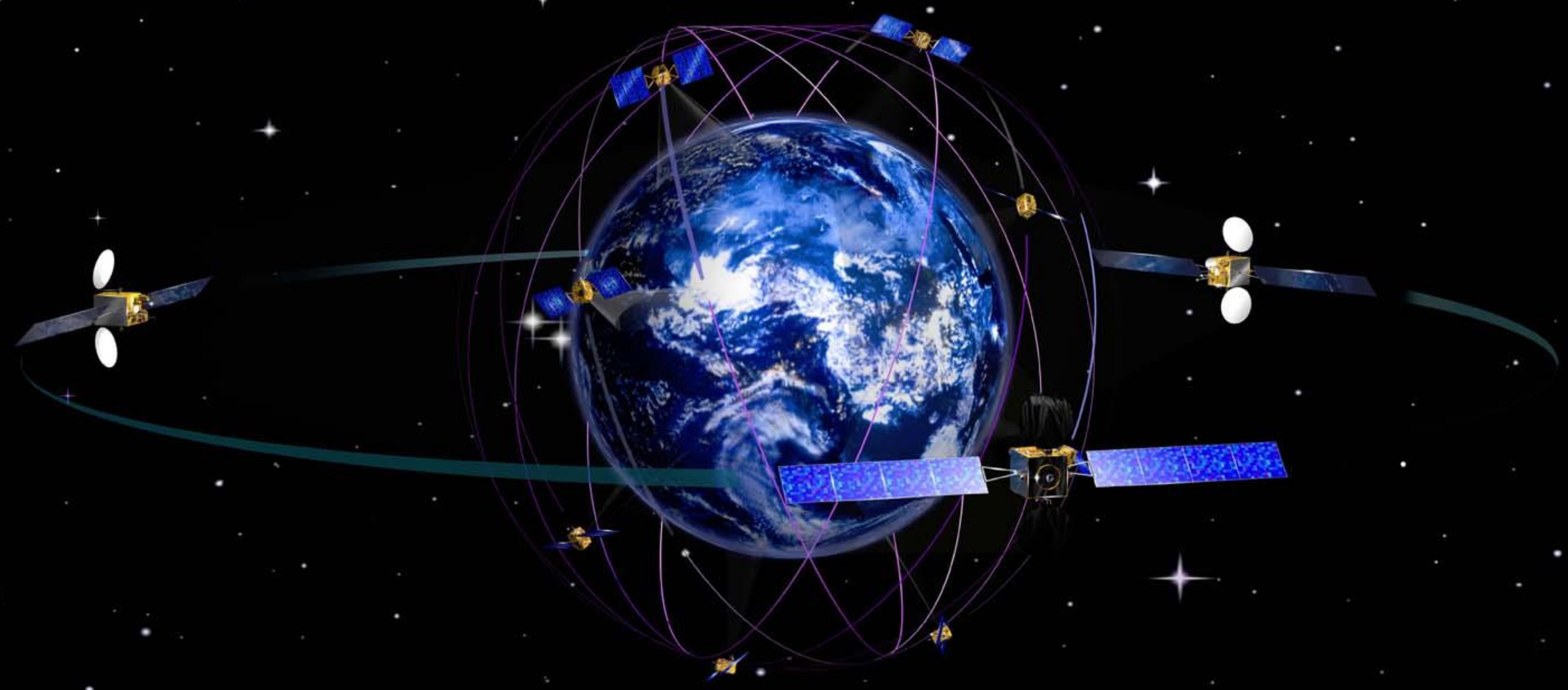
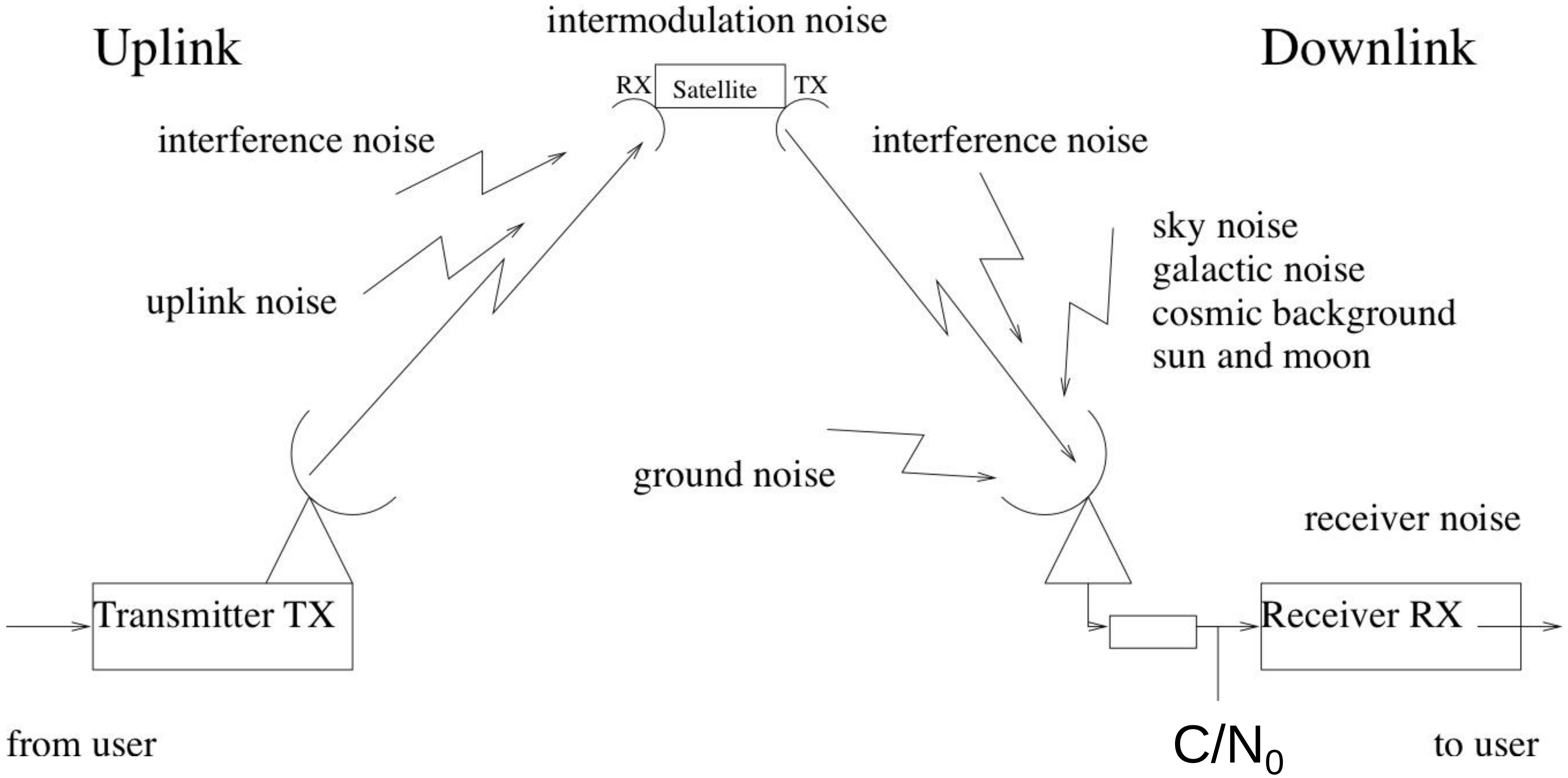
Satellite Communications
– RRY100 –



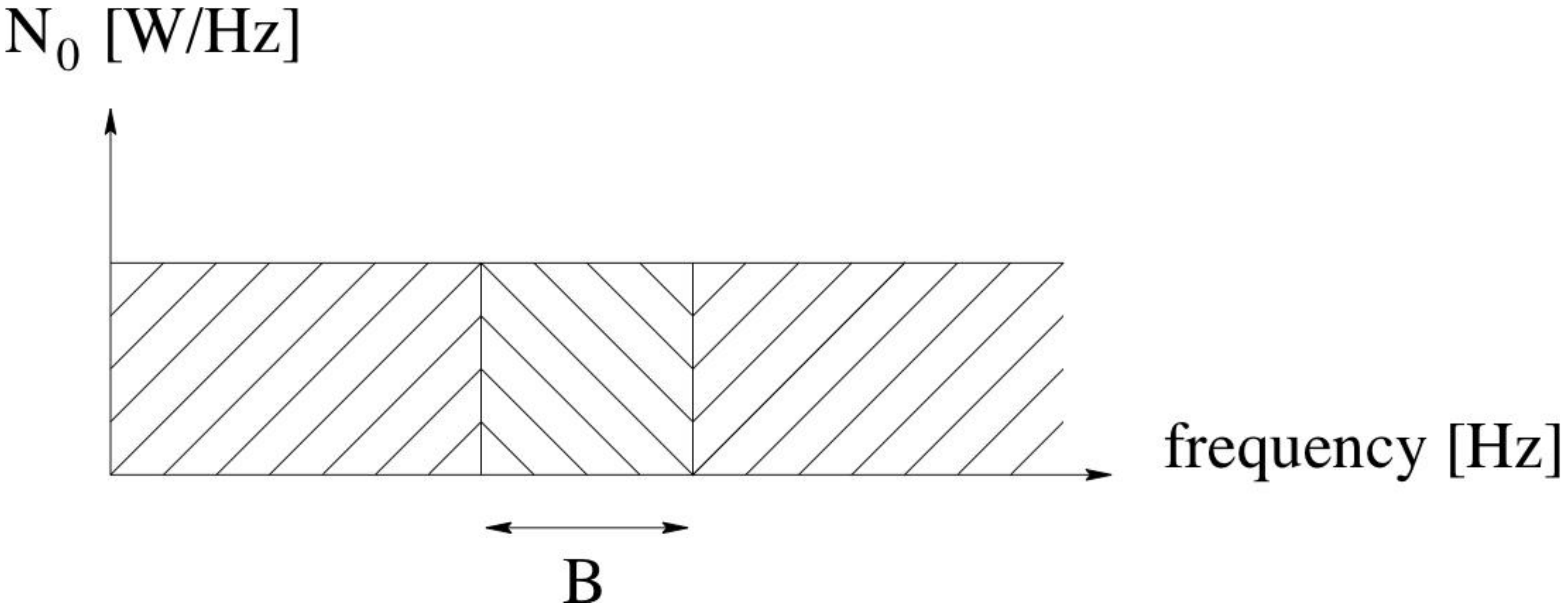
2024 Study Period 1
Lecturer: Rüdiger Haas

Lecture-3: Noise on satellite links

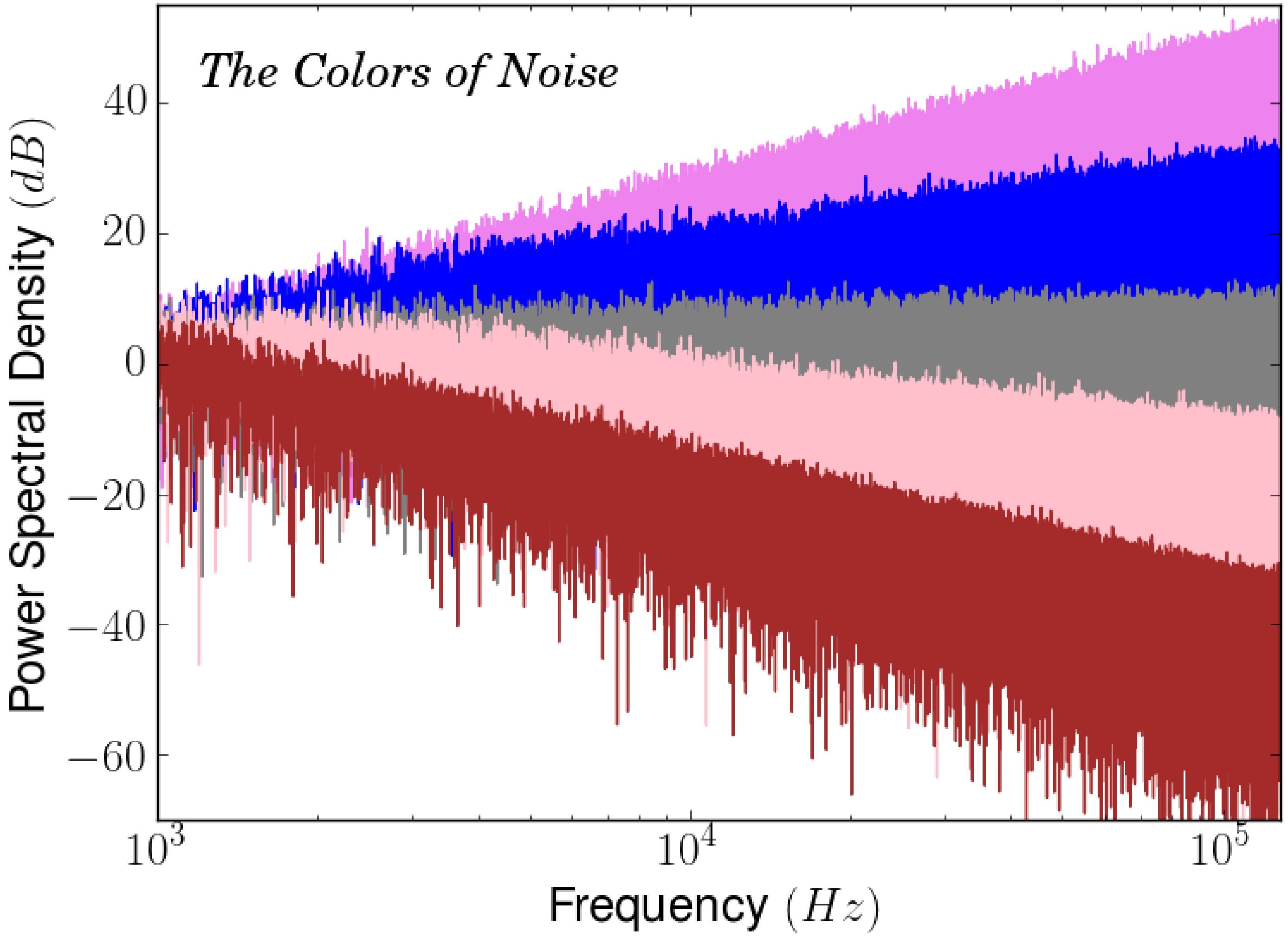
Noise in satellite communications



- Noise model:
  - We usually work with limited bandwidth only
  - An appropriate model is ’white noise’
  - Real noise over larger bandwidth usually is ’coloured’, i.e. not constant over frequency



Different noise models



"Violet noise" $\sim f^2$

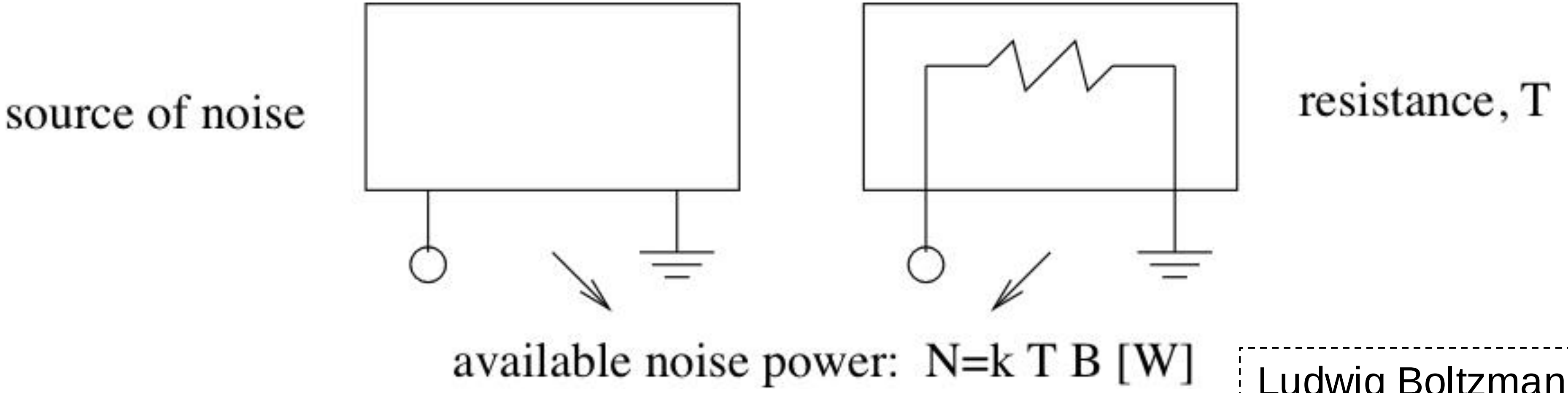
"Blue noise" $\sim f^1$

"White noise"

"Pink noise" $\sim f^{-1}$

"Red noise" $\sim f^{-2}$

- Concept of ’Noise Temperature’:
  - All objects with a physical temperature T generate electromagnetic radiation
  - We compare the noise power of the source of noise (its physical temperature may be different from T) with an object that has a physical temperature T
  - If they have the same noise power N we identify the amount of noise by the ’noise temperature T’ in Kelvin



Ludwig Boltzmann (1844-1906)

$$N_0 = k \cdot T \qquad \text{[Ws] or [W Hz}^{-1}\text{]}$$

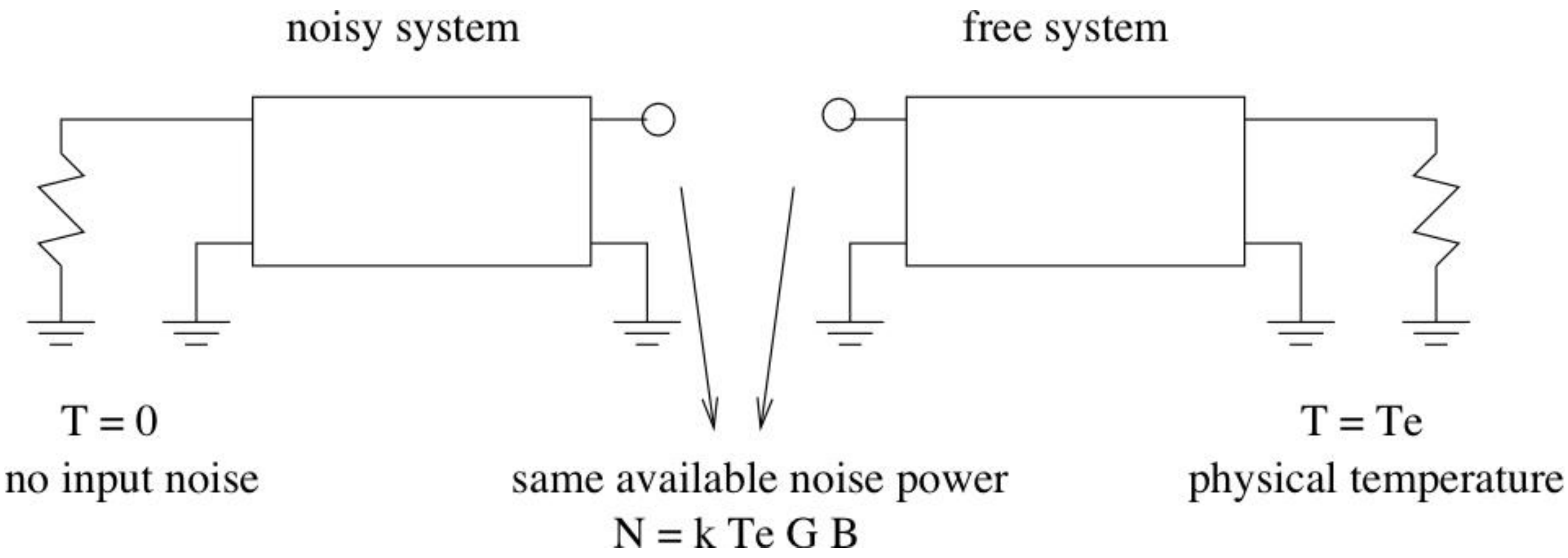
$$N = k \cdot B \cdot T \qquad \text{[W]}$$

Boltzmann’s constant:

$$k = 1.3806 \times 10^{-23} \quad \text{[W s K}^{-1}\text{]}$$

$$k = -228.599 \quad \text{[dB W Hz}^{-1}\text{ K}^{-1}\text{]}$$

- Concept of ’Effective Input Noise Temperature’:
  - Is a measure of the noise generated by internal components of a two-port element
  - Thermodynamic temperature of resistance connected at the input to the four-port element (assumed to be noiseless) that gives the same noise power at the output of the element

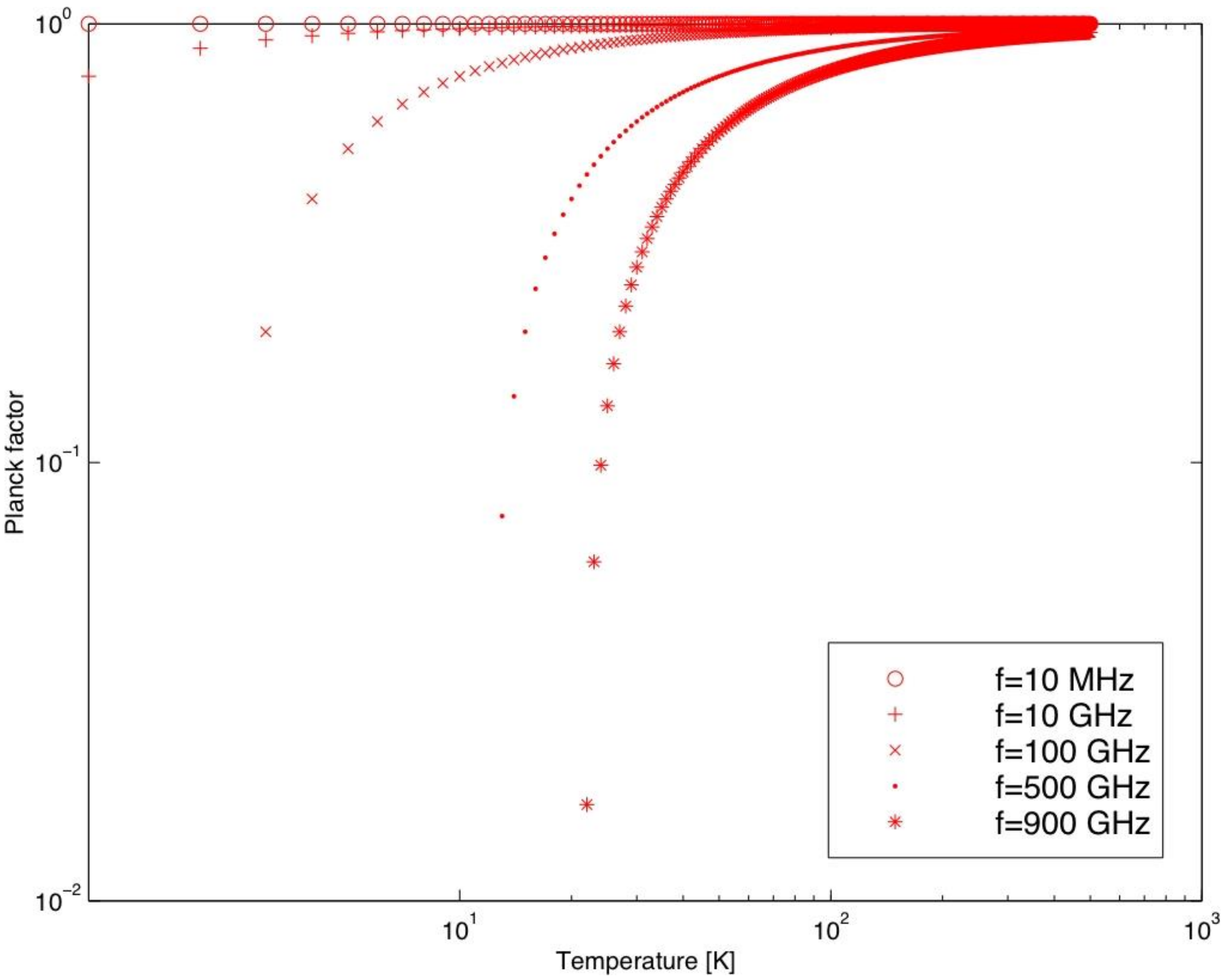


- Planck's radiation law:
  - The noise power *N* of an electric circuit in thermodynamical equilibrium at a temperature *T* within a given bandwidth *B* is:

$$N = k \times T \times B \times p(f)$$

  - With a frequency dependent Planck's factor *p(f)*
  - For satellite communications with frequencies *f* < 100 GHz the simple formula for noise is good enough

$$N = k \times T \times B$$

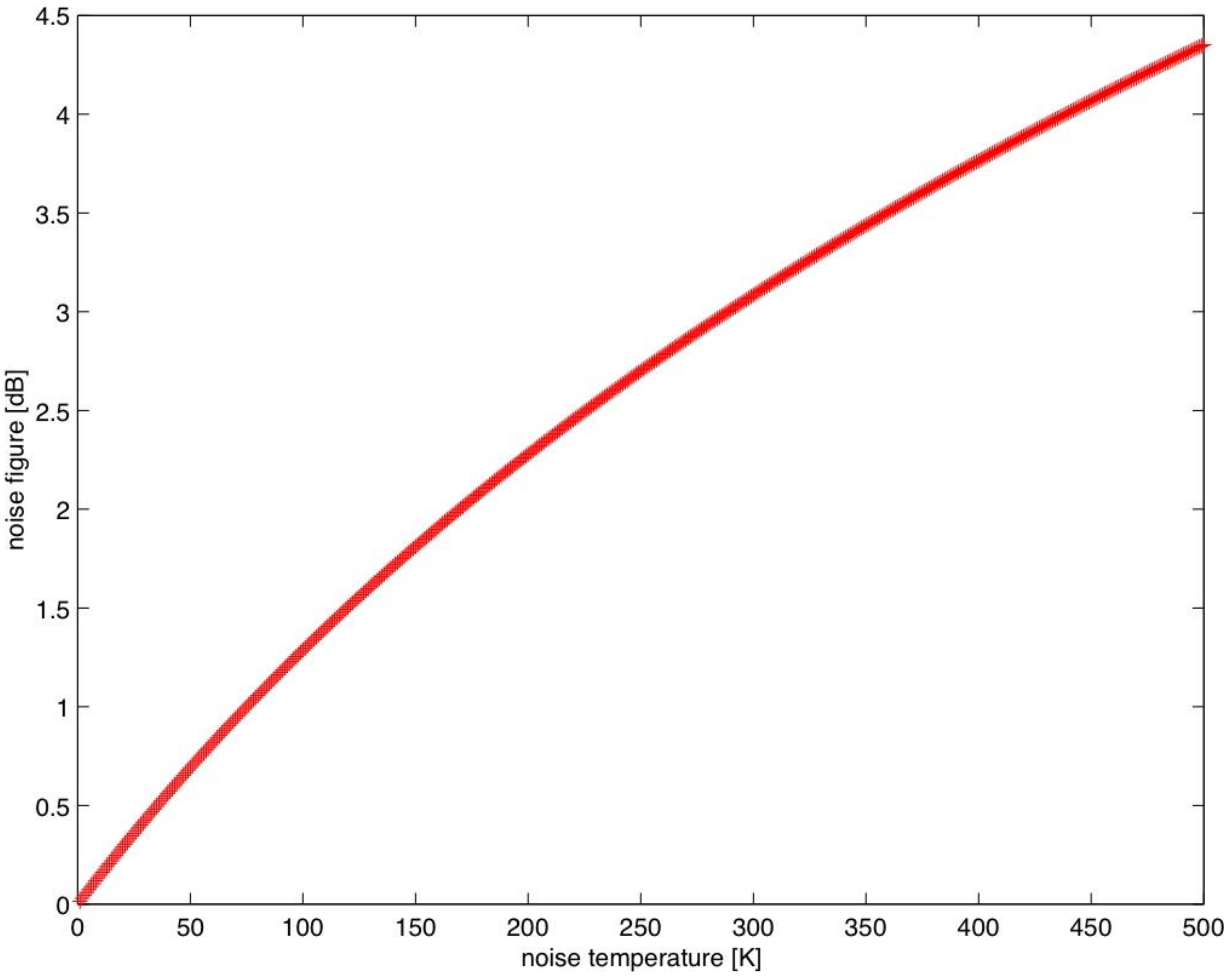


Planck’s factor as function of temperature and frequency.

- Noise figure:
  - The ratio of total noise at the output of a 4-port element to the contribution of the input noise with reference temperature T_0
  - Reference temperature is T_0=290 K, (in Japan T_0=293 K)
  - For electronic equipment often given in dB

$$F = \frac{G \cdot k \cdot (T_e + T_0) \cdot B}{G \cdot k \cdot T_0 \cdot B} = \frac{T_e + T_0}{T_0}$$

$$= 1 + \frac{T_e}{T_0} \qquad [/]$$



Noise figure F versus noise temperature T.

- System noise temperature,
  - For example at receiving earth station or satellite
  - At the receiver input (useful convention)
  - Contributions from antenna, feeder and receiving system

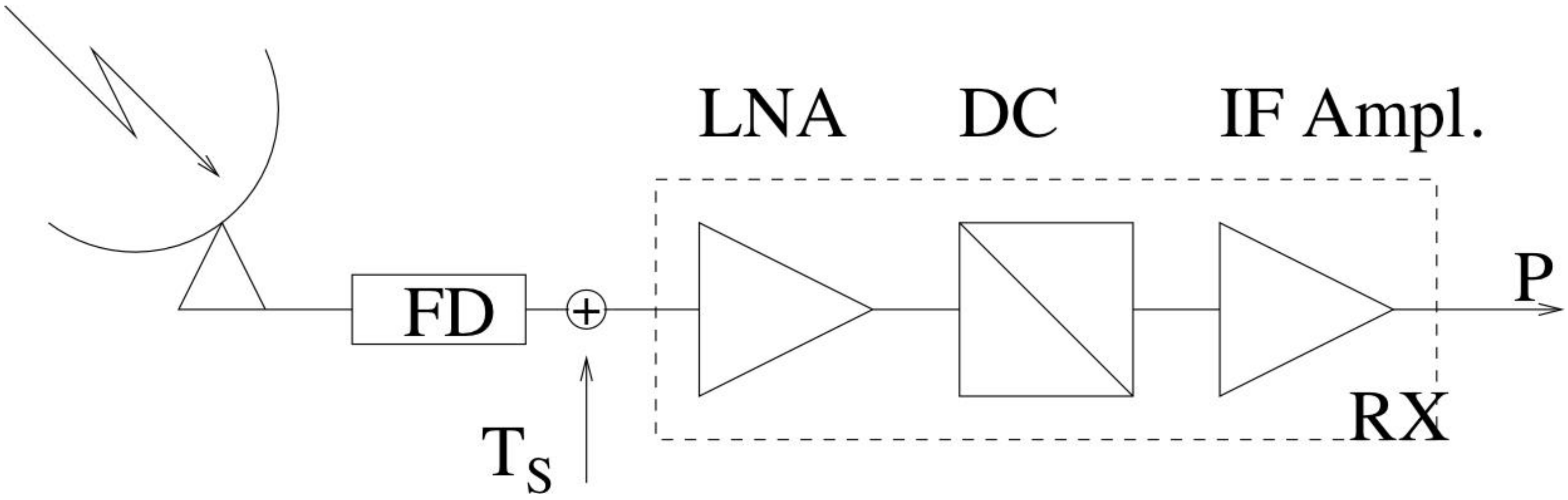
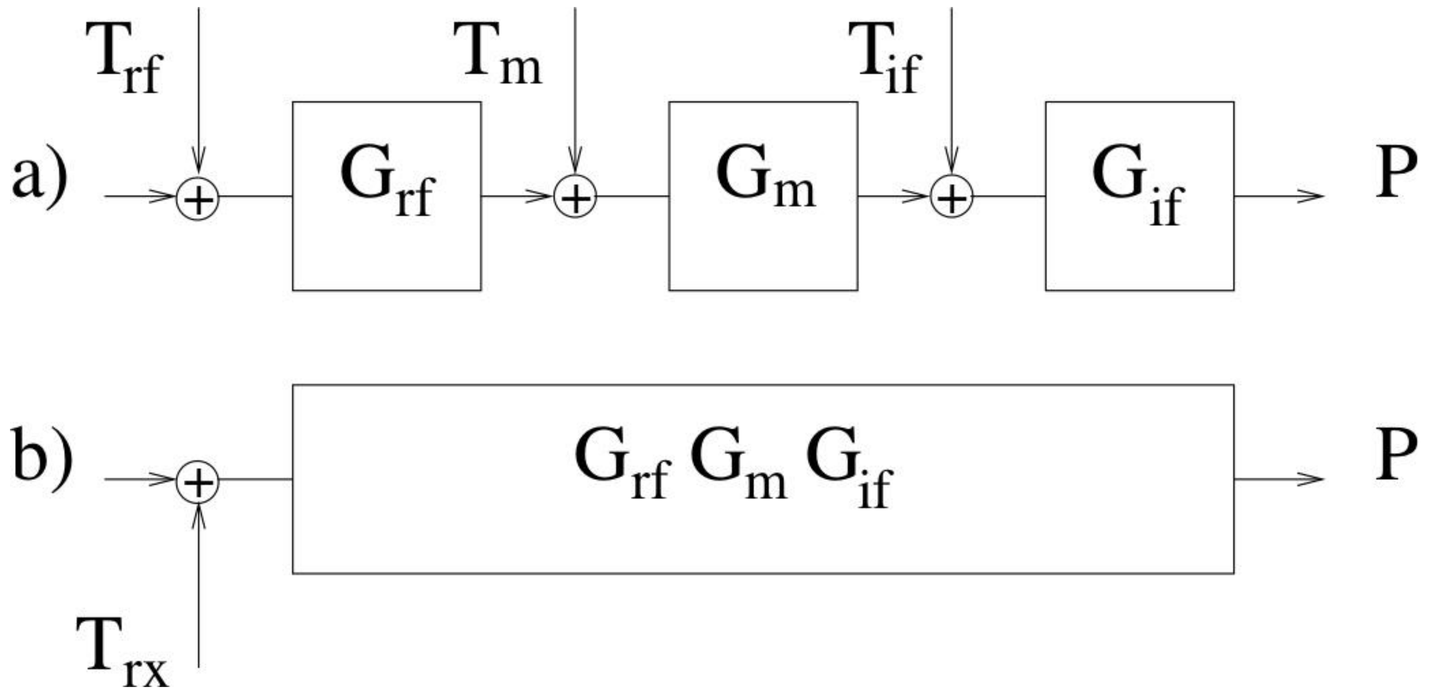


Figure: Schematic drawing of an earth station receiver.

- Cascaded systems:
  - Compare the power at the output of

    a) the series of individual elements and b) one combined element



  - First element should have high gain and low effective input noise temperature (==> low noise amplifier – LNA)
  - The temperatures and gains of the following elements are less important

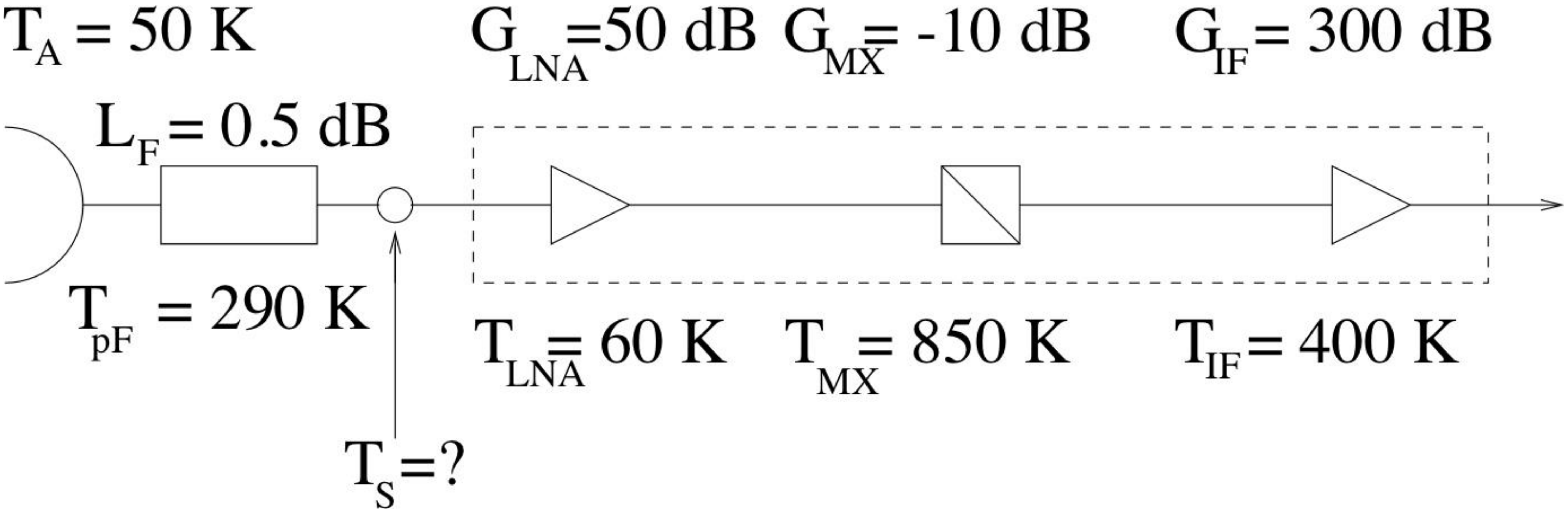
- Noise temperature of an attenuator:
  - Attenuator contains passive elements at ambient physical temperature T_p
  - Attenuation L_{att} (gain $G_{att} = 1/L_{att}$)
  - Effective input noise temperature

$$T_{e.att} = (L_{att} - 1) \cdot T_P$$

  - An antenna picks up noise from all radiating bodies within its radiation pattern
  - Brightness temperature of a radiating body in a specific direction $T_b(\theta,\phi)$
  - Antenna gain in this direction $G(\theta,\phi)$
  - Antenna noise temperature T_A

$$T_A = \frac{1}{4 \cdot \pi} \iint T_b(\theta,\phi) \cdot G(\theta,\phi) \sin(\theta)\, d\theta\, d\phi$$

- Example-1:
  - Calculate the system noise temperature for the following receiving system



- Figure of merit (G/T):
  - Relation of gain to system noise temperature (G/T)
  - Useful as a measure for the quality of a receiving station
  - Quality of the overall link (C/N_0) can be split up in contributions from (equation in dB):
    - sending side (EIRP, losses)
    - path loss (L_{FS}, L_A)
    - receiving side (Figure of merit G/T, losses)

$$\frac{C}{N_0} = (P_{tx} + G_{t.max} - L_t - L_{f.tx})$$

sending side

$$(-L_{FS} - L_A)$$

path loss

$$(+G_{r.max} - L_r - L_{pol} - L_{f.rx} - k - T_s)$$

receiving side

Some examples:

Type	f [GHz]	Te [K]	G [dB]	cost
Cryogenic	4	15	30	high
Parametric	20	<100	30	
Cooled	4	35	30	medium
Parametric	12	85	30	
(Peltier)	20	150	30	
Ambient	4	55	30	medium
Parametric	12	150	30	
FET cryogenic	20	200	30	
FET cooled	4	40	60	low
(Peltier)	12	120	60	
	12	160	60	
	20	180	45	
FET ambient	4	70	60	low
	12	130	60	
	12	180	60	
	20	350	22	
HEMT	22	300	16	low

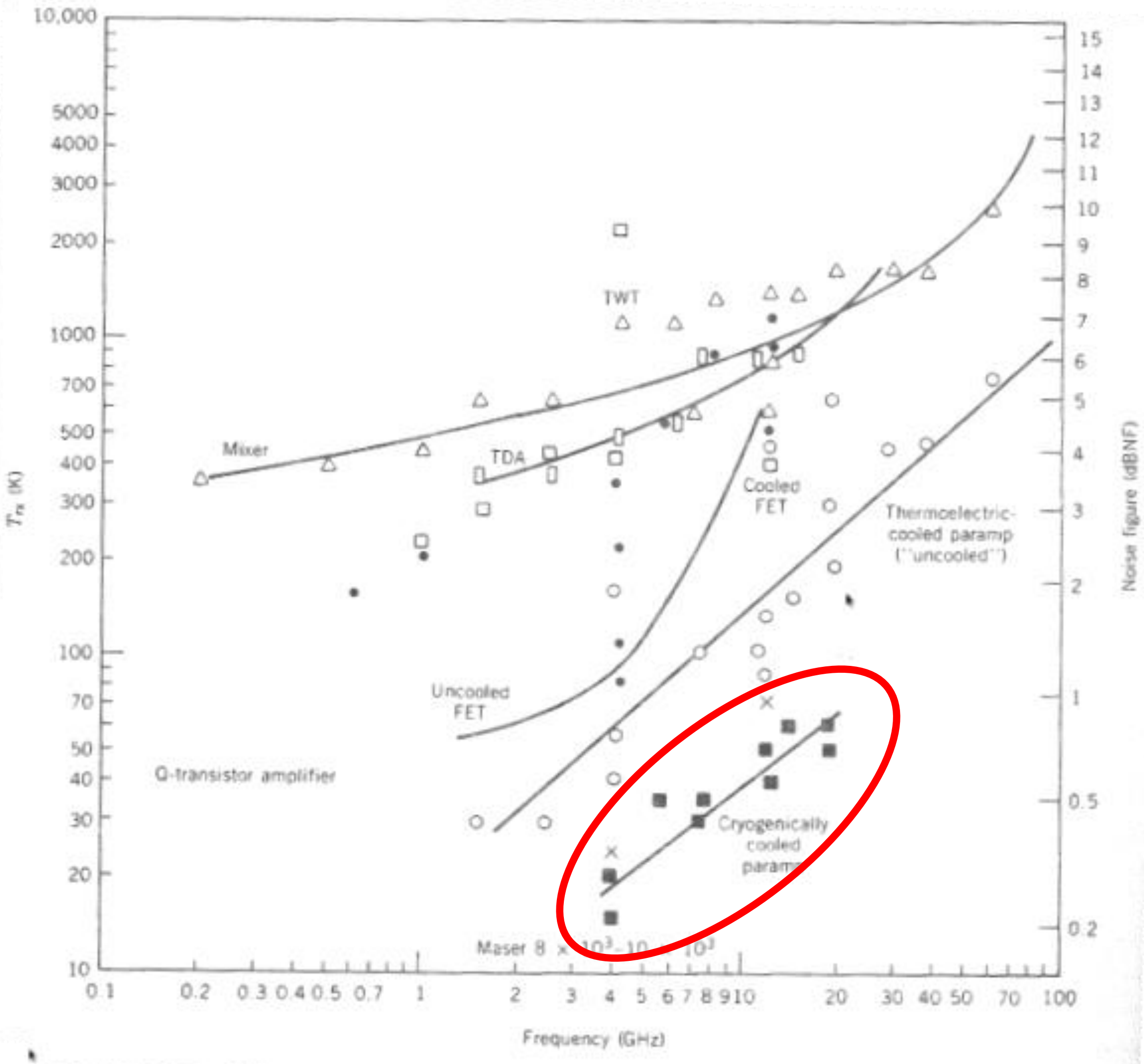
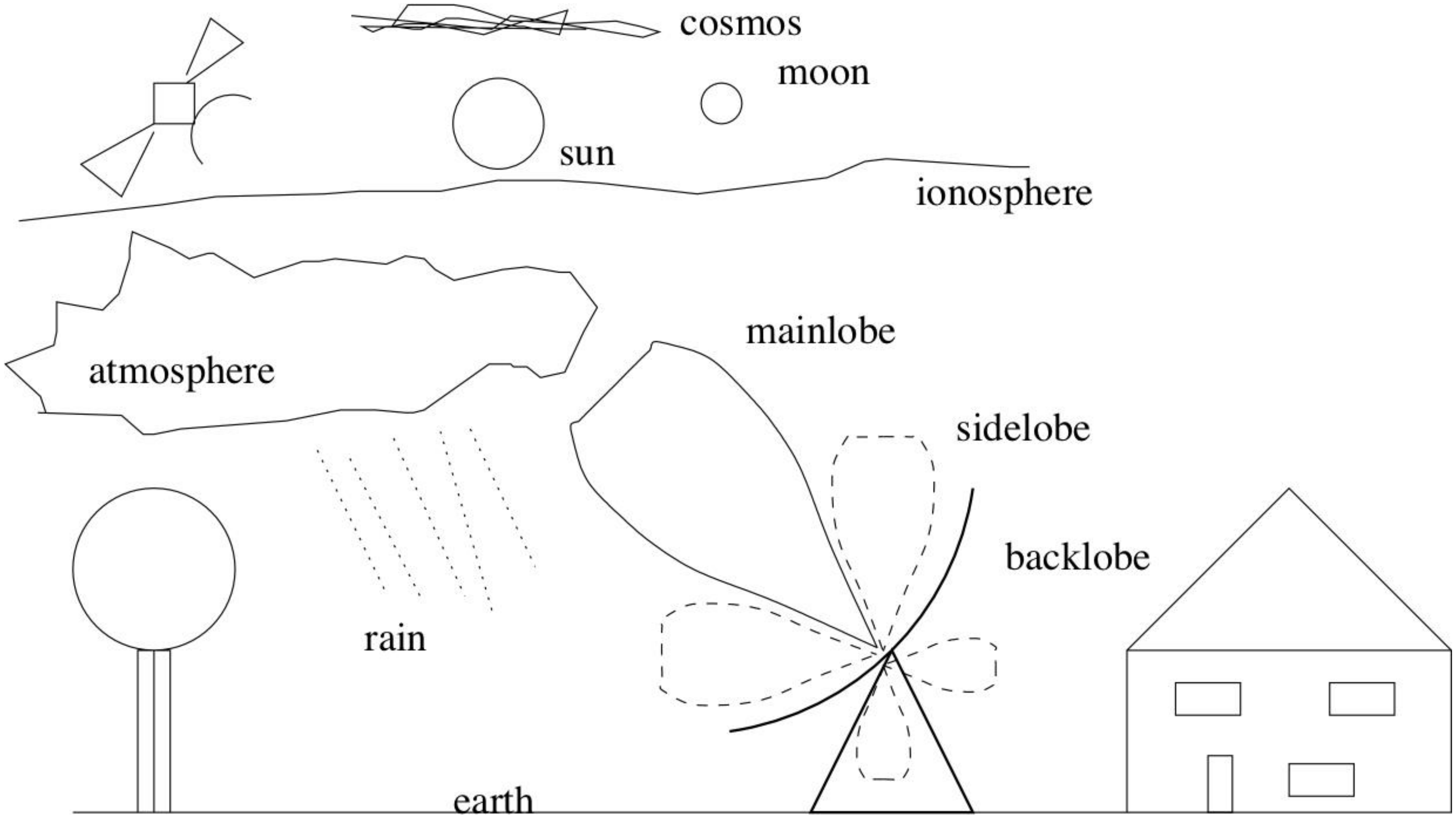
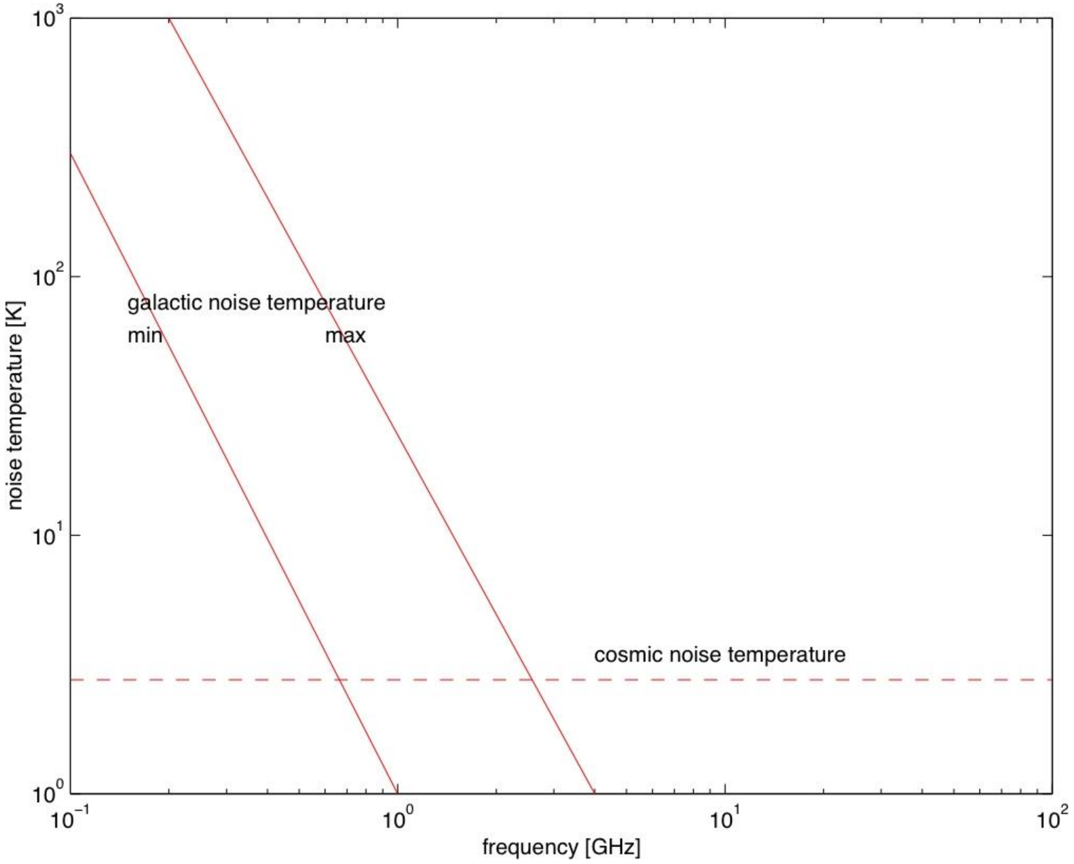


FIGURE 9.20 Noise temperature and noise figure (T_R = 290 K) for RF amplifiers and mixers.

■ = Cryogenically cooled paramp
○ = Thermoelectrically cooled paramp
▯ = Tunnel diode amplifier
△ = Mixer
● = Uncooled paramp
□ = Travelling wave tube amplifier
× = High electron mobility transistor (HEMT) low noise converter (1993)

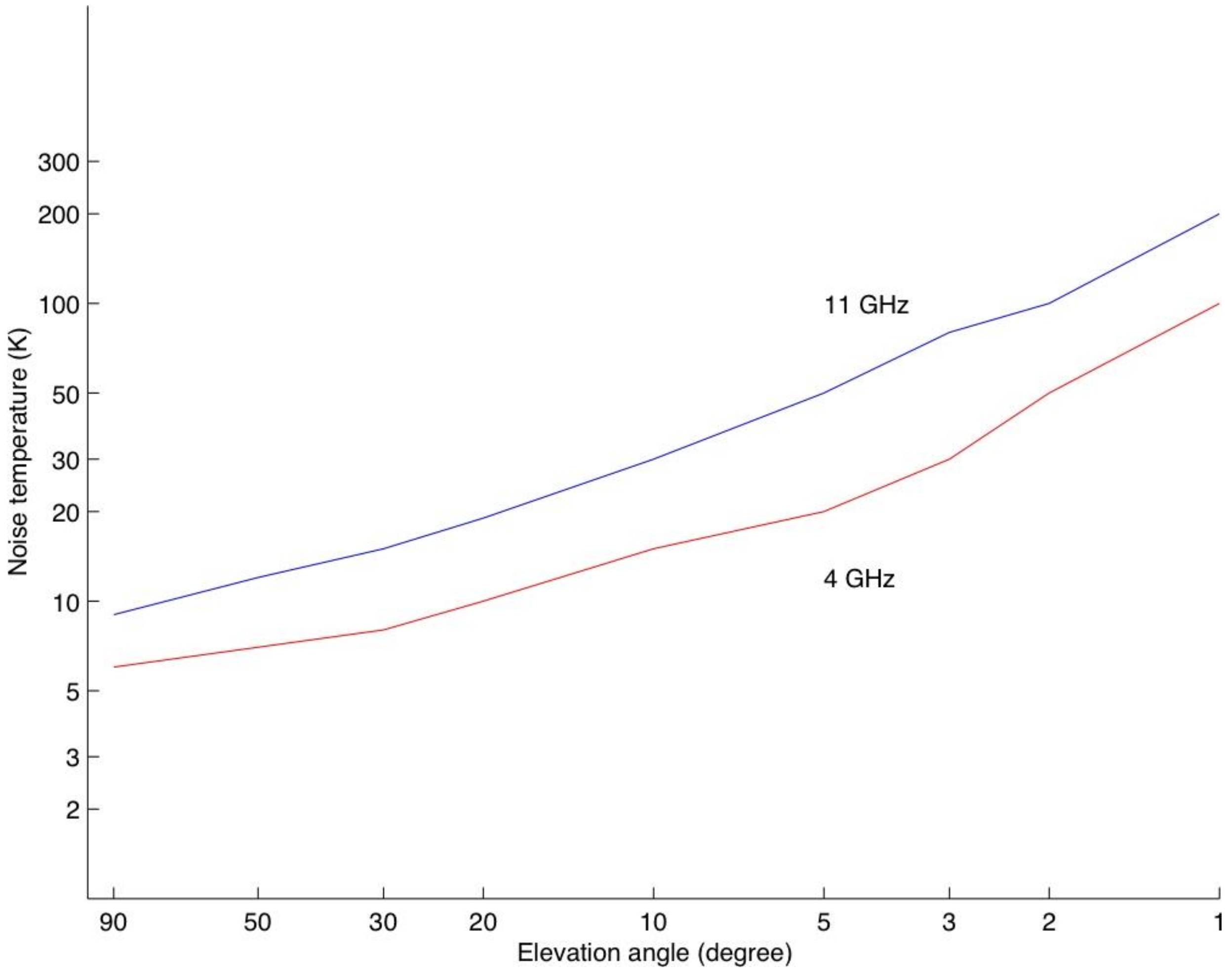
- Contributions to the antenna noise temperature of an earth station:





Example for cosmic and galactic noise temperatures

Example for atmospheric noise temperature (”clear-sky”) as function of frequency and elevation



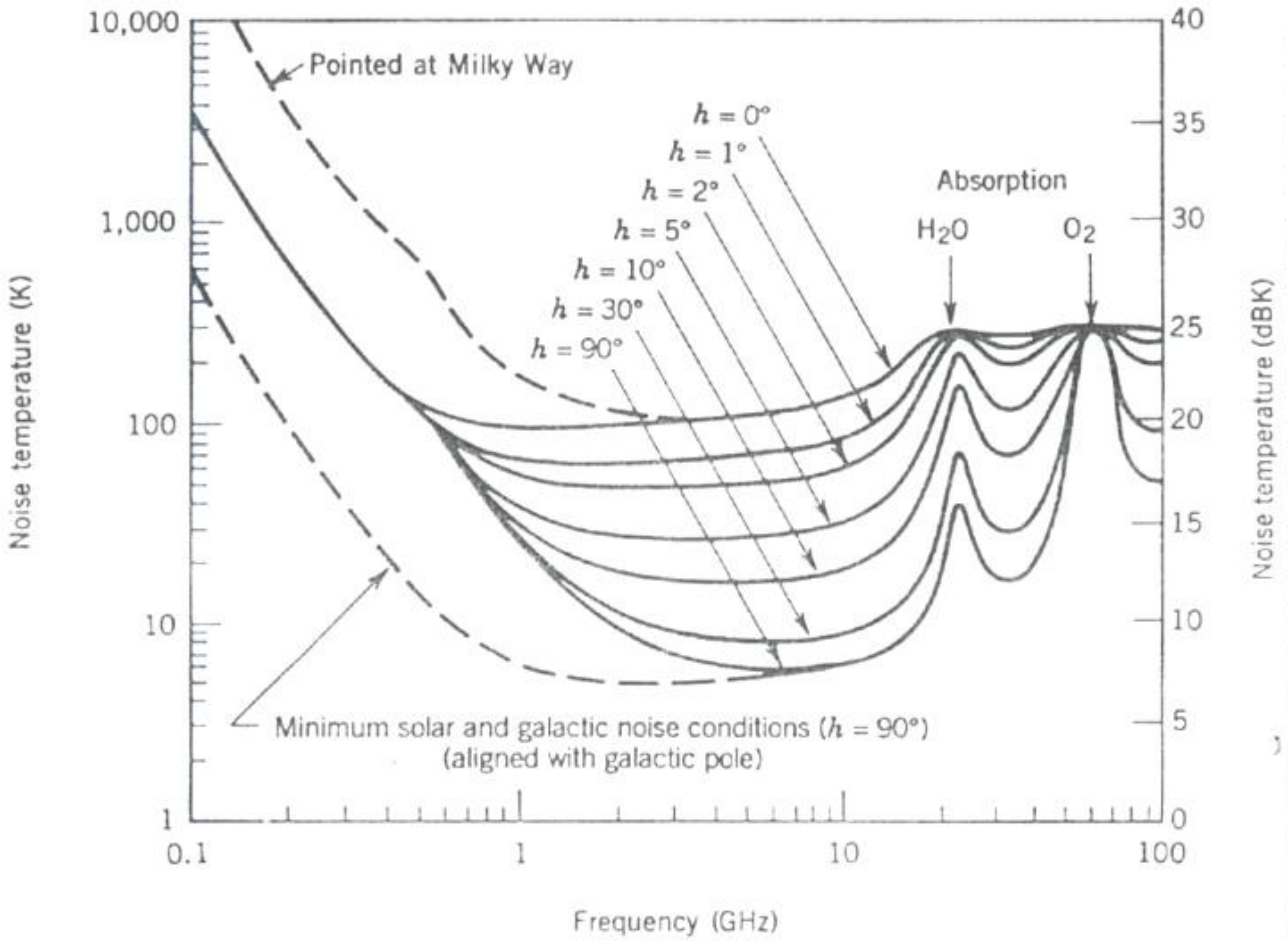


FIGURE 9.8 Earth station antenna noise temperature.

Assumptions:

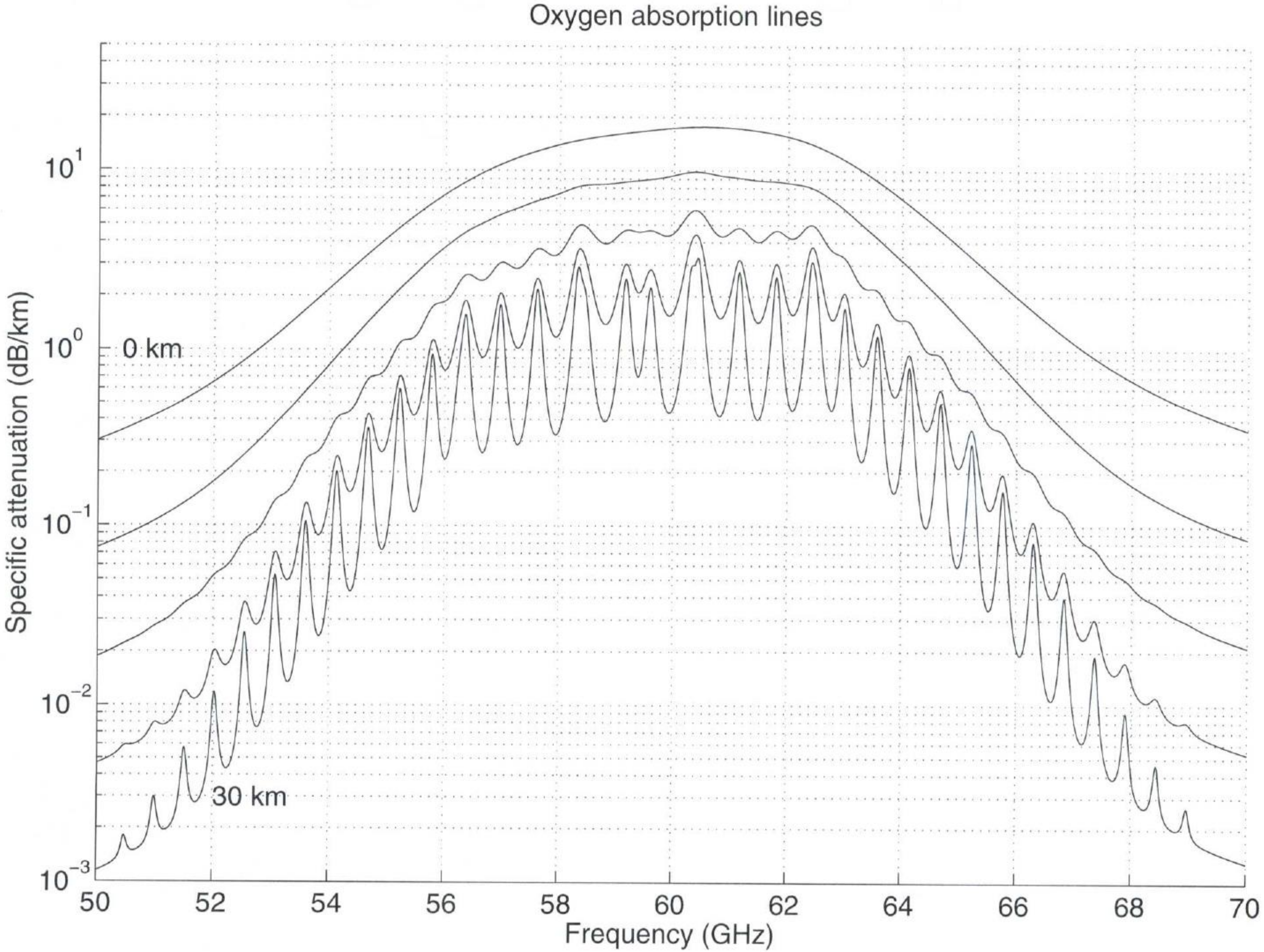
Antenna has no earth-looking sidelobes or a backlobe (zero ground noise)

Antenna is lossless

h is antenna elevation angle (deg)

Sun not considered

Cool, temperate-zone troposphere


Oxygen absorption lines
Specific attenuation (dB/km)
Frequency (GHz)
0 km
30 km
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
50
52
54
56
58
60
62
64
66
68
70

- Rain has two effects:
  - Rain acts as an attenuator with temperature T_m = 275 K and contributes with a noise temperature:

$$T_{Rain} = T_m \cdot (1 - 1/A_{Rain})$$

  - Rain increases the sky noise (for downlink)

$$T_{sky,rain} = T_{sky}/A_{Rain}$$

- Noise from the ground T_G:
  - Picked up from mainlobe in low elevations
  - Picked up from back- and sidelobes
  - Approximate calculation:

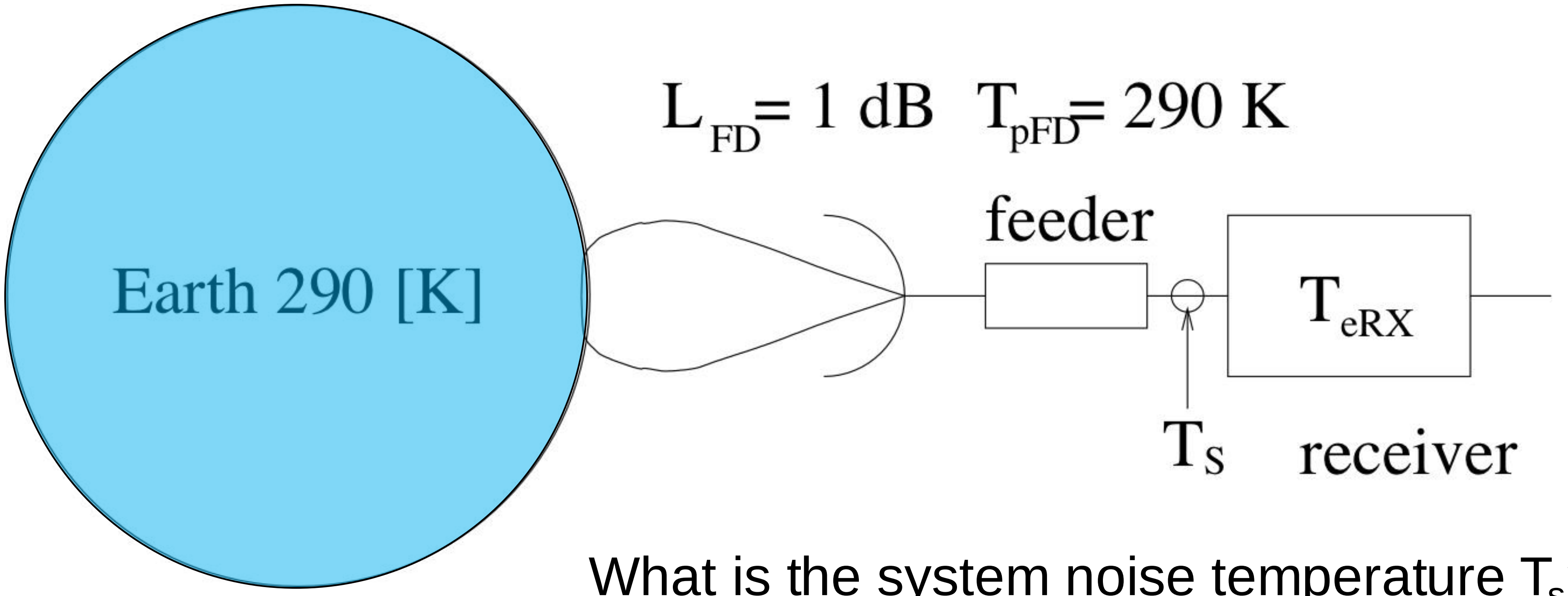
$$T_{Ground} = \sum_{i}^{lobes} G_i \cdot \frac{\Omega_i}{4 \cdot \pi} \cdot T_G$$

  - Where G_i and Ω_i are the mean gain and the solid angle of the lobe, respectively, T_G the ground contribution is depending on elevation

    T_G = 290 K for $\varepsilon < -10°$ $\quad$ T_G = 150 K for $-10° < \varepsilon < 0°$

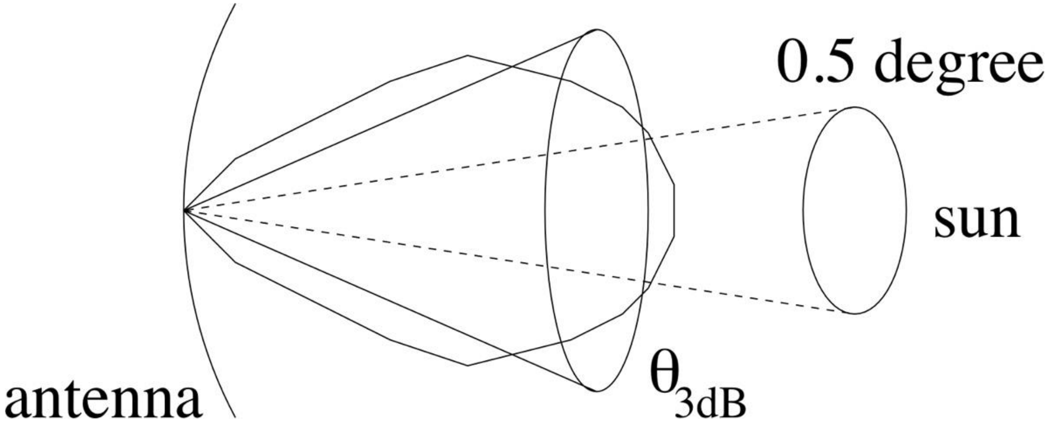
    T_G = 50 K for $0° < \varepsilon 10°$ $\quad$ T_G = 10 K for $10° < \varepsilon < 90°$

- Satellite antenna noise temperature:
  - Satellite captures noise from the earth and space
  - Satellites ”sees” the earth approximately as ”black body” of about 290 K
  - Thus there is always high antenna noise temperature onboard satellites
  - Not much can be gained by using LNAs onboard satellites



What is the system noise temperature T_s?

- Additional noise due to sun interference

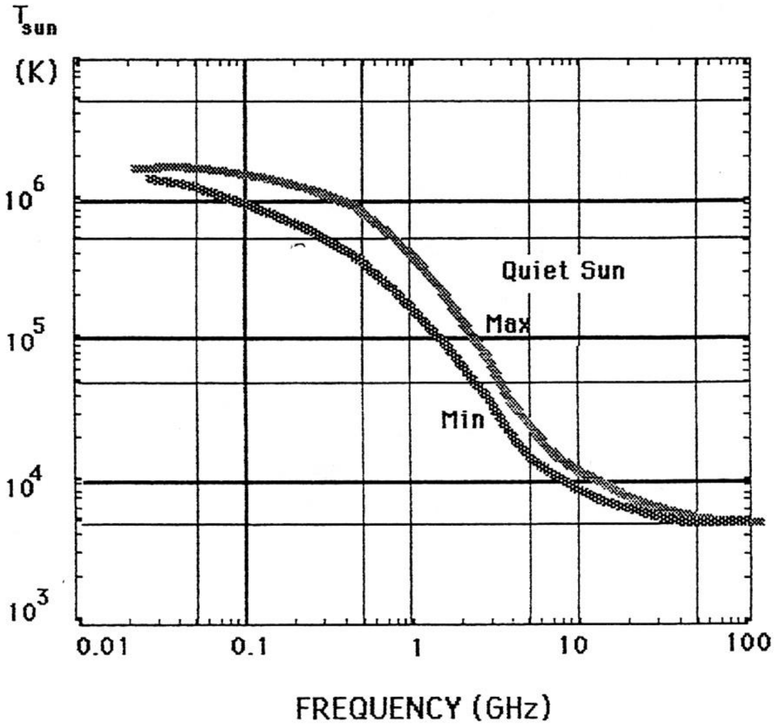


$$\Delta T_A = T_{sun}\left(\frac{0.5}{\theta_{3dB}}\right)^2 \quad \text{if} \quad \theta_{3dB} > 0.5^\circ$$

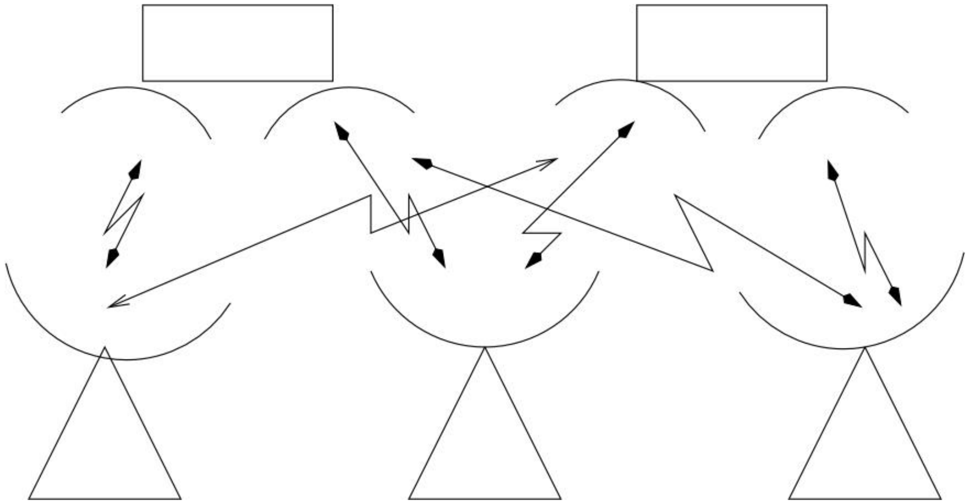
$$\Delta T_A = T_{sun} \quad \text{if} \quad \theta_{3dB} \le 0.5^\circ$$

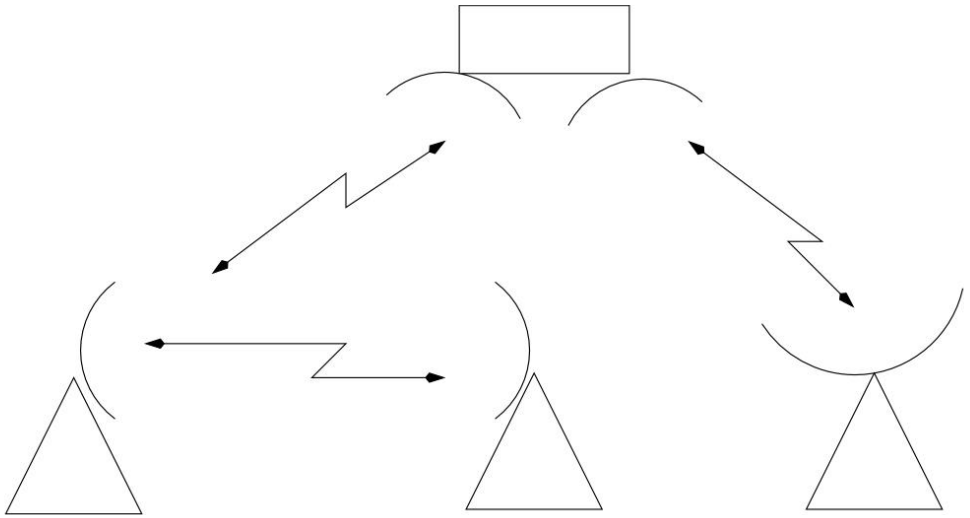
The mean brightess temperature of the sun is frequency dependent, e.g.:

$$T_{Sun} = \frac{1.9610^5}{f}\left[1 + \frac{\sin 2\pi\left(\frac{\log 6(f-0.1)}{2.3}\right)}{2.3}\right]$$



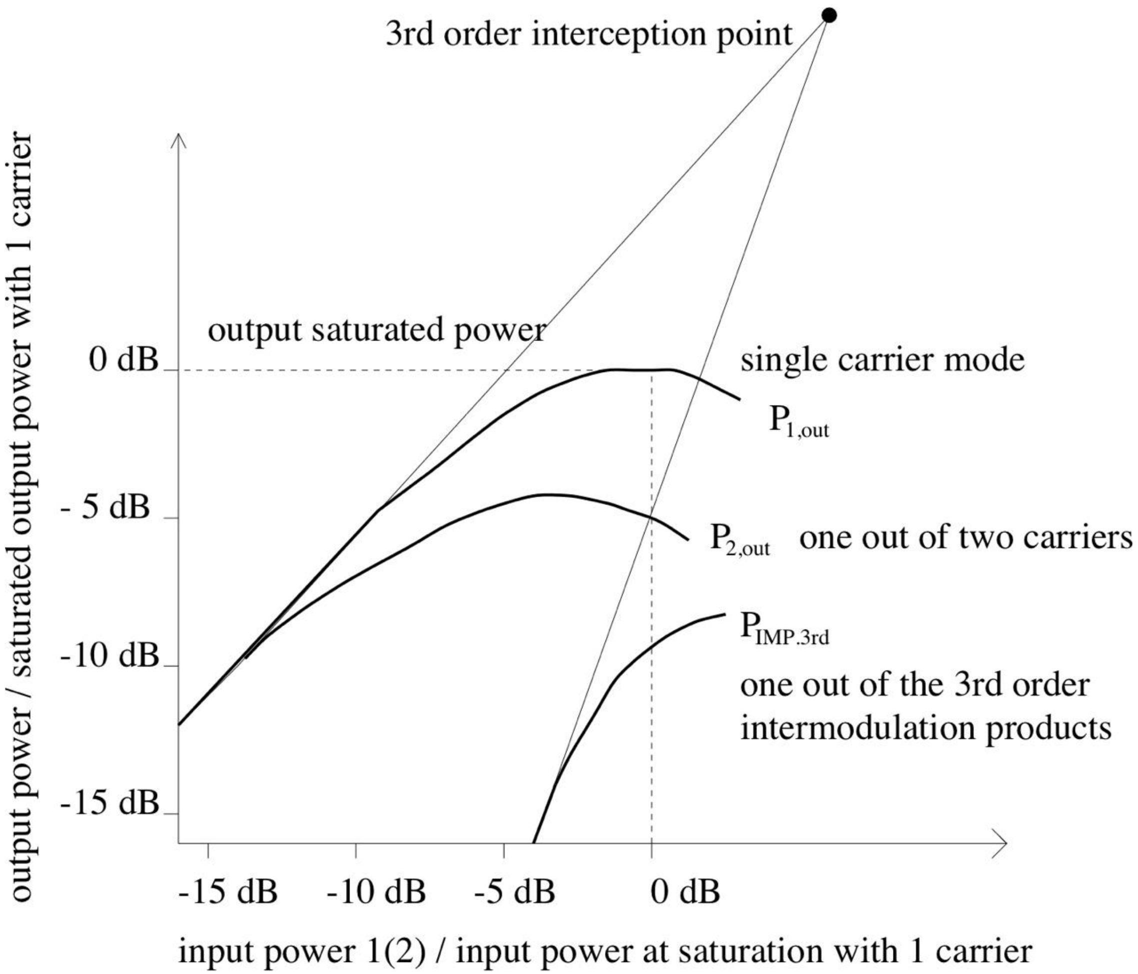
- Interference noise:
  - Between different satellite systems
  - Between satellite and terrestrial systems





- Intermodulation noise:
  - Due to non-linearity of satellite transponders
  - Transponders have a saturation point
  - Intermodulation products are generated when the transponder is operated in the saturation region

Simplified model of a satellite channel:

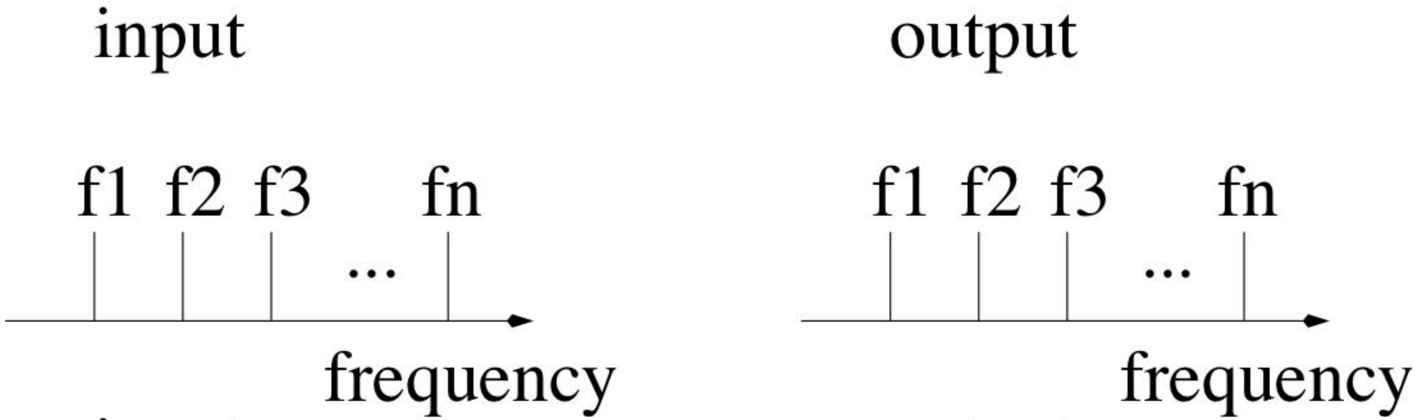


- Output in linear region is the amplified carriers
- Output in the saturation region is amplified carriers plus intermodulation products f_{IM}:

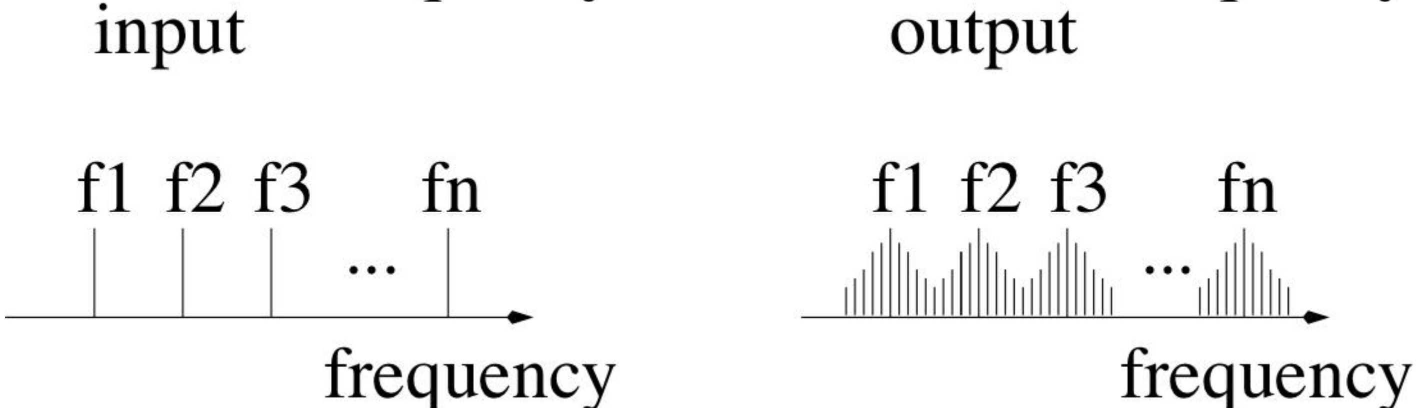
$$f_{IM} = m_1 \cdot f_1 + m_2 \cdot f_2 + \cdots + m_n \cdot f_n$$

- Only odd products of intermodulation noise are dangerous
- 3rd and 5th order intermodulation products are most important
- Of interest is the third order interception point

Linear Operation



Operation in Saturation region



- Repeater as non-linear device:
  - Input voltage of e.g. two carriers with $f_i=\omega_i$

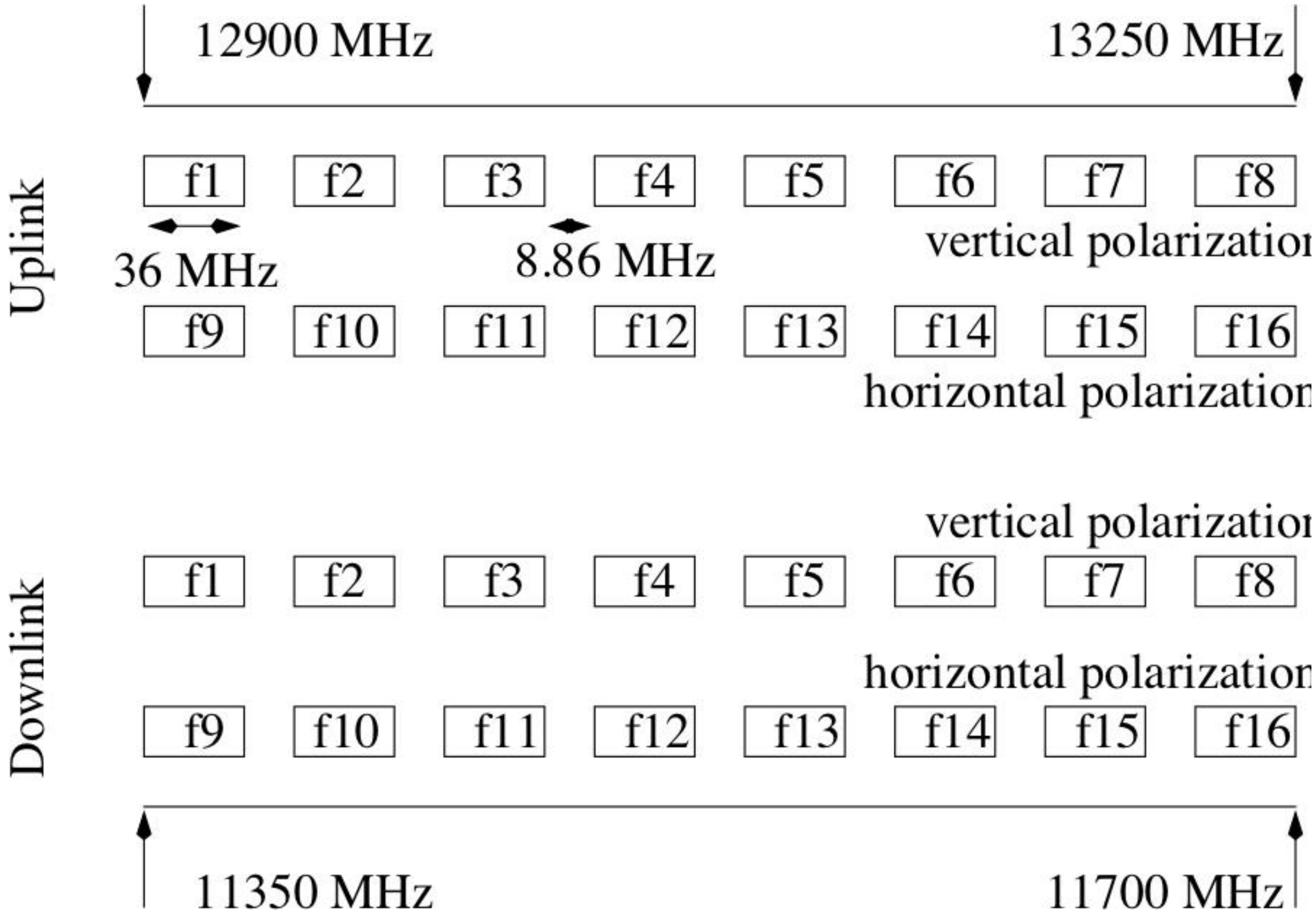
$$V_i = A \times \cos(w_1 \times t) + B \times \cos(w_2 \times t)$$

  - Output voltage includes higher order products

$$\begin{aligned}
V_o = {} & a \times \left(A \times \cos(w_1 \times t) + B \times \cos(w_2 \times t) \right) \\
& + b \times \left(A \times \cos(w_1 \times t) + B \times \cos(w_2 \times t) \right)^2 \\
& + c \times \left(A \times \cos(w_1 \times t) + B \times \cos(w_2 \times t) \right)^3 \\
& + \ldots + \\
& + \ldots + \frac{3}{4} c \times A^2 \times B \times \cos\left((2 \times w_1 - w_2) \times t \right) \\
& + \ldots + \frac{3}{4} c \times B^2 \times A \times \cos\left((2 \times w_1 - w_2) \times t \right)
\end{aligned}$$

Example for a satellite payload:

16 transponders with 36 MHz each, uplink frequencies 12.90–13.25 GHz and downlink frequencies 11.25–11.70 GHz



f1=12918.00 MHz	f5=13097.43 MHz
f2=12962.86 MHz	f6=13142.29 MHz
f3=13007.71 MHz	f7=13187.14 MHz
f4=13052.57 MHz	f8=13232.00 MHz

- 2nd order intermodulation products:
  => outside carriers
- 3rd order intermodulation products:
  => affect f2 and f5
- 4th order intermodulation products:
  => outside carriers
- 5th order intermodulation products:
  => affect f6 and f1

Example-2

A satellite transponder with power P_{tx} = 10 W is connected via a feeder (feeder loss $L_{f.tx}$ = 1 dB) to a transmitting antenna with maximal gain G_{max} = 33 dBi and depointing loss L_t = 3 dB. An earth station with a reflector of diameter D = 3.6 m and aperture efficiency of 0.6 is connected via a feeder of loss $L_{f.rx}$=0.5 dB with physical temperature $T_{ph.fd}$ = 290 K to a receiver with effective input noise temperature of $T_{e.rx}$ = 60 K. The depointing loss of the antenna is L_t = 1 dB and the half-power beam-width of the reflector is θ_{3dB}= 0.5 degrees. The sky temperature is T_{sky} = 8 K and the ground noise temperature is T_{Ground} = 20 K. The free space loss is L_{FS} = 206 dB.

Questions:

1. What is the system noise temperature T_{sys} of the earth station under clear-sky conditions?

2. What is the system noise temperature of the earth station under rain conditions, assuming a rain attenuation of $A_{rain} = 6$ dB and thermodynamic temperature of $T_{ph} = 275$ K?

3. What does the the rain mean for the link performance of this downlink?

Suggested solutions

Antenna temperature in clear sky: $T_A = T_{sky} + T_{ground} = 28$ K

$T_{A.clear\text{-}sky} = 28$ K

Antenna temperature in rain: $T_A = T_{sky}/A_{rain} + T_m\,(1\text{-}1/A_{rain}) + T_{ground}$

$T_{A.rain} = 228$ K

System noise temperature: $T_S = T_A/L_{f.rx} + T_{ph.frx}\,(1\text{-}1/L_{ph.frx}) + T_{e.RX}$

1) T_S in clear sky: $T_S = 117$ K

2) T_S in rain: $T_S = 295$ K

Suggested solutions

Satellite EIRP: $EIRP = P_{tx} + G_{t.max} - L_{ftx} - L_t$

$EIRP = 39$ dBW

Gain of earth station: $G_{r.max} = \eta \cdot ((\pi \cdot 70°)/\theta_{3dB})^2$ [/]

$G_{r.max} = 51$ dBi

$G_r = G_{r.max} - L_r - L_{frx} = 49.5$ dBi

Suggested solutions

Figure of merit of earth station: $(G/T)_{es} = G_r - T_S$

$(G/T)_{es}$ in clear sky: $(G/T)_{es} = 28.5\ dBi\ K^{-1}$

$(G/T)_{es}$ in rain: $(G/T)_{es} = 24.5\ dBi\ K^{-1}$

Path loss:

L_{path} in clear sky: $L_{path} = L_{FS}$ = 206 dB

L_{path} in rain: $L_{path} = L_{FS} + A_{rain}$ = 212 dB

Suggested solutions

Downlink performance: $(C/N_0)_{down} = EIRP - L_{path} + (G/T_S)_{es} - k$

$(C/N_0)_{down}$ in clear sky:	$(C/N_0)_{down} = 90.1$ dBHz
$(C/N_0)_{down}$ in rain:	$(C/N_0)_{down} = 80.1$ dBHz

3) Rain reduces the system performance by 10 dB.

Short summary of today's topics

- Noise models
- Noise temperature, effective input noise temperature
- Noise figure
- System noise temperature T_{sys}
- Cascades systems
- Figure of merit
- Gases and rain
- Non-linear devices, intermodulation noise