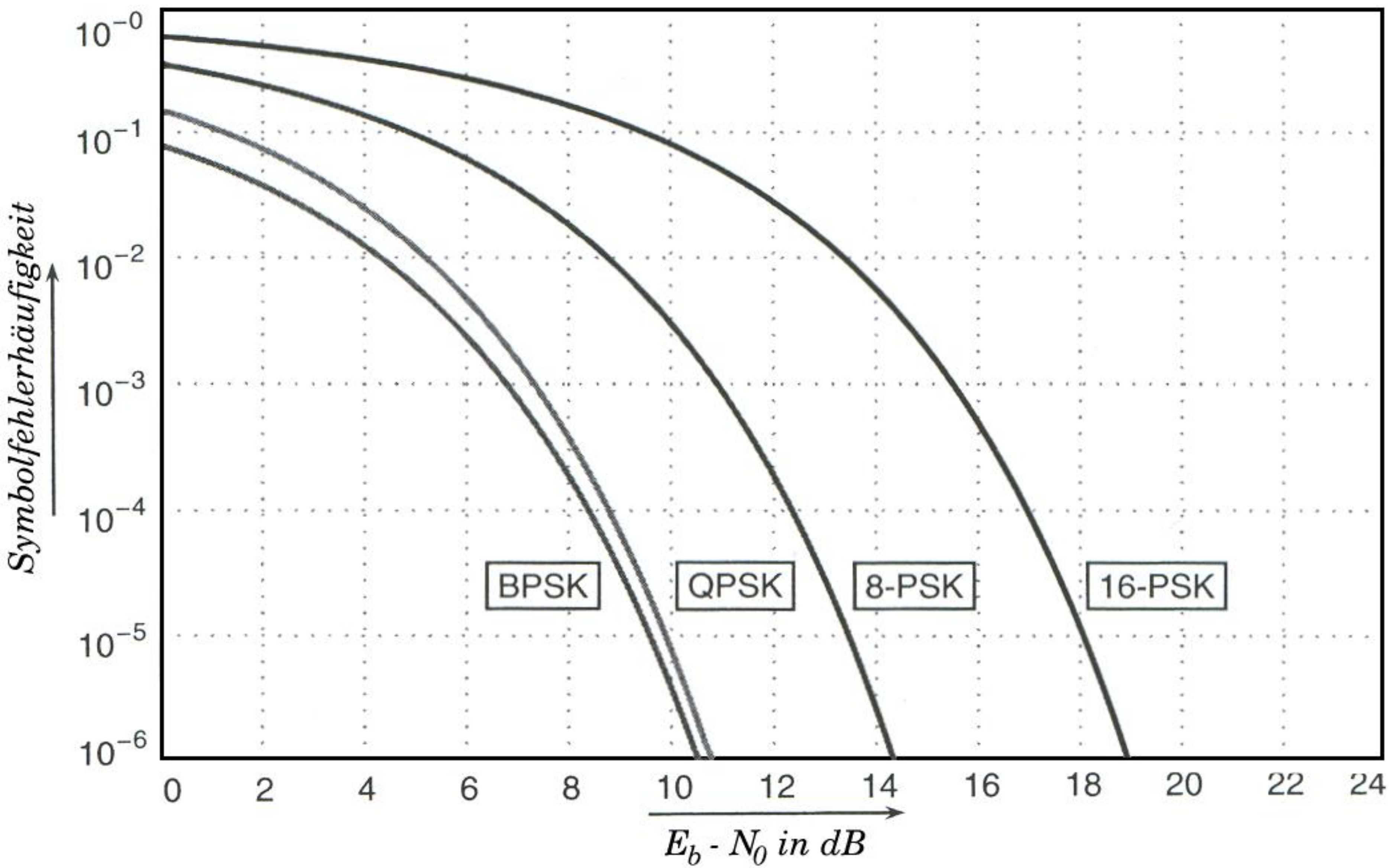
E_b/N_o

- Bandwidth = 200 kHz,
- Uncoded, user data rate= 200 kbit/s
- E_b/N_o = C/N*B/r
- E_b/N_o = 12.34 dB
- Coded, code rate = ½
- B/r = 200.000/100.000 = 2 = 3 dB
- E_b/N_o = 15.34 dB

BER



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Probability of bit error
$P_e = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{E_{av}}{N_o}} = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{E_b}{N_o}}$
$E_{av} = E_b$
average bit energy
$\frac{E_b}{N_o}$ (dB)
4 6 8 8.4 10 12 14 16
9 11 11.4 13 15 17
C/N



Symbolfehlerhäufigkeit
10^{-0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
BPSK
QPSK
8-PSK
16-PSK
0
2
4
6
8
10
12
14
16
18
20
22
24
E_b - N_0 in dB

SYSTEM MARGIN

- Min E_b/N_o= 7 dB (BER = 10^{-6}, 1 dB implementation loss)

- Margin = E_b/N_o -E_b/N_{omin}
- Margin = 15.34 – 7 = 8.34 dB