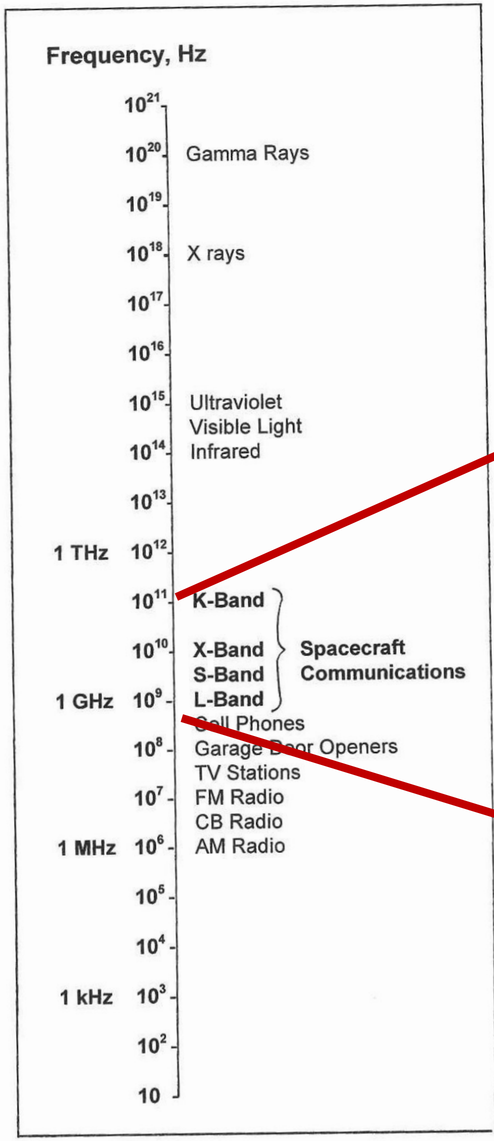
Section 6 – Spacecraft telecom subsystem

- **Objectives**
  - Describe the most significant telecom architectures for Earth satellites, and define the methodology used for the radio-link preliminary design at system level

- **Topics**
  - Introduction to satellite communications: EM spectrum and modulation
  - Space communication architectures for Earth satellites
  - Onboard telecom subsystem: functional diagram and main components
  - Link equation
  - Link preliminary design

Introduction: electromagnetic spectrum



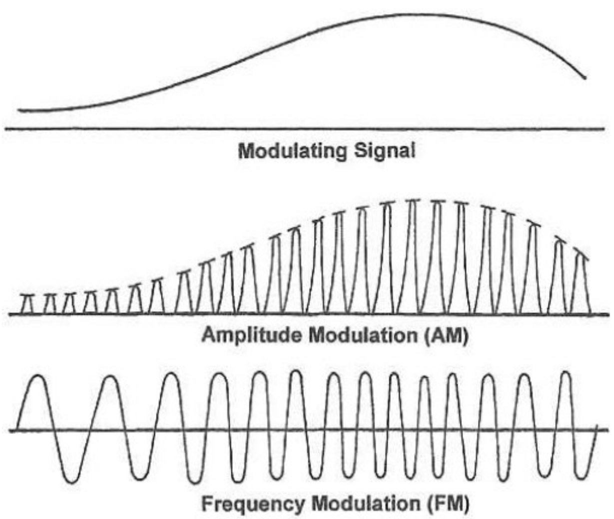
Band	Freq. range, GHz
P	0.225–0.39
J	0.35–0.53
L	0.39–1.55
Q	36.0–46.0
V	46.0–56.0
W	56.0–100.0

Introduction: modulation – 1/2

- **Frequency content of satellite data (range)**
  - House-keeping telemetry: up to few Hz
  - Voice: up to 10 kHz
  - Video: tens of MHz

- **Carrier frequency is significantly higher** than frequency content of typical satellite data (atmospheric permeability, limitation of antennas size)

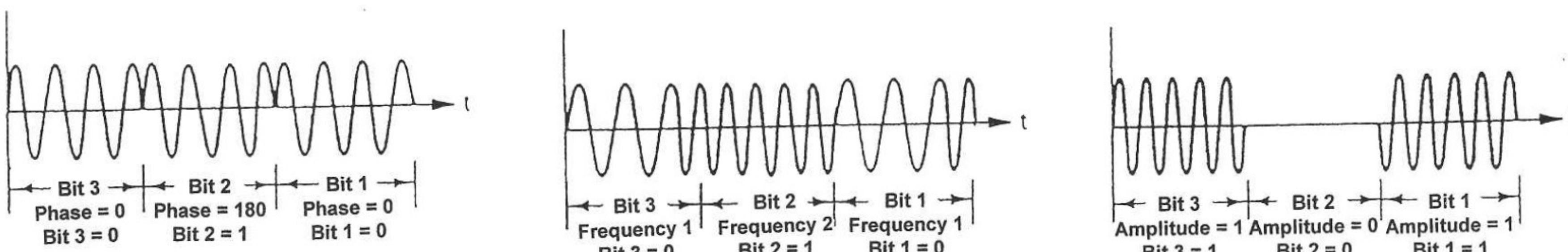
➔ Data are coded in the carrier through modification of one or more of the carrier properties (**modulation**)
  - Amplitude
  - Frequency
  - Phase



Introduction: modulation – 2/2

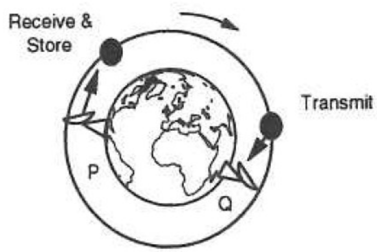
- **Digital modulation** is preferable to analog because of:
  - Low sensitivity to interference/distortion
  - Simple signal reconstruction
  - Compact and cheap hardware
  - Large variety of coding options available
  - Hight data security

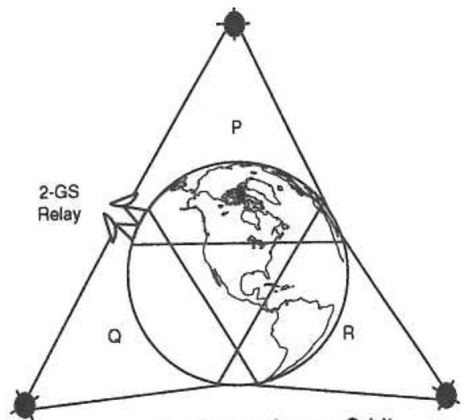
- Digital modulation examples



Phase Shift Keying (PSK) | Frequency Shift Keying (FSK) | Amplitude Shift Keying (ASK)

Space communication architectures – 1/2



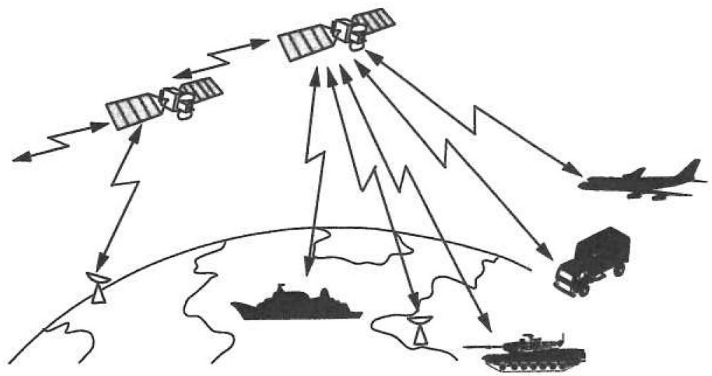


- ✓ Low-cost launch
- ✓ Low-cost satellite
- ✓ Polar coverage with inclined orbits
- × Long **access time** and transmission delay (**data latency**)

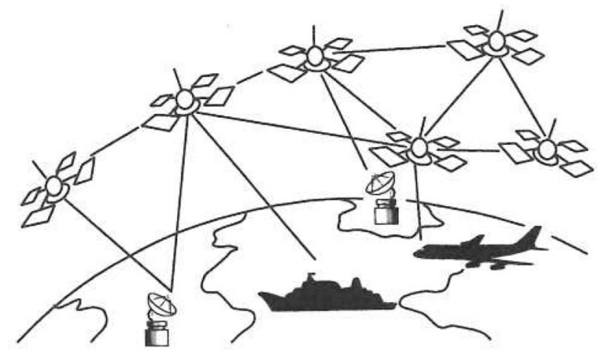
- ✓ No switching between sats
- ✓ GS antenna tracking often not required
- × **High-cost launch**
- × **High-cost satellite**
- × **Need for station keeping**
- × **No coverage of polar regions**

- ✓ Low-cost launch
- ✓ Polar coverage
- × Requires several sats for continuous coverage of one hemisphere
- × Need for **GS antenna tracking** and **complex network control**
- × **Need for station keeping**

Space communication architectures – 2/2



D. Crosslink in Communication Satellite System

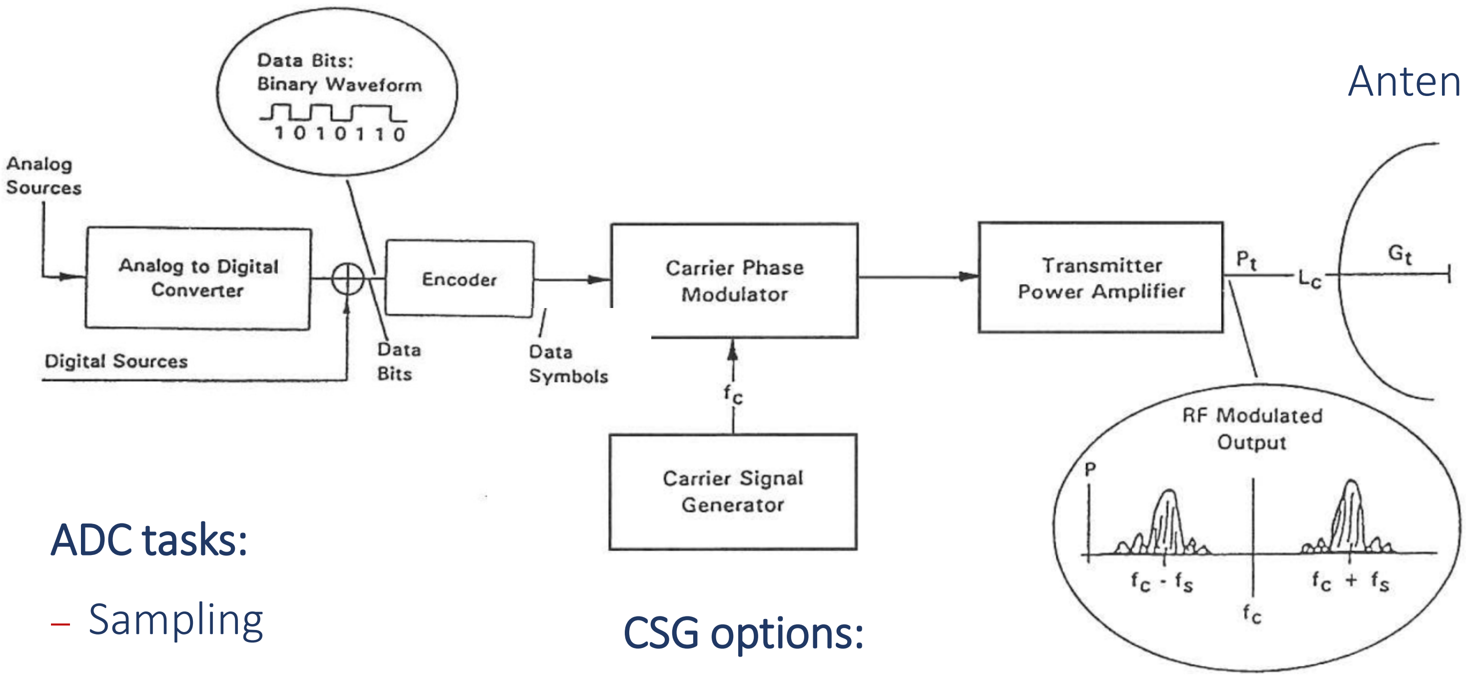


E. Low-altitude, Crosslinked Comsat Network

- ✓ No need for GS relay (reduced propagation delay and cost)
- ✓ No need for GS in foreign territory (increased security)
- × **Hi satellite complexity and cost**
- × **Need for station keeping**
- × **No coverage of polar regions (GEO)**

- ✓ Hi **survivability** (multiple paths)
- ✓ Limited Earth view area (**security**)
- ✓ Reduced transmitted power
- ✓ **Low-cost satellites** and launches
- ✓ Polar coverage with inclined orbits
- × **Large constellation**
- × **Complex link acquisition (pointing, frequency, time) and network control**

Onboard telecom subsystem – 1/3



ADC tasks:

- Sampling
- Digitization

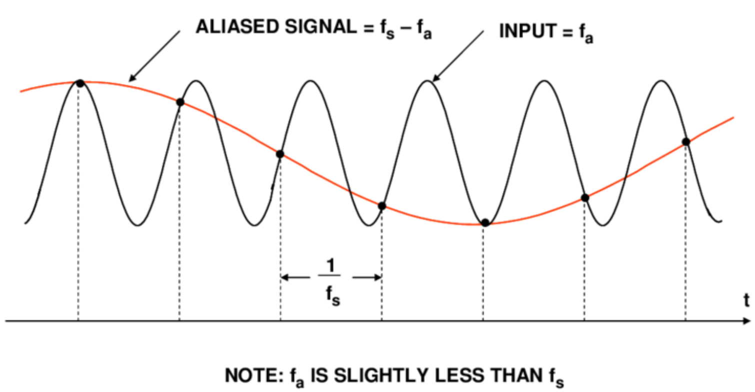
CSG options:

- Oscillator
- Transponder

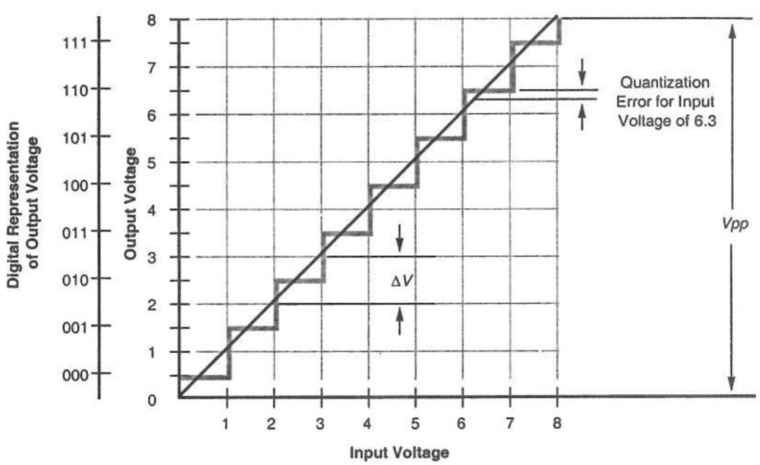
- Hardware @GS is symmetric, but is subject to lesser constraints (size, mass, power, thermal control)

Onboard telecom subsystem – 2/3

- **Analog to Digital Converter (ADC)**
  - Performs sampling and digitization of analog signals
  - Key performance parameter: **sampling frequency** f_s and **resolution (~number of bits)**
  - To avoid **signal aliasing** sampling frequency shall be $f_s > 2*f_c$ (**Shannon theorem**), with f_c: signal's frequency content



  - **Quantization error** depends on the ADC's resolution (number of bits) ⇒ $\Delta V = 1/2^{bit}$

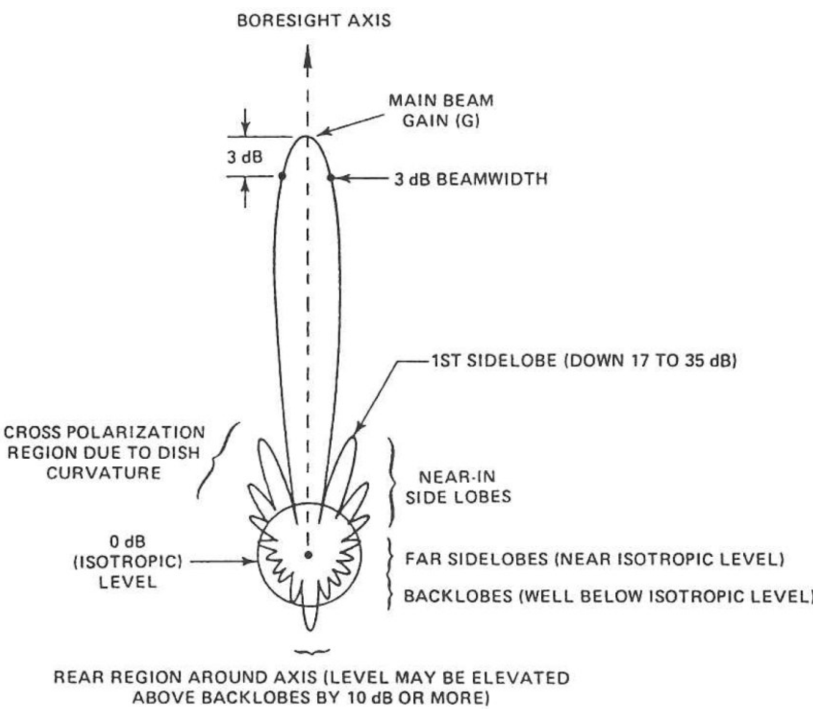


Onboard telecom subsystem – 3/3

- **Antenna**
  - Device which focuses the EM radiation in a given direction
  - Key performance parameter: **gain** (focusing factor)

$$G := \frac{4\pi\ [sr]}{beamwidth\ [sr]} = \frac{4\pi\eta A}{\lambda^2} = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

A: area; D: diameter; η: aperture efficiency; λ: carrier wavelength



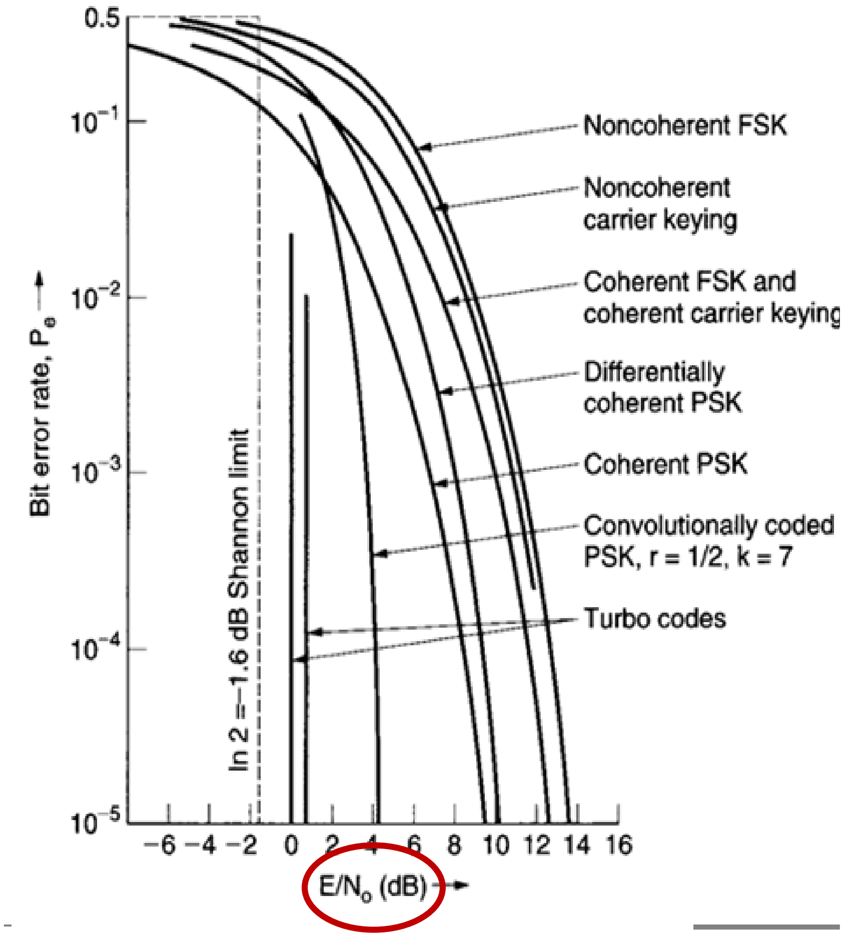
Configuration	Peak gain, dBi	Beam width, deg	Pattern
Half-wave dipole	1.64	—	+
Planar array	$10\log\left(\frac{A}{\lambda^2}\right)+8$	—	
Turnstile	0.6	—	—
Horn	$20\log\left(\frac{D}{\lambda}\right)+7$ (Typically 5 to 20 dBi)	$\frac{72\lambda}{D}$	—
Bi-cone	$5\log\left(\frac{D}{\lambda}\right)+3.5$ (Typically 5 dBi)	Typically 45 × 360	+
Helix	$10\log\left(\frac{D^2L}{\lambda^3}\right)+20.2$ (Typically 5 to 20 dBi)	$\frac{16.6}{\sqrt{D^2L/\lambda^3}}$	
Yagi	$\approx 12dBi$	—	

Link equation – 1/6

$$\frac{E_b}{N_0} = \frac{P_t G_t L_l L_s L_\theta L_a G_r}{k T_S R}$$

E_b/N_0: ratio of the energy transmitted per bit to band noise density. From engineering diagrams, it depends on Bit Error Rate (BER) and modulation/coding technique

$P_t G_t$: **Effective Isotropic Radiated Power** (EIRP): product of transmitter power and gain of the transmitter antenna



Link equation – 2/6

$$\frac{E_b}{N_0} = \frac{P_t G_t L_l L_s L_\theta L_a G_r}{k T_S R}$$

L_l: Line loss (depends on the HW between TX and antenna, < 0.1 dB)

L_S: Space loss (radio-link attenuation due to distance D)

$$L_S = \left(\frac{\lambda}{4\pi D}\right)^2$$

L_θ: Pointing loss (attenuation due to partial intersection of TX-RX antennas' main lobes

$$L_\theta = -12\left(\frac{error[°]}{beamwidth}\right)^2 [dB]$$

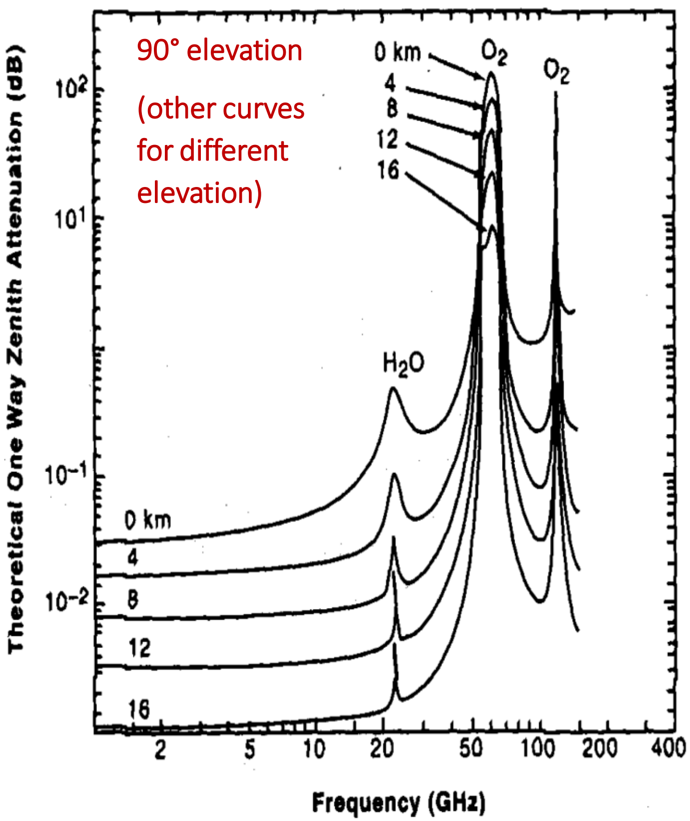
G_r: Gain of RX antenna

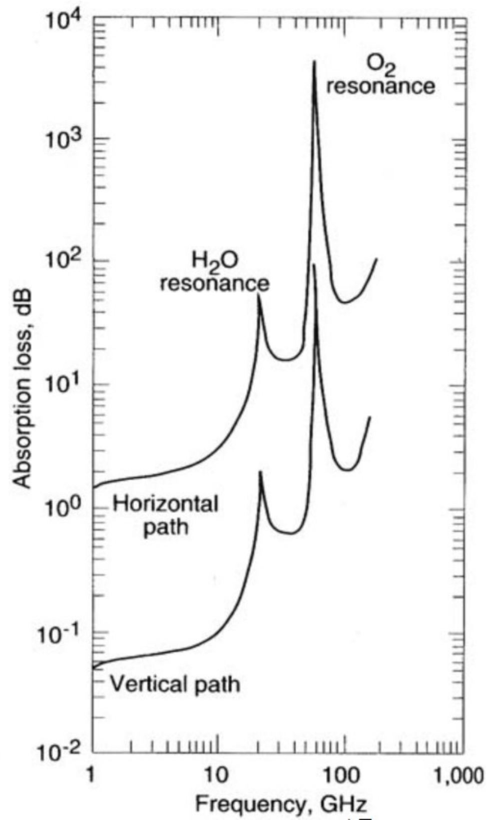
k: Boltzmann constant, k = 1.3806485279 E-23 J/K

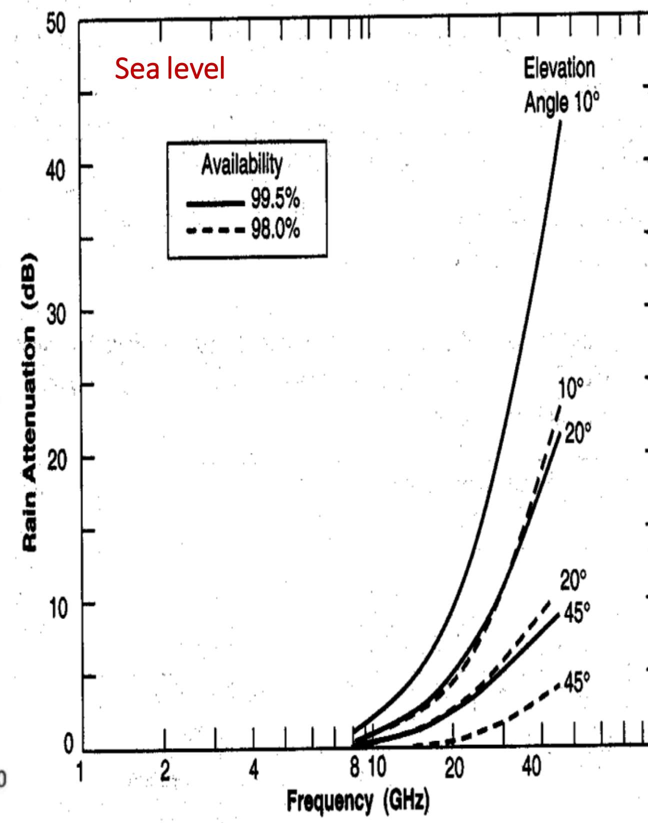
Link equation – 3/6

$$\frac{E_b}{N_0} = \frac{P_t G_t L_l L_s L_\theta L_a G_r}{k T_S R}$$

L_a: Atmospheric loss [dB]





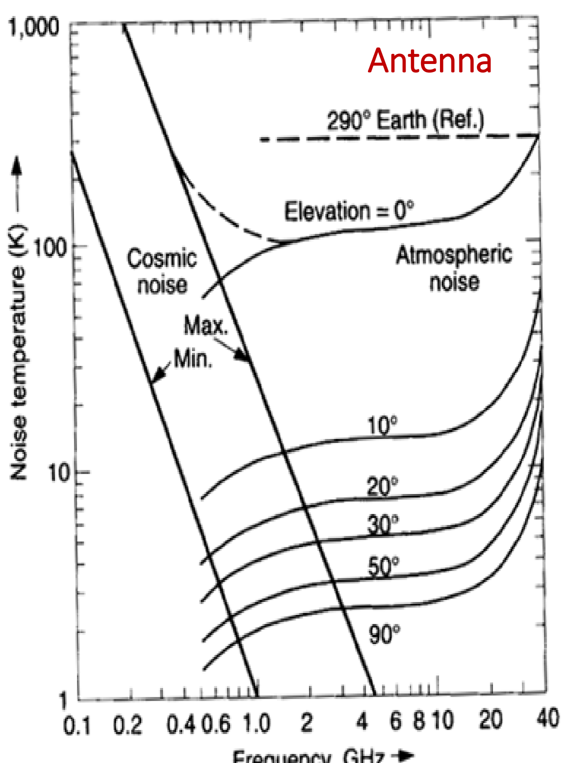


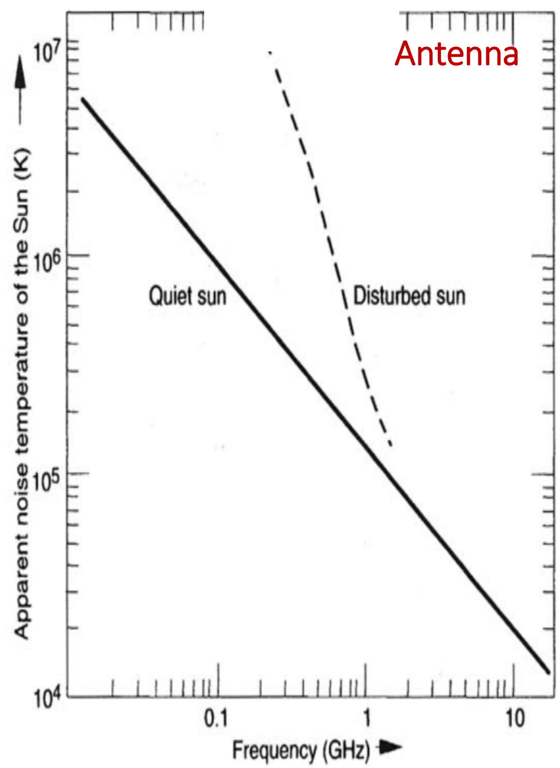
Link equation – 4/6

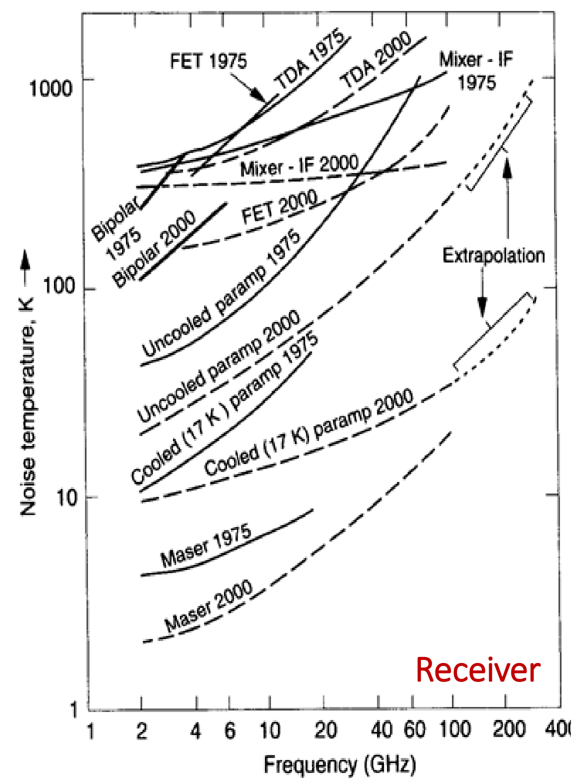
$$\frac{E_b}{N_0} = \frac{P_t G_t L_l L_s L_\theta L_a G_r}{k T_S R}$$

T_S: Equivalent noise temperature at GS receiver [K]

$$T_S = T_{ant} + T_{cables} + T_{RX}$$







Link equation – 5/6

$$\frac{E_b}{N_0} = \frac{P_t G_t L_l L_s L_\theta L_a G_r}{k T_S R}$$

R: Data rate [bps] $\Rightarrow$ $R = \dfrac{V}{\tau_a}$

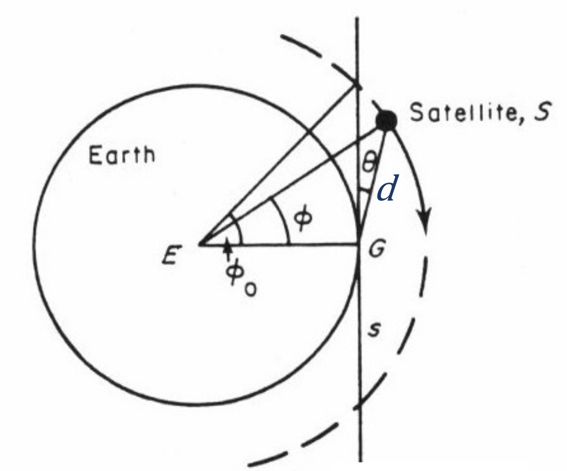
V: Data volume [bit]

τ_a: Link availability (time period over which the link can be established)

$$\tau_a = \frac{2\phi}{\omega_{ES}}$$

Φ: visibility half-angle (radio)

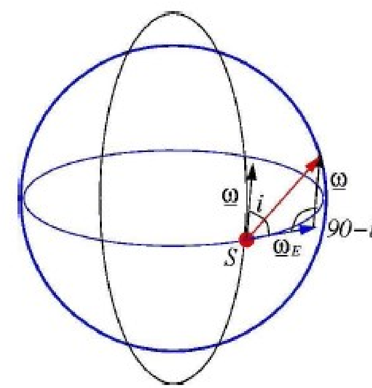
ω_{ES}: satellite velocity relative to GS



$$\phi = -\theta + \cos^{-1}\left\{\frac{R_E}{R_E+h}\cos\theta\right\}$$

$$\omega_{ES}^2 = \omega_E^2 + \omega^2 - 2\omega_E\,\omega\cos i$$

$$d = \frac{(R_E + h)\sin\phi}{\cos\theta}$$



θ: min elevation above which radio-link can be established; i: orbit inclination;
h: orbit altitude; ω_E: Earth rotation rate; ω: satellite inertial rotation rate; d: slant range

Link equation – 6/6

- **Data volume evaluation (example)**
  - Obtain a monochrome image of the Sun from LEO with a **resolution of 10 arcsec**. The solar intensity should be measured to **1% accuracy** in each pixel, time varying features at **rate of 5Hz** must be resolved
  - Calculate the word length required to describe a pixel, and the data volume for an image, and what the data rate should be

  - Sun diameter from LEO: 0.53° $\Rightarrow$ dividing up the Sun disc into 10 arcsec pixels requires (0.53*3600)/10=191 elements. If we divide up the image plane into a number of square pixels in convenient binary quanta, it is appropriate to oversample. Since the analog step is $\Delta V/V=1/2^b$, if we choose b=8 then we get $2^8=256>191$. Then, an 8-bit word can be used to identify the x-coordinate of any single pixel to better than 10 arcsec. Similarly y.
  - 1% intensity measurement accuracy required $\Rightarrow$ $\Delta V/V=1/2^b<1\%$. If we choose b=7 we get $\Delta V/V=1/2^7=1/128<1\%$. Then, brightness requires 7 bit.
  - Word length = 8+8+7=23 $\Rightarrow$ a 23-bit word adequately describe data in each pixel
  - Data volume = 23*256*256 = 1.507 Mbit
  - Data rate = 1.507*5*2.2 = 16.577 Mbps (2.2 comes from the Shannon theorem)

Link preliminary design

$$\frac{E_b}{N_0} = \frac{P_t G_t L_l L_s L_\theta L_a G_r}{k T_S R}$$

- The objective is to **determine the EIRP** starting from **requirements** (link reliability – BER and/or SNR) and **constraints** (Data Volume, orbit, type of satellite, ground station):

$$SNR = \frac{P_{RX}}{P_{noise}} = \frac{P_t G_t L_l L_s L_\theta L_a G_r}{k T_S B} = \frac{E_b}{N_0} \cdot \frac{R}{B}$$

B: bandwidth

- BER and/or SNR $\Rightarrow E_b/N_0$
- Data volume and orbit $\Rightarrow R$
- Orbit $\Rightarrow L_s$ and L_a
- Type of satellite (ACS) $\Rightarrow L_\theta$
- Ground station $\Rightarrow G_r,\ T_s$

Link equation $\Rightarrow$ EIRP

For given HW and operations, the resulting BER (or SNR) is called **link budget,** and the number of dB exceeding the required BER (or SNR) is called **link margin**