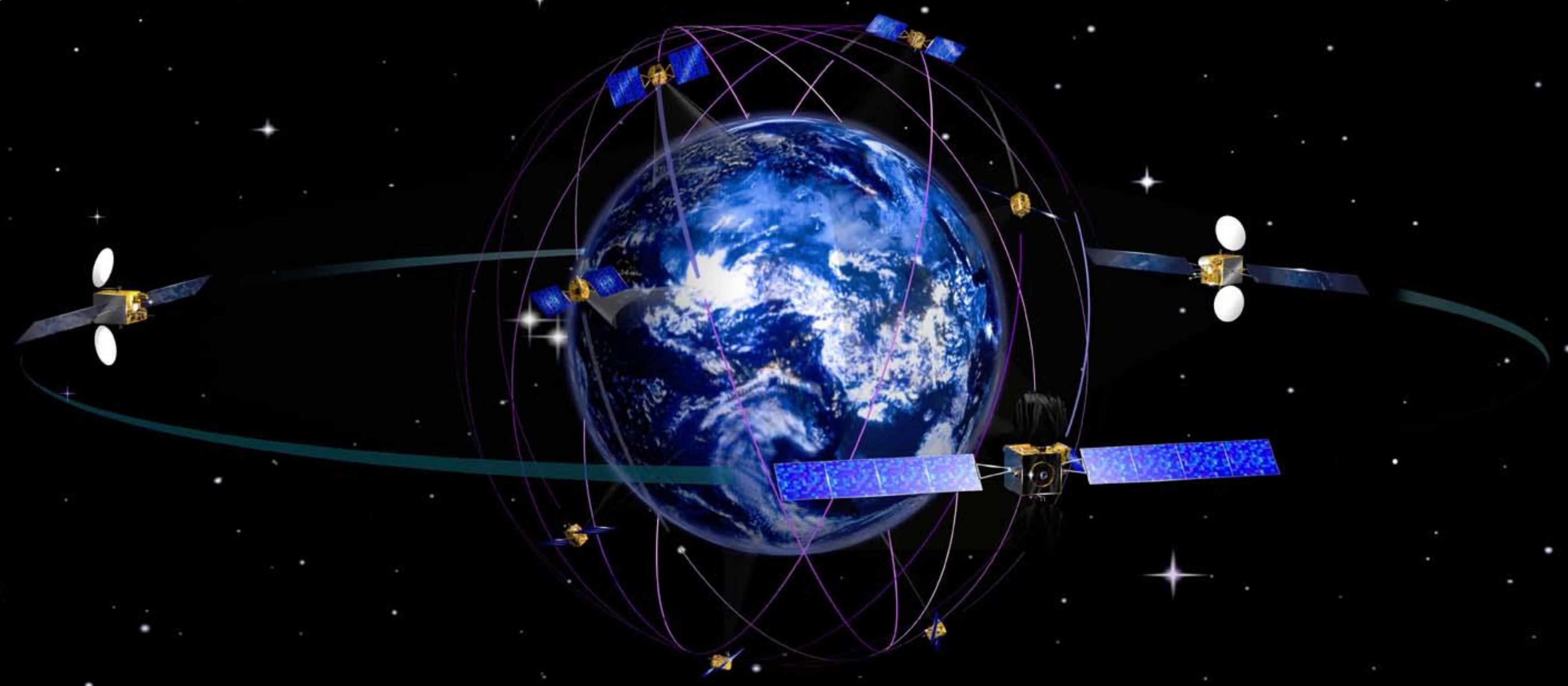
Satellite Communications
– RRY100 –

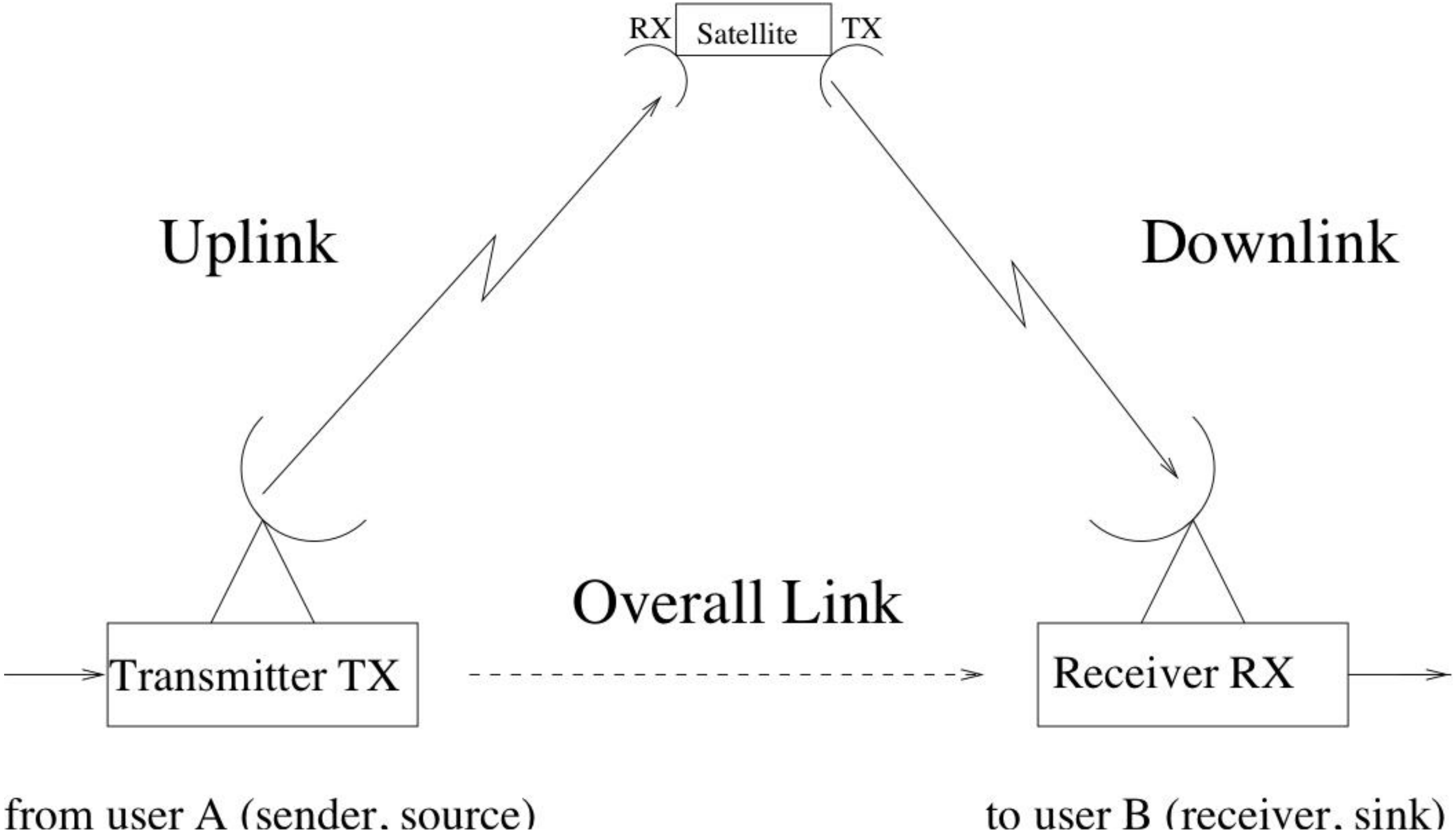


2024 Study Period 1

Lecturer: Rüdiger Haas

Lecture-2: Link analysis

A satellite communications link:



- Satellite communications links:
  - Uplink: from earth station transmitter to satellite receiver
  - Downlink: from satellite transmitter to earth station receiver
  - Overall link: performance of the overall radiofrequency (RF) link depends on the performance of the RF uplink and the RF downlink

- Purpose of link analysis:
  - Identify parameters that condition the link quality
  - Establish a balance of gains and losses for carrier and noise
  - Identify hardware constraints (power amplifiers, antenna type and size, low noise amplifiers, losses, …)

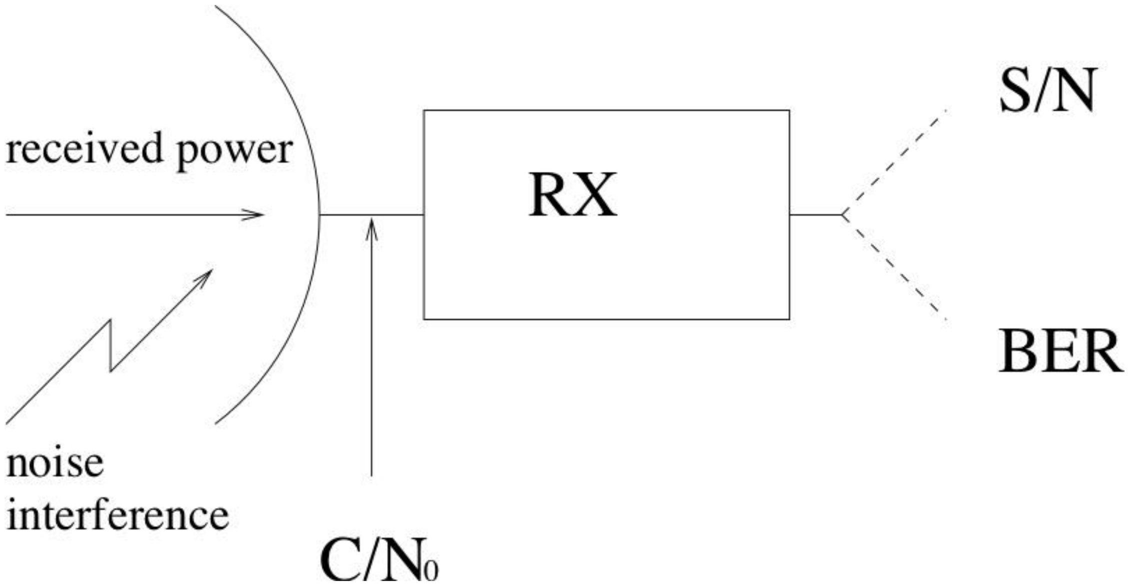
Link performance objectives

- RF link performance:

  C/N_0

- User link performance:

  S/N, BER, system availability, propagation time



RF link performance

- the measure of RF link performance is the ratio of carrier power C and noise spectral density N_0 **at the receiver input**

=> C/N_o <=

- C is the power of the received carrier in [W]
  (power of the wanted signal)
- N_0 is the power spectral density of noise in [W/Hz]
  (energy/frequency of the unwanted signal)

User link performance

- Signal quality
  - Depending on modulation type S/N or BER
  - e.g. BER below a threshold for x % of time
  - (e.g. BER < 10e-6 for 20 % of the time)
- System availability
  - SysAv = (required time – down time) / (required time)
- Propagation time
  - (e.g. PropTime < User defined threshold)

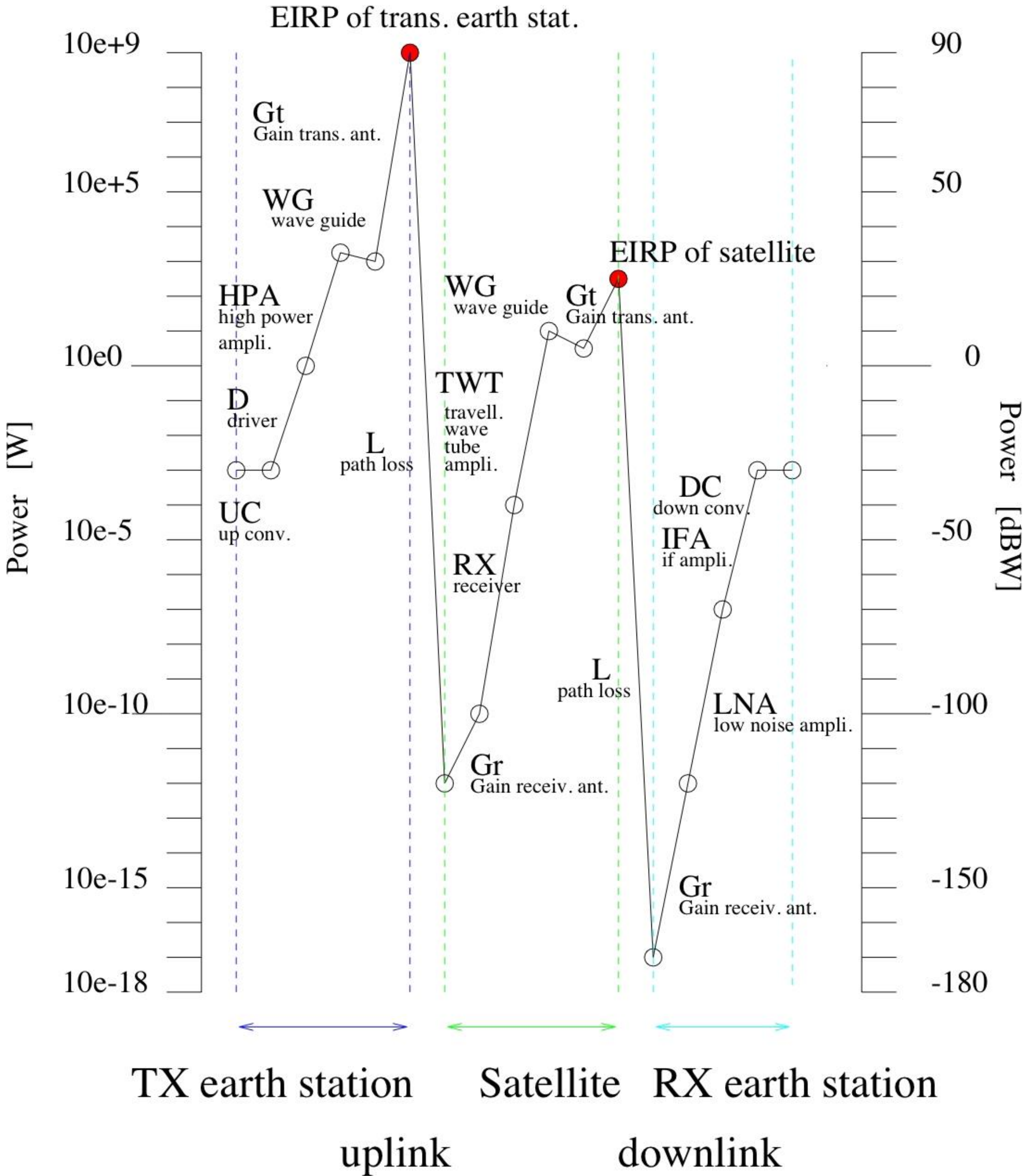
A power budget visualizes

- power levels
- gains and losses

Either in form of a graph or a table.

A complete link budget compares
power and noise

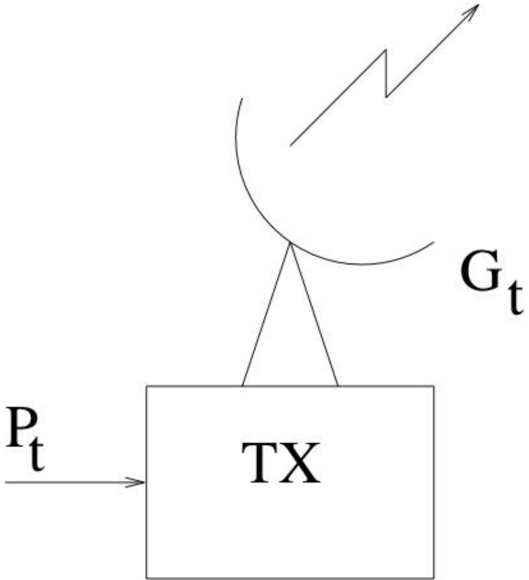
Figure on the right:
A typical power budget for a geostationary INTELSAT satellite.

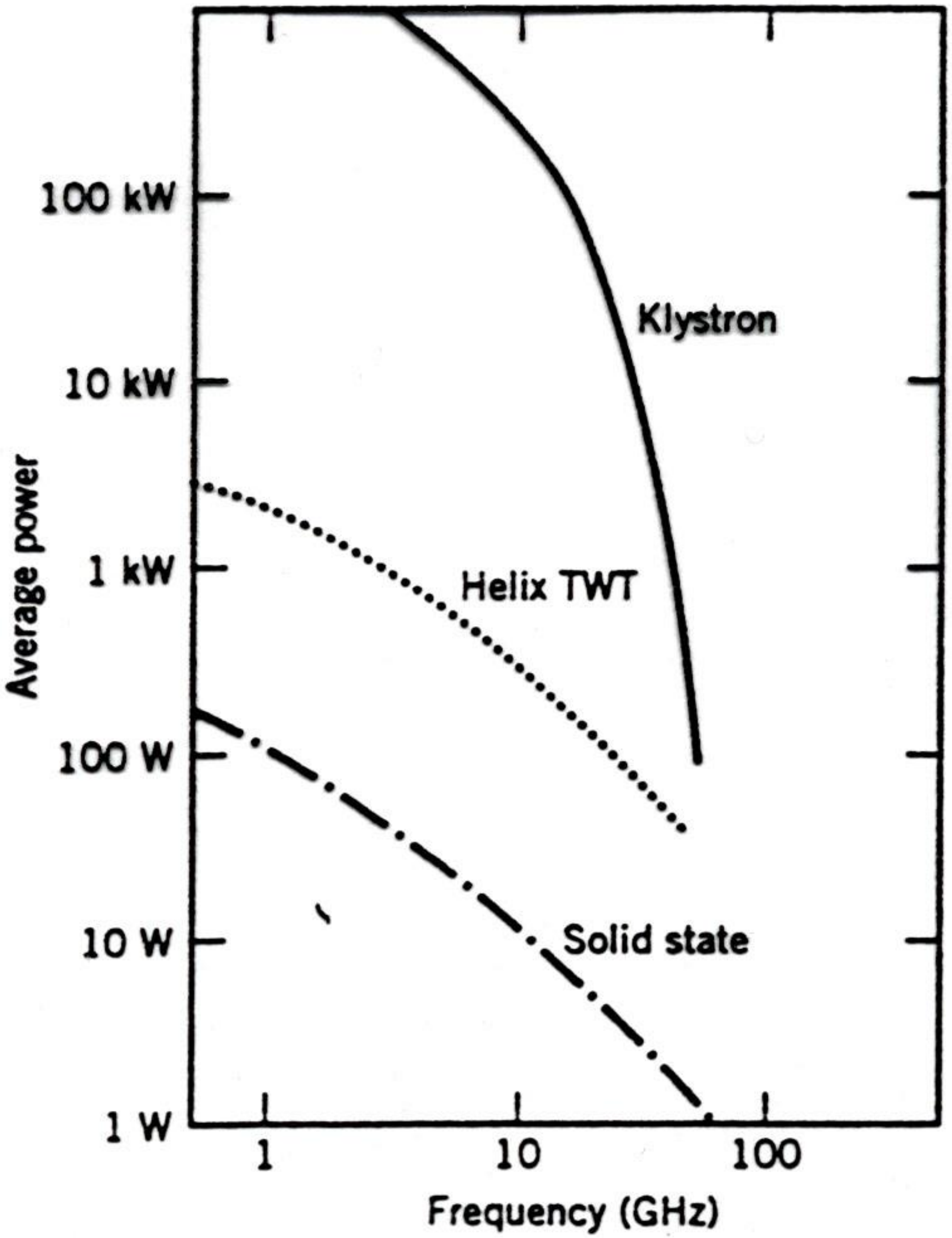


- Influences on the links to be studied:
  - Uplink
    - Transmitting earth station (electronics, antenna)
    - Uplink path (atmospheric conditions)
    - Receiving satellite (antenna, electronics)
  - Downlink
    - Transmitting satellite (electronics, antenna)
    - Downlink path (atmospheric conditions)
    - Receiving earth stations (antenna, electronics)
  - Overall link
    - Depends on both uplink and downlink
    - Depends on repeater architecture (transparent or regenerative)

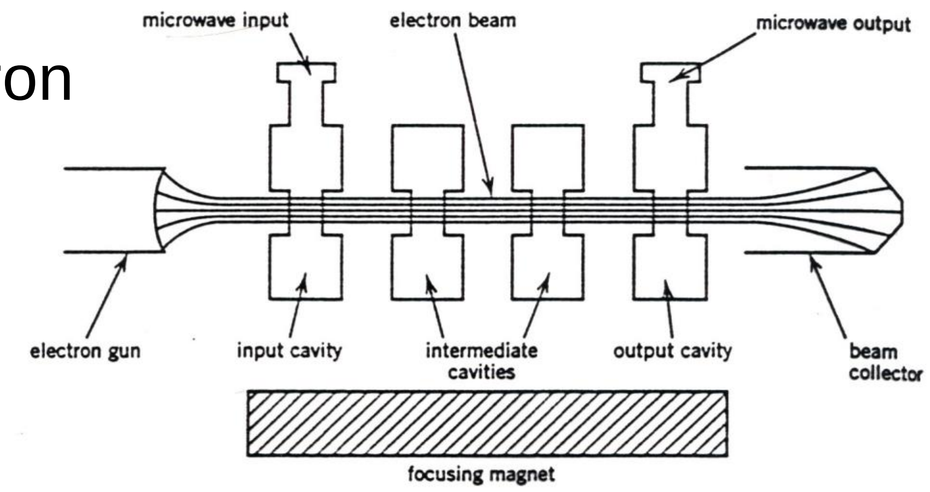
- Link budget calculation:

  - We start with the transmitting side (TX):
  - The first number to start a link budget calculation with is the transmitter power P_t
  - Typical values for earth stations: 1 W – 10 kW
  - Typical values for satellite transponders: 10 – 200 W
  - Klystron: very powerful, several kW, large in size, needs cooling, used for ground stations only
  - Travelling Wave Tube (TWT): up to some kW, ground stations and onboard satellites
  - Solid State Power Amplifiers (SSPA): several 100 W, used onboard satellites

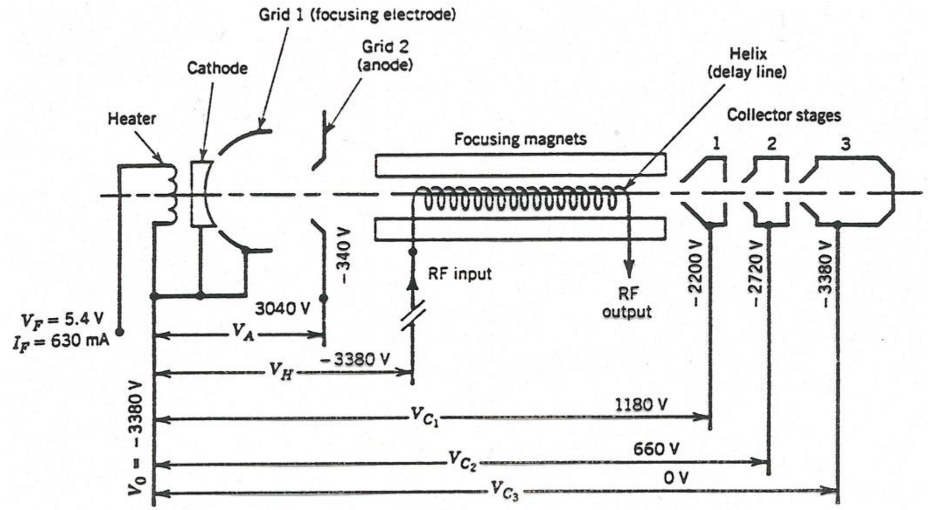




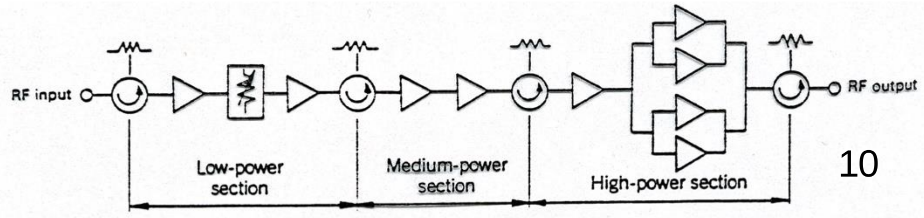
Klystron



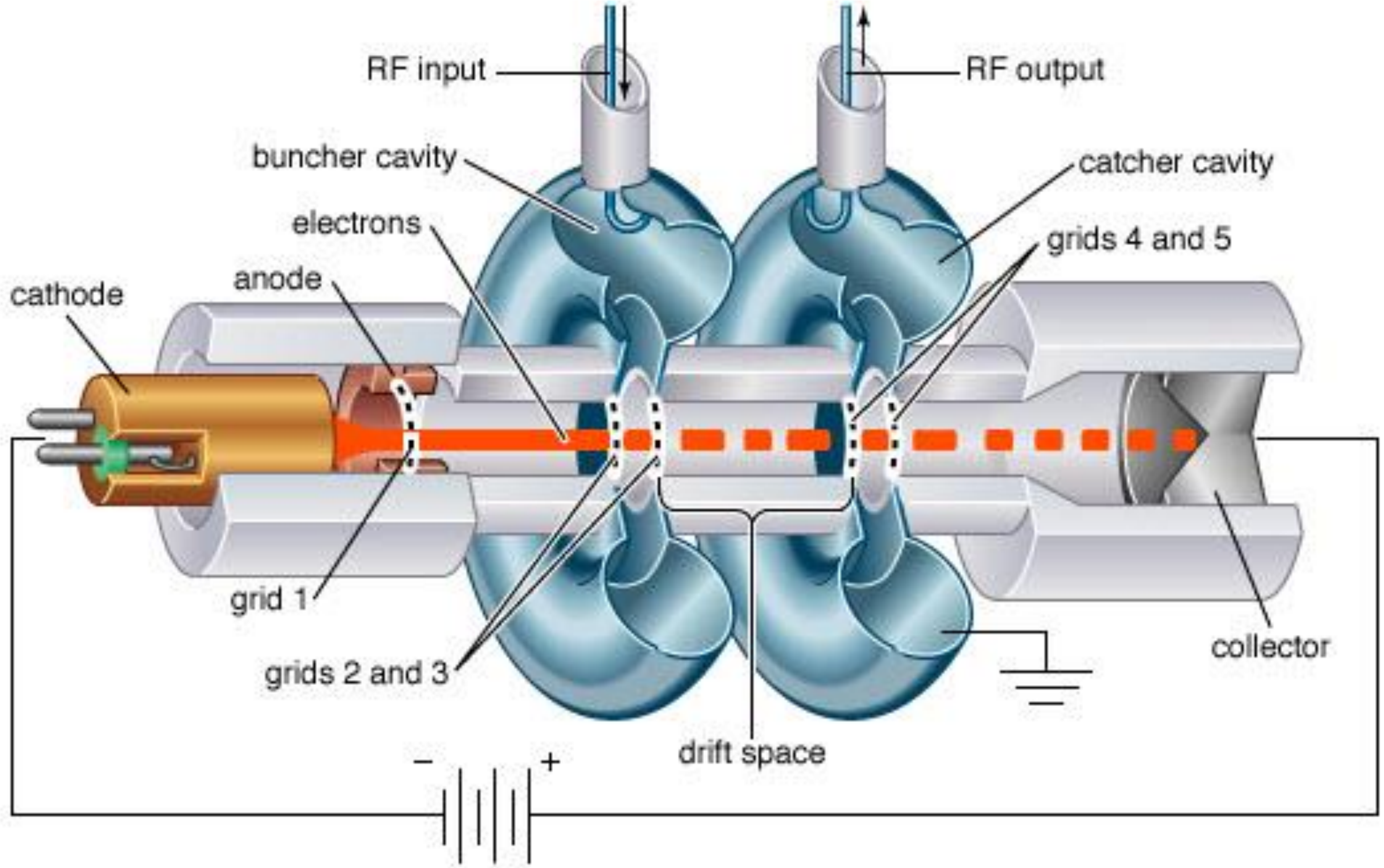
TWTA



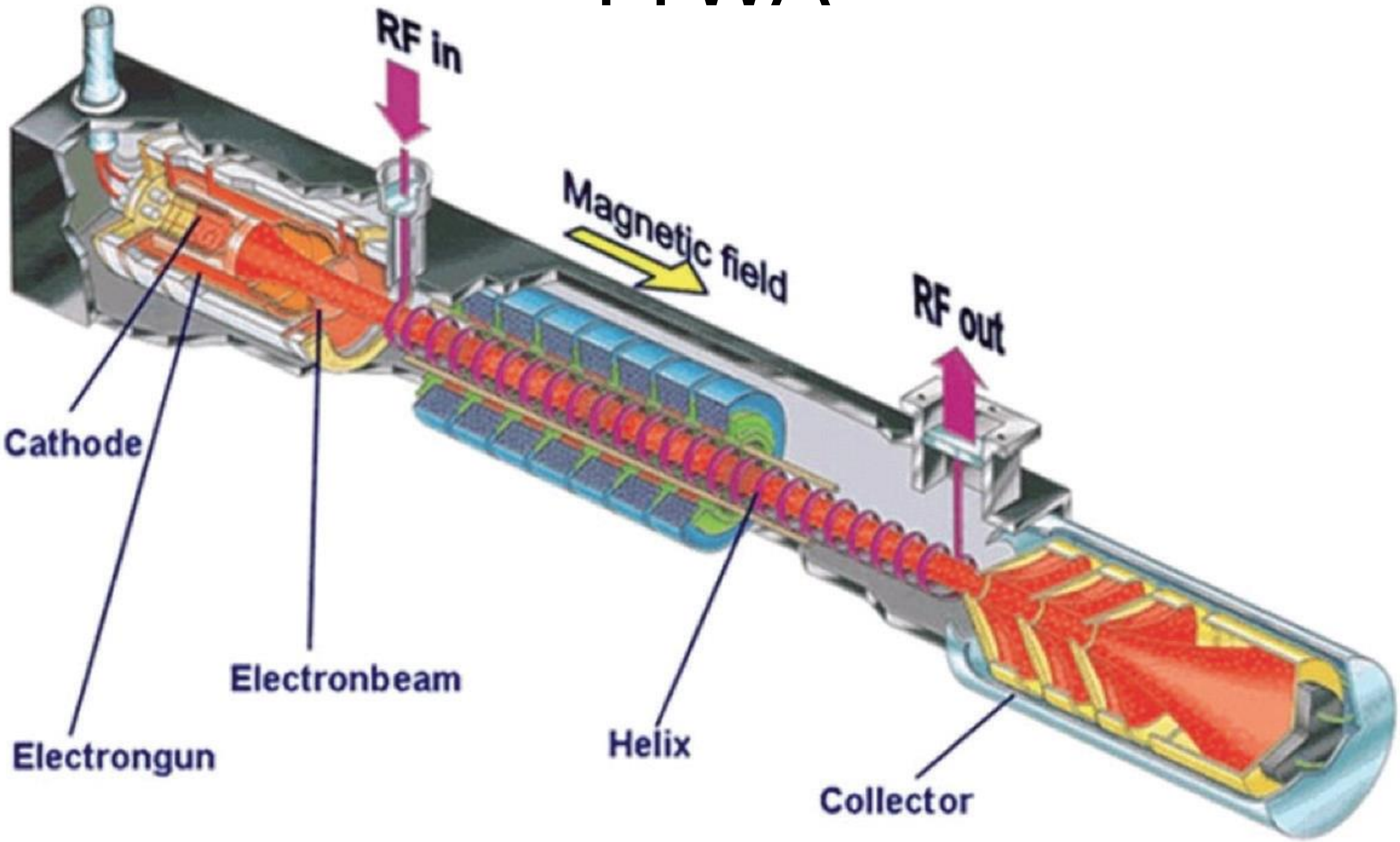
SSPA



Klystron


RF input
RF output
buncher cavity
catcher cavity
electrons
grids 4 and 5
anode
cathode
grid 1
collector
grids 2 and 3
drift space
−
+

TTWA


RF in
Magnetic field
RF out
Cathode
Electronbeam
Electrongun
Helix
Collector

SSPA

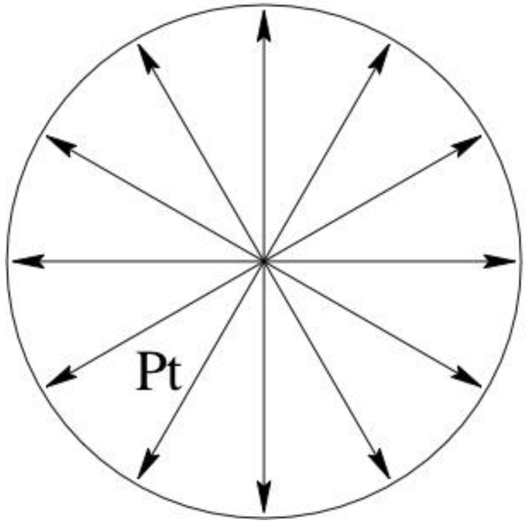
L-band

X-band

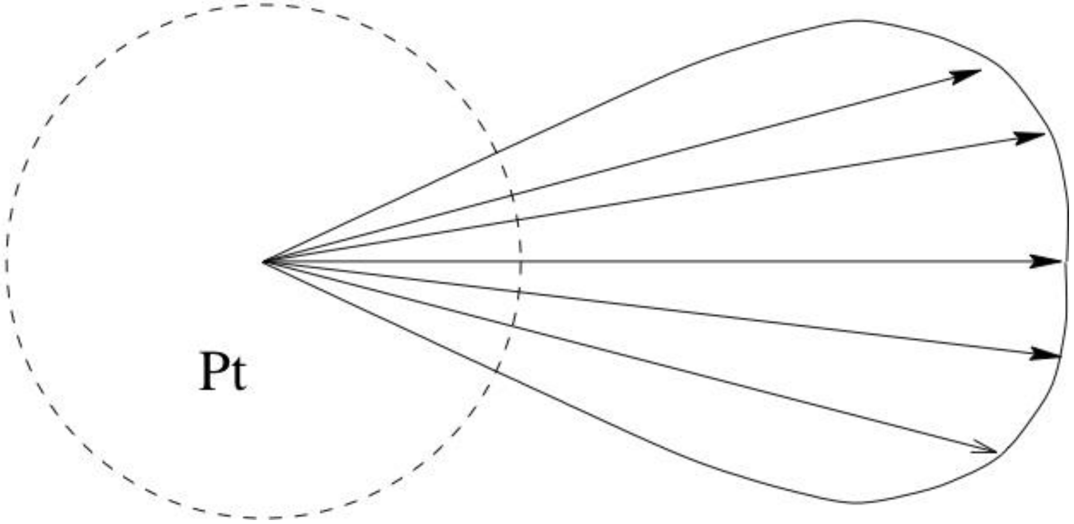
- Antenna:
  - Purpose is to focus the power in the direction of the receiver
  - Effectiveness of an antenna is measured as antenna gain G
  - Gain depends on wavelength and effective aperture of the antenna
  - Gain is usually expressed in units [dBi], where the ”i” refers to isotropic radiation

$$G = \frac{\text{(power transmitted with the antenna toward the receiver)}}{\text{(power transmitted without the antenna, i.e. isotropically)}}$$

Isotropic antenna



Actual directive antenna



Hypothetic isotropic antenna.
=> Cannot be build.
The best approximation
is maybe a star, e.g. the Sun

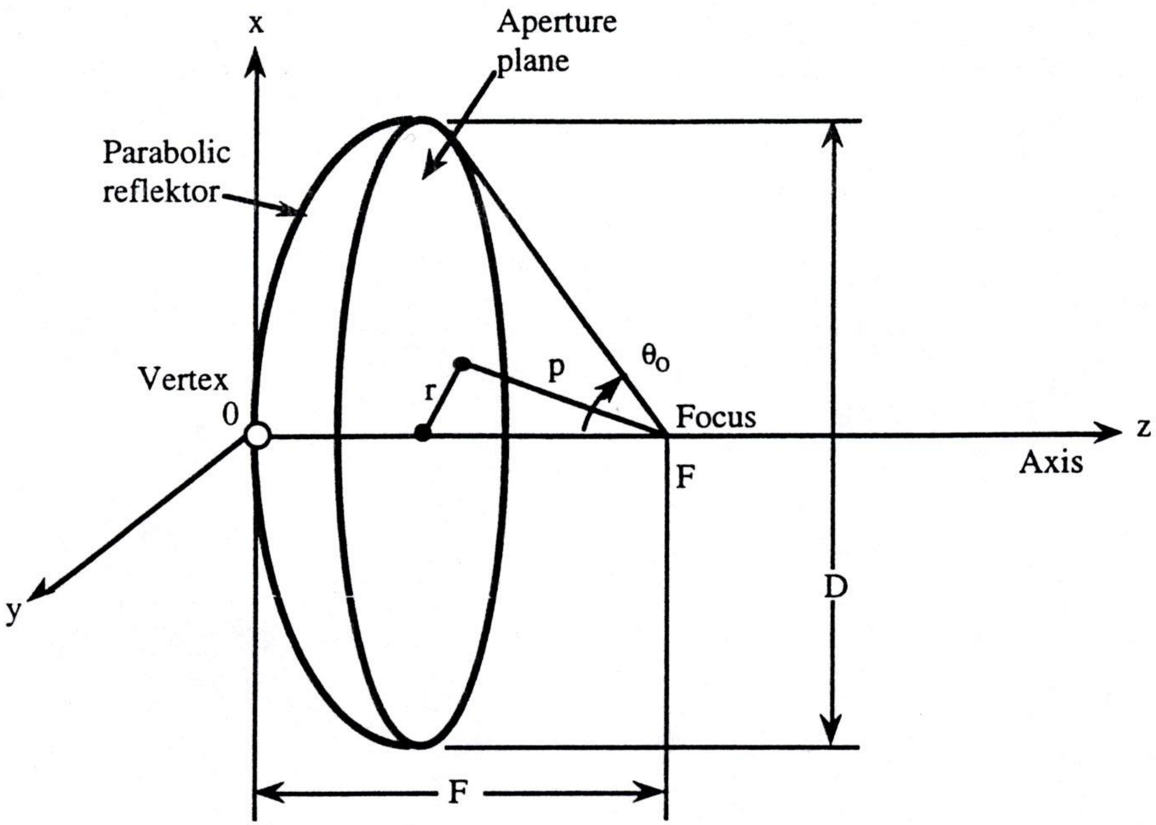
- Typical example reflector antenna:
  - Aperture is a disc with diameter D and area A: $A = \pi \cdot D^2 / 4$
  - There are losses due to unwanted reflections etc.
  - Aperture efficiency factor η typical values 0.4–0.8: $A_{eff} = \eta \cdot A$

- Gain of a reflector antenna (in natural values):

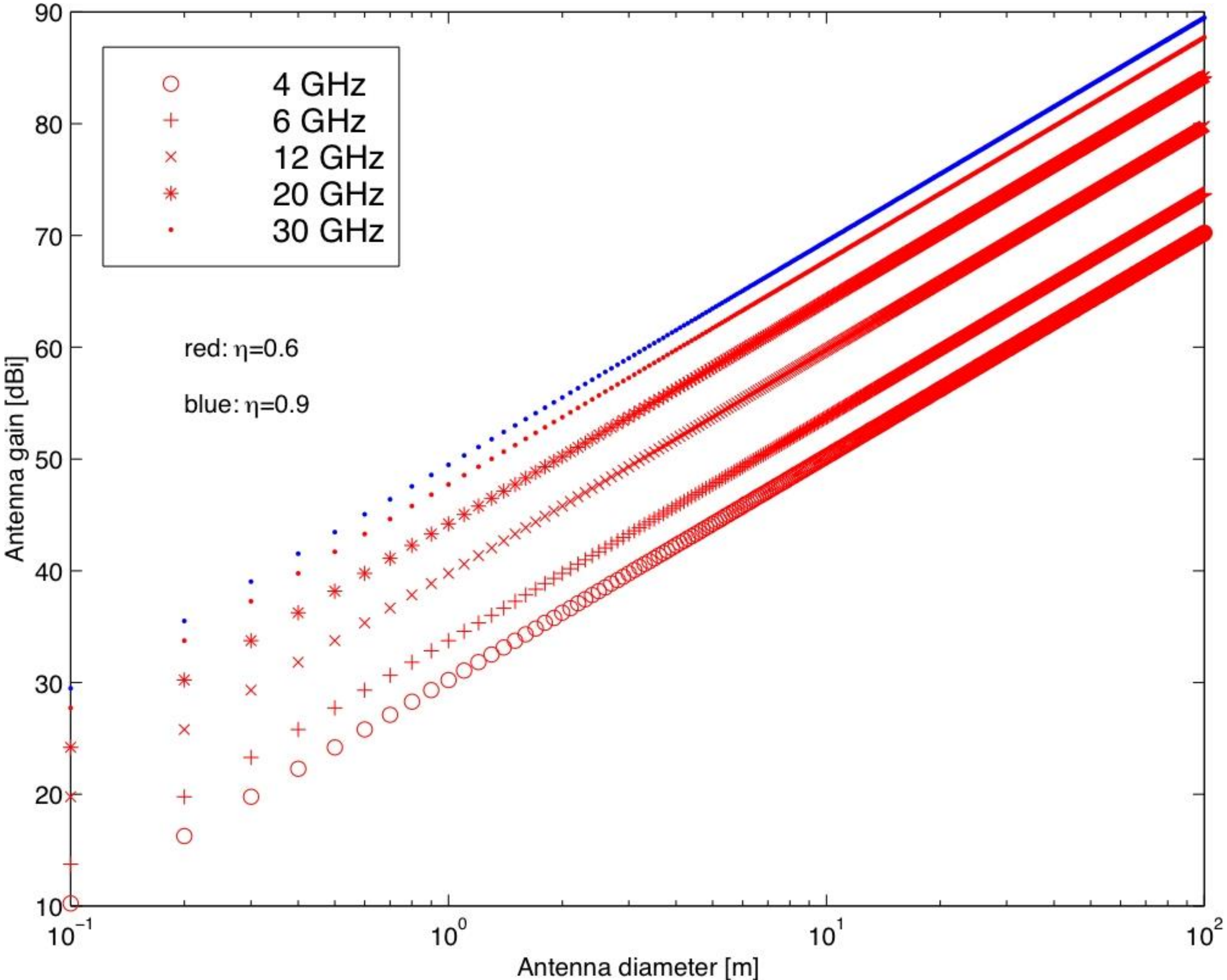
$$G = \left(\frac{4 \cdot \pi}{\lambda^2}\right) \cdot A_{eff} = \left(\frac{4 \cdot \pi}{\lambda^2}\right) \cdot \frac{\pi \cdot D^2}{4} \cdot \eta$$

$$= \eta \cdot \left(\frac{\pi \cdot D}{\lambda}\right)^2 = \eta \cdot \left(\frac{\pi \cdot D \cdot f}{c}\right)^2$$

Example of a parabolic reflector antenna



Reflector antenna: Gain as a function of antenna diameter, frequency and aperture efficiency



Reflector antenna: Gain as a function of antenna diameter, frequency and aperture efficiency

- Antenna diameter and antenna efficiency fixed:

  => higher frequency gives higher gain

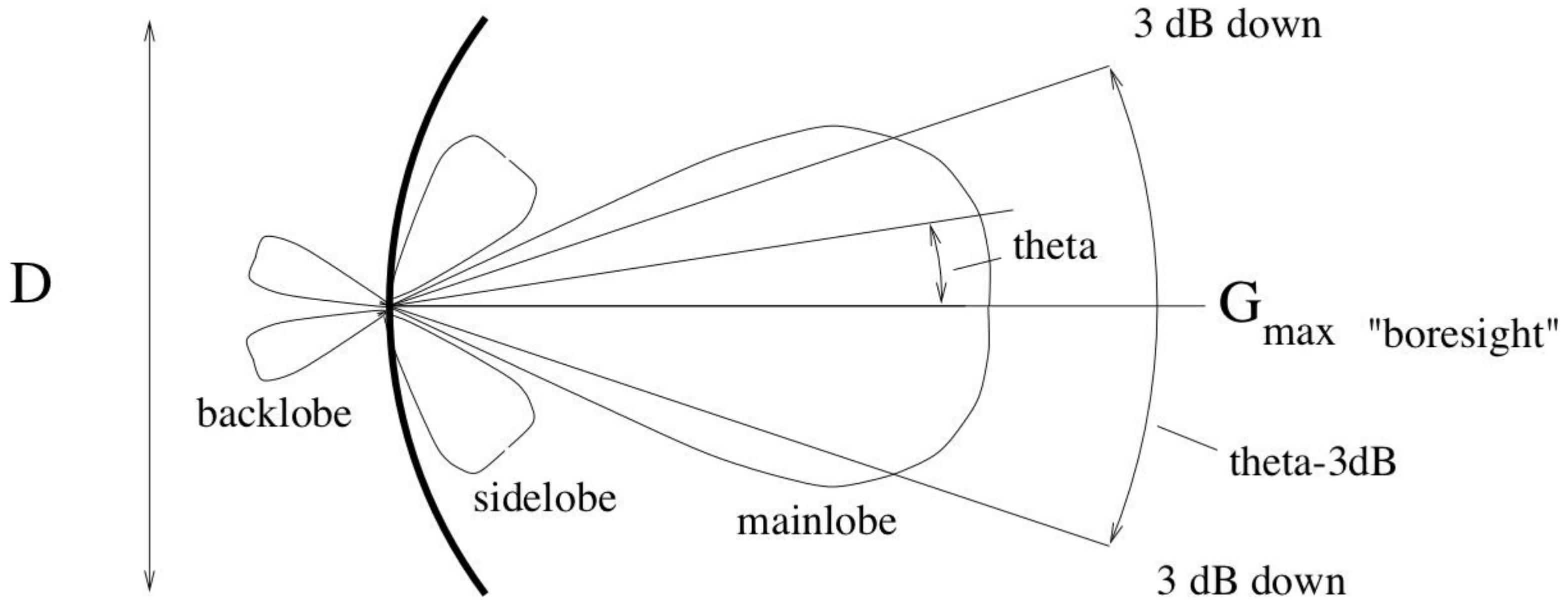
- Frequency and antenna efficiency fixed:

  => larger antenna diameter gives higher gain

- Antenna diameter and frequency fixed:

  => higher antenna efficiency gives higher gain

- Radiation pattern of a reflector antenna:
  - Main lobe, side lobes, even back lobes (!)
  - Maximal gain G_{max} in direction ”boresight”
  - The full angular width between the directions where the gain reduced by 3 dB below the maximal gain G_{max} is called the half-power beam width (HPBW), θ_{3dB}



- Gain in a specific direction can be calculated from G_{max} and θ_{3dB} :

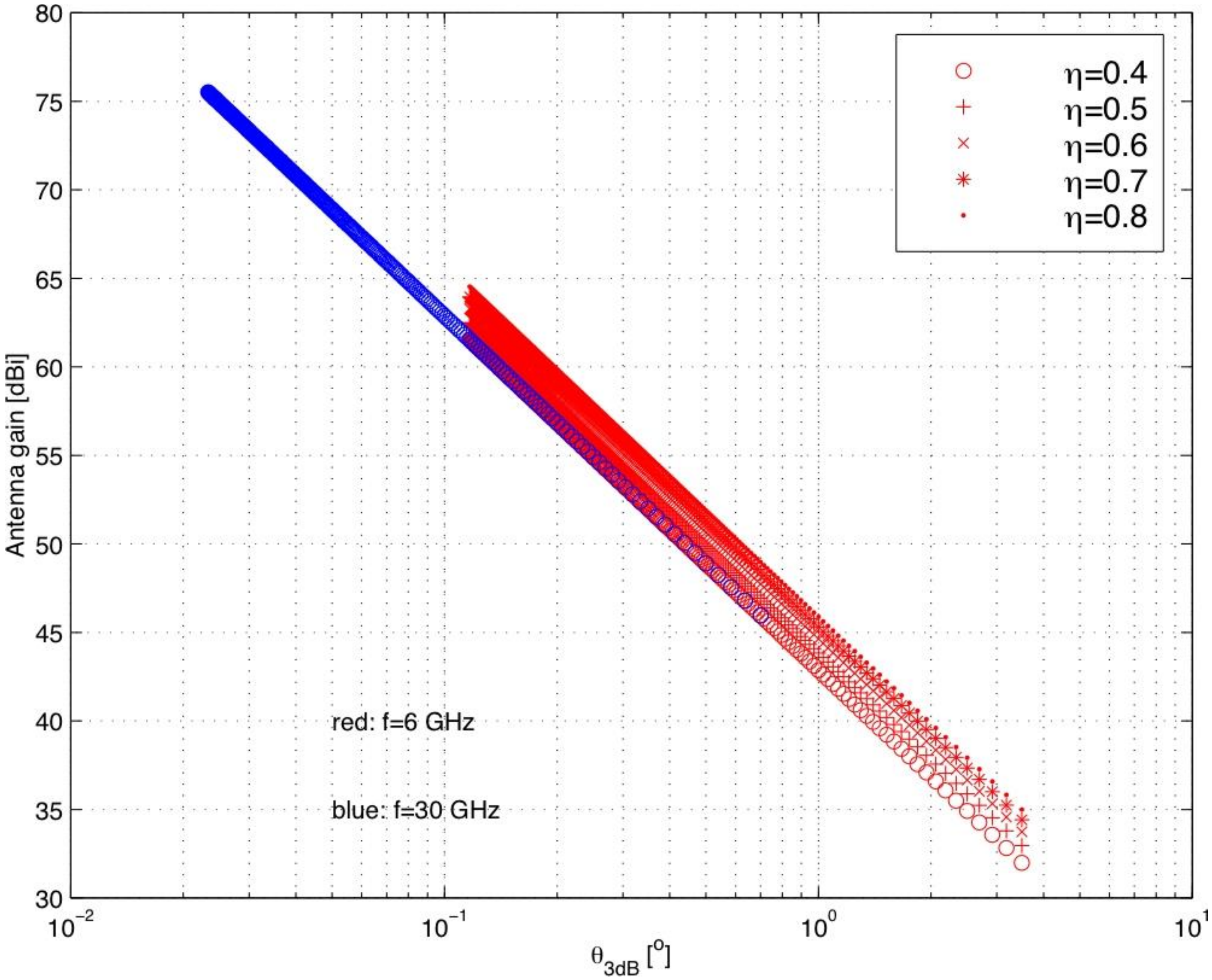
$$\theta_{3dB} = 70^o \cdot \frac{\lambda}{D} = \frac{70^o \cdot c}{D \cdot f} \quad \text{(in degrees)}$$

$$G(\theta) = G_{\max} - 12 \cdot \left(\frac{\theta}{\theta_{3dB}} \right)^2 \quad \text{(in dBi)}$$

- Gain and θ_{3dB} are related to each other (independent of frequency!):

$$G_{\max} = \eta \cdot \left(\frac{\pi \cdot 70^o}{\theta_{3dB}} \right)^2$$

Reflector antenna: Gain as a function of θ_{3dB}, frequency and aperture efficiency



Reflector antenna: Gain as a function of θ_{3dB}, frequency and aperture efficiency

- Keeping frequency and aperture efficiency fixed:

  => large gain corresponds to small half-power beam width;

  => low gain to wide half-power beam width

- Keeping frequency and half-power beam width fixed:

  => higher aperture efficiency gives higher gain

- Keeping antenna dimensions and aperture efficiency fixed:

  => higher frequency gives higher gain and lower half-power beam width

- Power flux density
  - Power flux density F = power per unit area [W/m^2]
  - A hypothetic isotropical antenna would illuminate a sphere with gain 1
  - But a reflector has gain G_t, so:

$$F = \frac{P_t \cdot G_t}{4 \cdot \pi \cdot R^2} \qquad [\mathrm{W/m^2}]$$

- Effectively isotropically radiated power EIRP:

$$EIRP = P_t \cdot G_t \qquad [\mathrm{W}]$$

Example-1

- A transmitter with power P_t=10 W and an antenna with gain G_t=40 dBi sends to a receiver at 36000 km distance.

- 1) What is the EIRP of the transmitter?
- 2) What is the flux density at the receiver?

Solutions for example-1

- $EIRP = P_t\ [dBW] + G_t\ [dBi]$

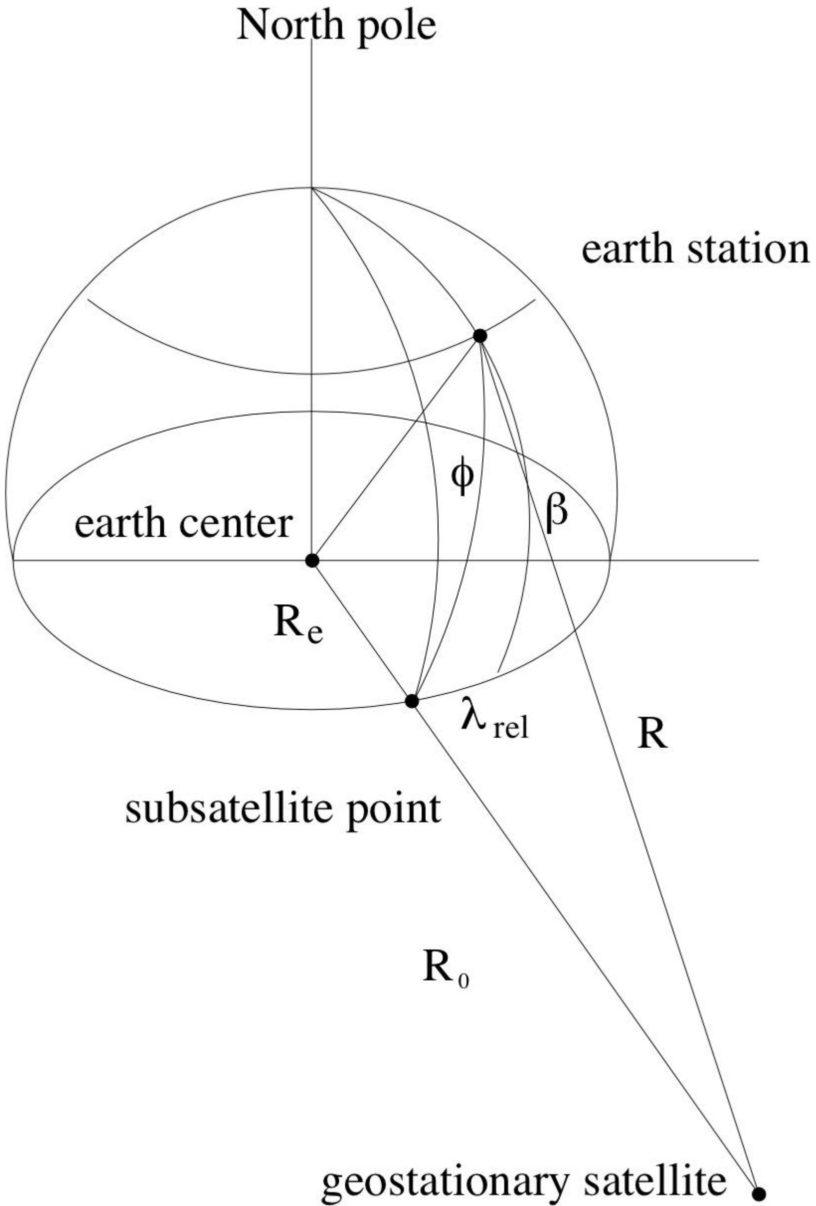
  $= 10\ [dBW] + 40\ [dBi] = 50\ [dBW]$

- $F = EIRP – 10 \cdot \log_{10} (4 \cdot \pi \cdot R^2)$

  $= 50\ [dBW] – 162.12\ [dBm^{-2}]$

  $= – 112\ [dBWm^{-2}]$

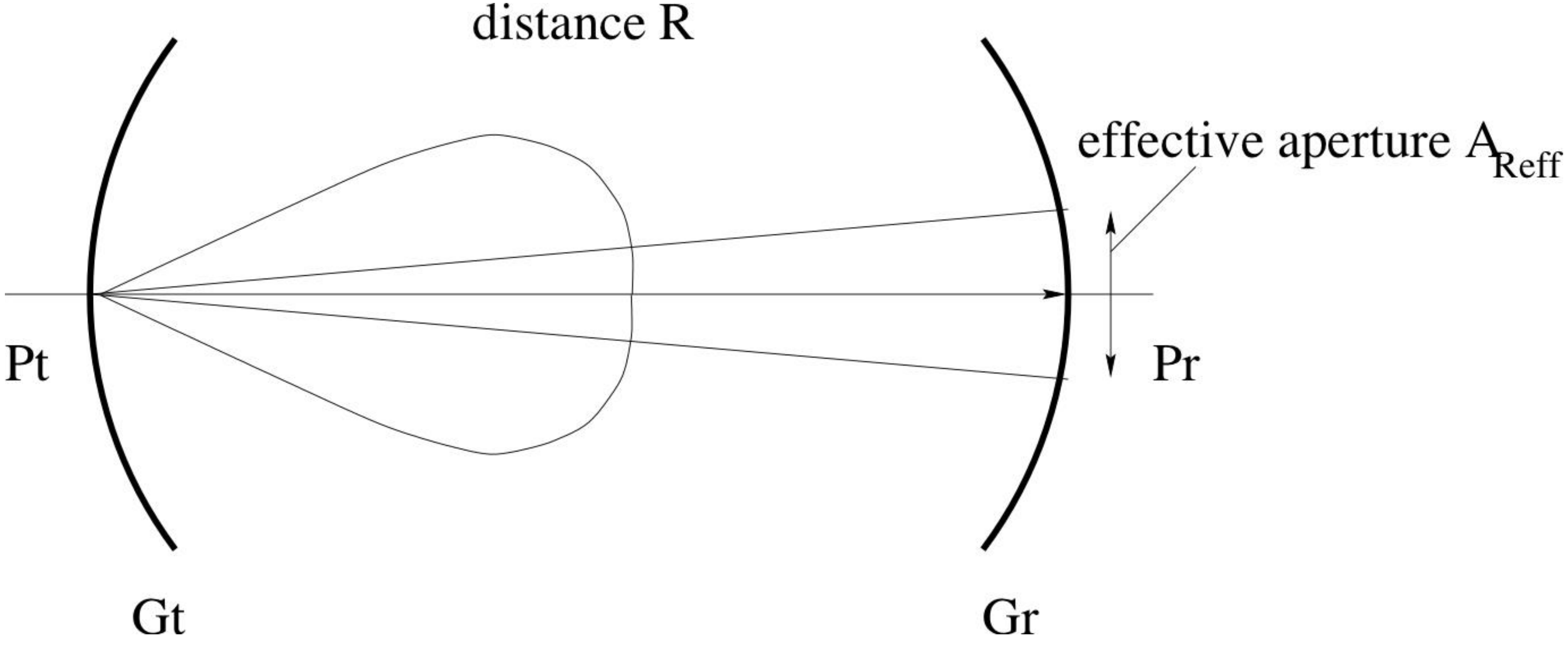
- Distance to a geostationary satellite:



Using the cosine-law we can derive:

$$\left(\frac{R}{R_0}\right)^2 = 1 + 0.42 \cdot (1 - \cos\beta \cdot \cos\lambda_{rel})$$

- Received power for a link:
  - The received power P_r is the flux density F at distance R collected with the effective aperture of the receiving antenna A_{Reff}



$$P_r = F \times A_{Reff} = \frac{P_t \times G_t}{4 \times p \times R^2} \times A_{Reff}$$

- Gain and effective aperture are related:

$$G_r = \left(\frac{4 \cdot \pi}{\lambda^2}\right) \cdot A_{\mathrm{Re}\,ff} \qquad A_{\mathrm{Re}\,ff} = \left(\frac{\lambda^2}{4 \cdot \pi}\right) \cdot G_r$$

So it follows:

$$P_r = \frac{P_t \cdot G_t}{4 \cdot \pi \cdot R^2} \cdot G_r \cdot \frac{\lambda^2}{4 \cdot \pi} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi \cdot R)^2}$$

$$= P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda}{4 \cdot \pi \cdot R}\right)^2 = \frac{EIRP \cdot G_r}{L_{FS}}$$

- Free space loss, L_{FS}:
  - Energy gets lost as radio wave spreads out, free attenuation
  - A function of distance
  - A function of wavelength (or frequency)

$$L_{FS} = \left(\frac{4 \cdot \pi \cdot R}{\lambda} \right)^2 = \left(\frac{4 \cdot \pi \cdot R \cdot f}{c} \right)^2$$

- Examples for free space loss at GEO distance:

– C-band	4-8	GHz	196–202 dB
– X-band	8-12	GHz	202–205 dB
– Ku-band	12–18	GHz	205–209 dB
– K-Band	18–26	GHz	209–212 dB
– Ka-band	26–40	GHz	212–216 dB

Example-2

- An earth station with power P_t = 1 kW, antenna of diameter D= 4 m, antenna efficiency of η=0.6 at location λ=12° E and β=60° N, sends with uplink frequency f = 14 GHz to a geostationary satellite at λ=8° E with antenna gain G_r = 40 dBi. R_0 is 35768 km.

  1) What is the EIRP of the sending station?
  2) What is the free space loss L_{FS}?
  3) What is the received power P_r at the satellite?

Solutions for example-2

- G_t = 53.1 [dBi]
- EIRP = 30 [dBW] + 53.1 [dBi]

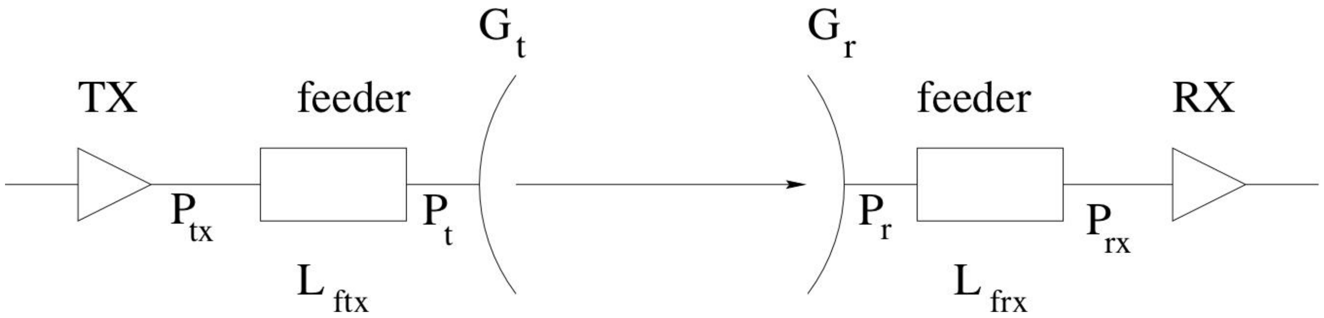
  = 83.1 [dBW]

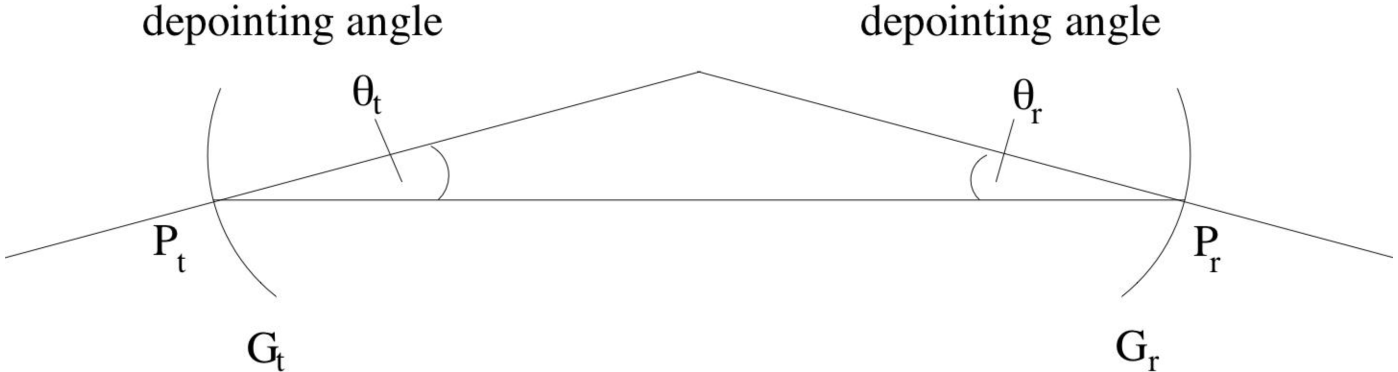
- LFS = – 207.2 [dB]

- P_r = 83.1 [dBW] –207.2 [dB] +40 [dBi]

  = – 84.1 [dBW]

- Further losses:
  - Atmospheric losses: $L_A = A_{AG} + A_{rain}$
  - Feeder losses: L_{fTX}, L_{fRX}
  - Misalignment losses: L_t, L_r
  - Polarization loss: L_{pol}





$$L_t = 12 \cdot \left(\frac{\theta_t}{\theta_{3dB}} \right)^2$$

L_t in (dB)

- For one link:

$$P_{rx} = P_{tx} + G_{t.\max} - L_t - L_{f.tx}$$
$$- L_{FS} - L_A$$
$$+ G_{r.\max} - L_r - L_{r.tx} - L_{pol} = C$$

- The received power including all losses for a link

  ground station => satellite => ground station:

  1) atmospheric losses on up- and downlink (2)

  2) free space loss on up- and downlink (2)

  3) feeder losses: transmitting ground station, receiving satellite antenna, transmitting satellite antenna, receiving ground station (4)

  4) misalignment losses: transmitting ground antenna, receiving satellite antenna, transmitting satellite antenna, receiving ground antenna (4)

  5) polarization losses on up- and downlink (2)

- Now we can calculate the received power on a satellite link.
- To get the link performance we need to relate this power to the noise.
- Noise is the unwanted contribution of energy that corrupts the wanted signal.
- Noise refers to the input of the receiver.
- Sources of noise:
  - Radiating bodies (e.g. Earth)
  - Galactic and cosmic sources
  - Atmospheric gases and rain
  - Ground
  - Electronics
  - Interference

Short summary of today’s topics

- Meaning of link budget calculations
- Power transmitters
- Reflector antennas and properties
- Power flux density
- Power-budget equation (”Friis equation”)
- Free-space loss
- Other losses