UNIVERSITY OF Southampton

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Astronautics

Chapter 9: Communications

Contents

The Communications Subsystem

Function

The function of the communications subsystem is to receive spacecraft operating commands and data from the ground, and to downlink payload and telemetry data to Earth.

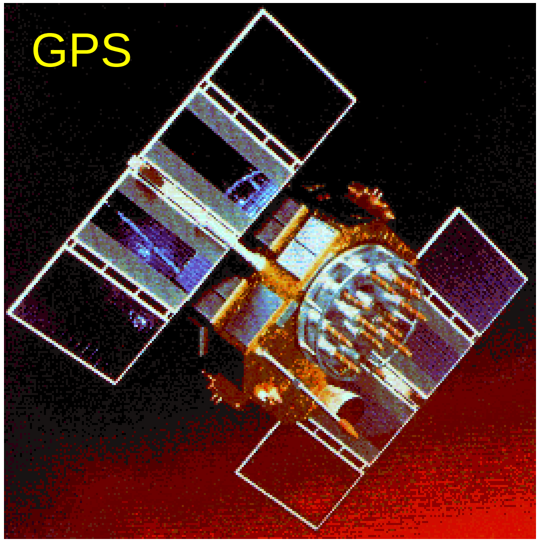
Voyager spacecraft

The Communications Subsystem

Spacecraft

Spacecraft with a predominantly communications payload include:

- Comsats
- Navigation satellites
- Tracking and data relay satellites



The Communications Subsystem

The Decibel

- The dB is a commonly used unit in communications link analysis to express power level ratios

e.g.

$$\left(P_R / P_T\right)_{dB} = 10\log_{10}\left(P_R / P_T\right)$$

- We can also express power levels relative to 1 Watt (dBW)

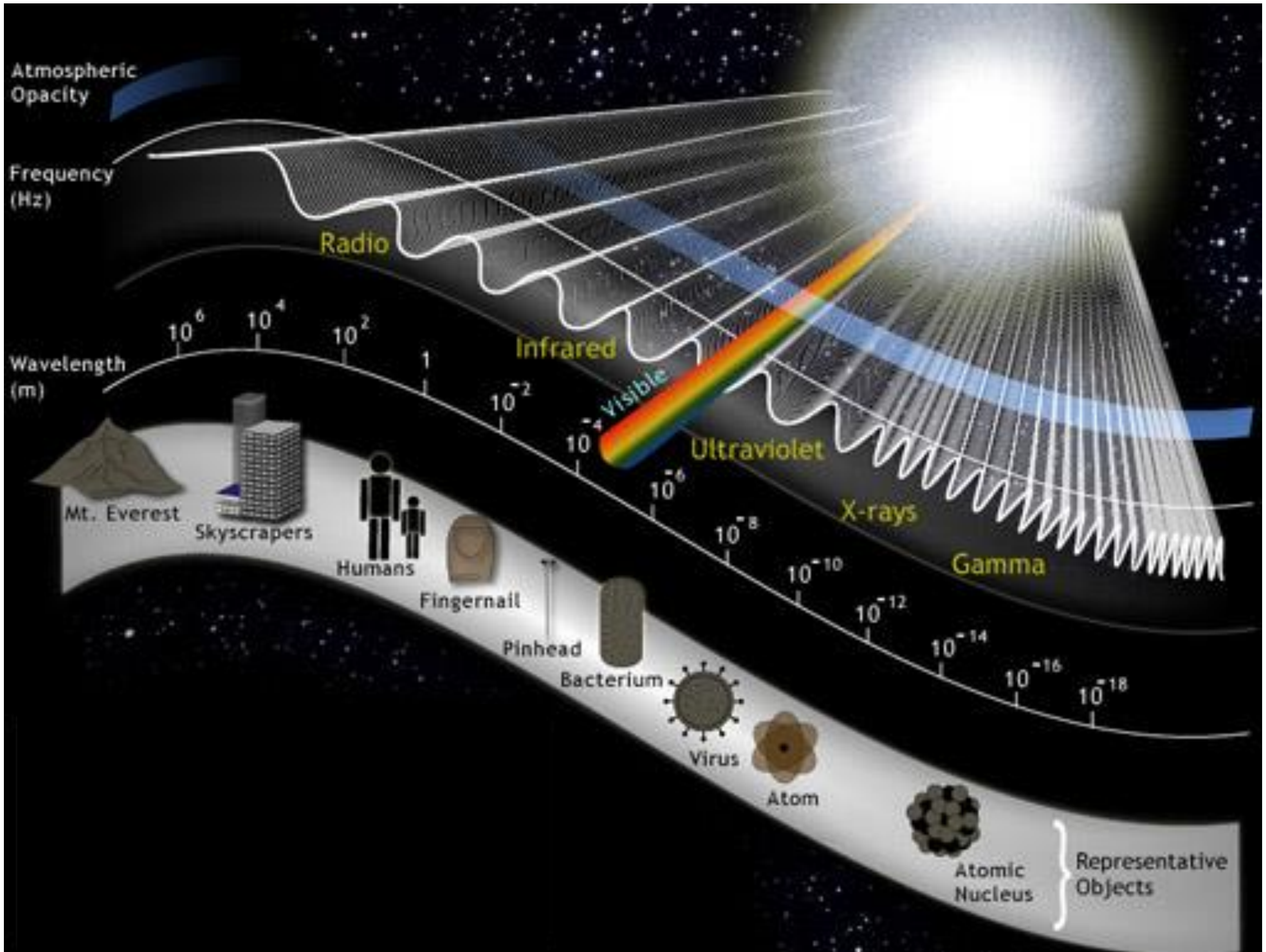
$$\left(P_T\right)_{dBW} = 10\log_{10}\left(P_T / 1\,\mathrm{Watt}\right)$$

e.g.

$$P_T = 42.3\,\mathrm{dBW} \quad \Rightarrow \quad P_T = 16.98\,\mathrm{kW}$$

The Communications Subsystem

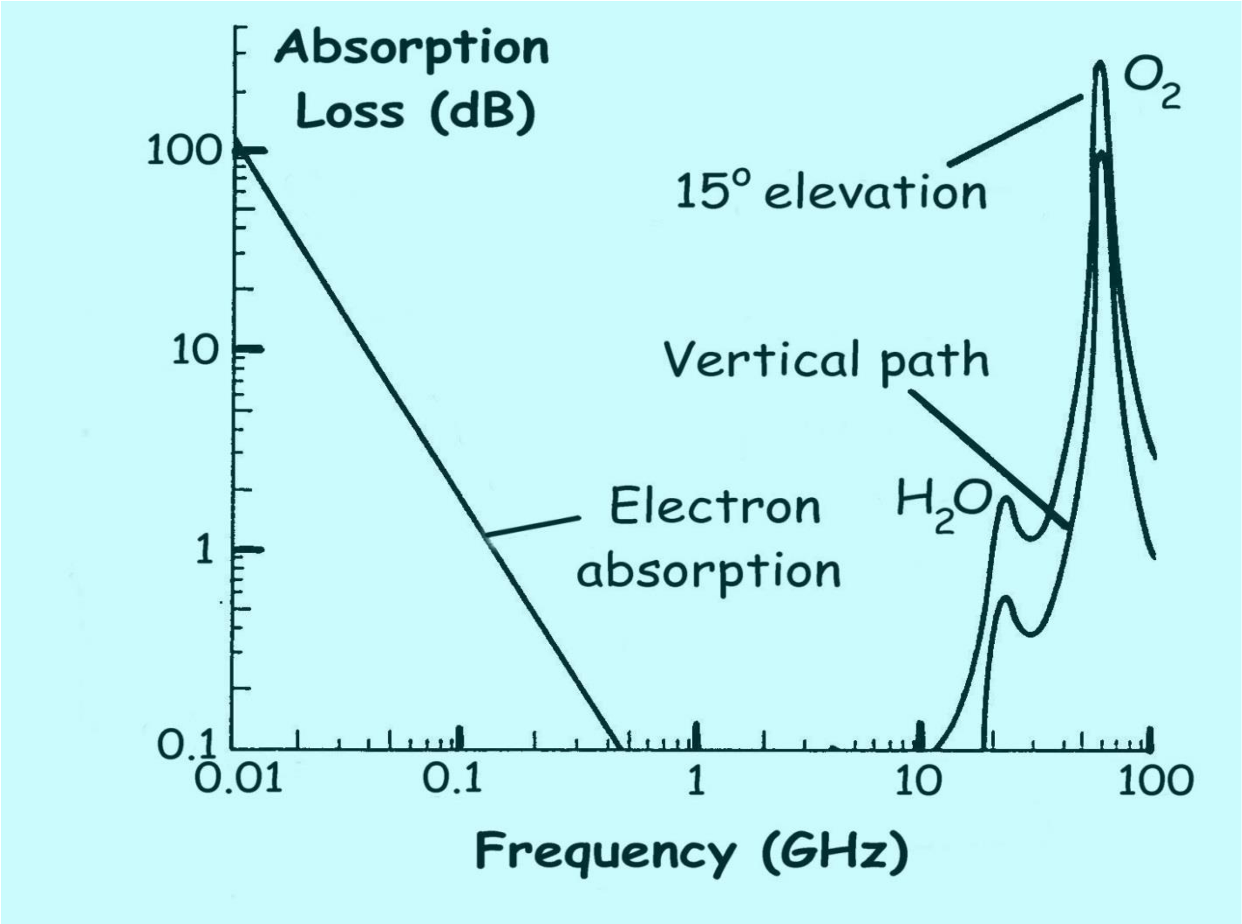
Transmission



The communications system uses focused microwave beams to send and receive data.

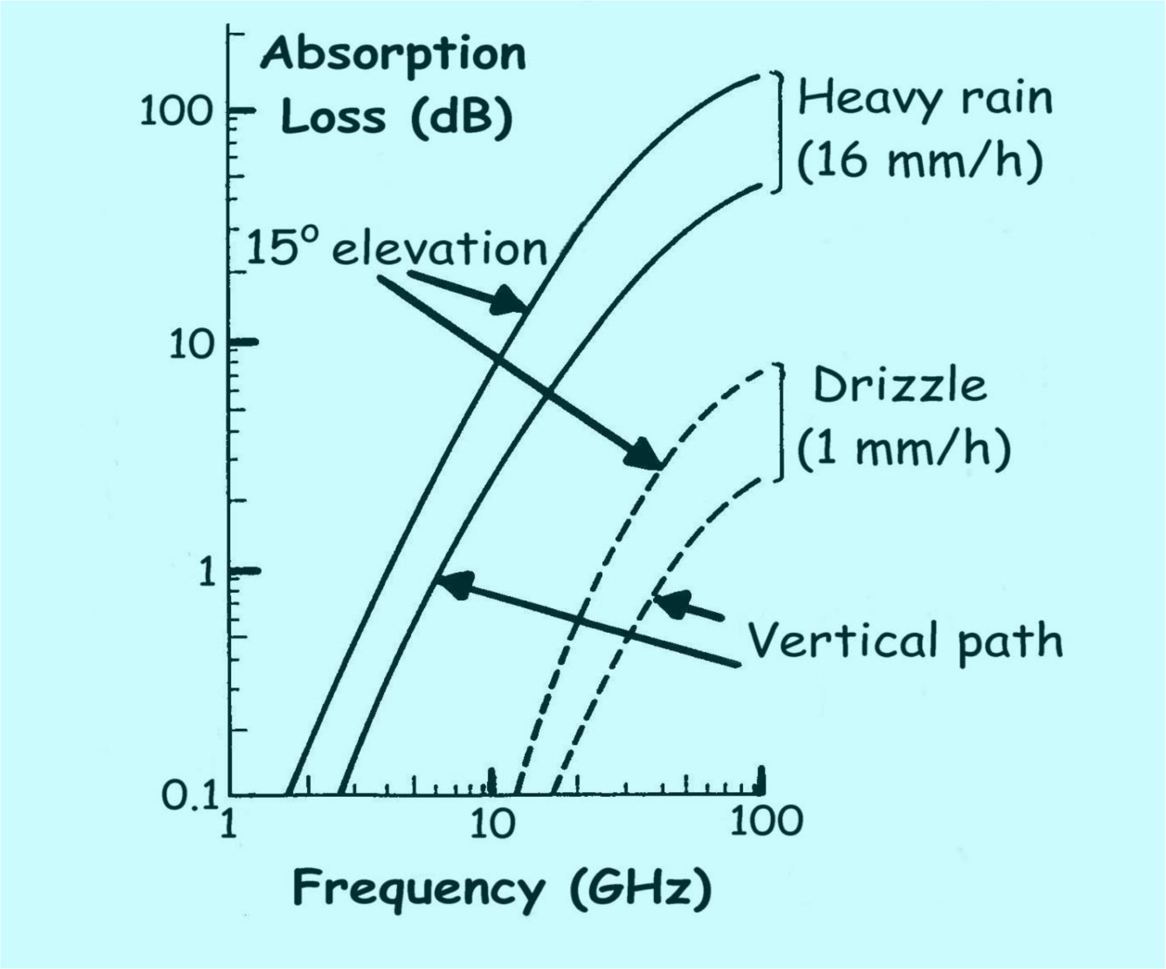
Atmospheric Windows

Atmospheric and Ionospheric Absorption (fairly constant)



Atmospheric Windows

Absorption due to rain (highly variable)



Atmospheric Windows

Frequency Bands

– Satellite frequency bands are allocated by the ITU (International Telecommunications Union)

Usage	Downlink (GHz)	Uplink (GHz)
TT&C*	0.137 – 0.138	1.427 – 1.429
Fixed comms		
- C-Band	3.7 – 4.2	5.925 – 7.075
- K-Band	10.7 – 12.2	14.0 – 14.5
Mobile comms		
Maritime (L-Band)	1.530 – 1.544	1.627 – 1.646
Aero (L-Band)	1.545 – 1.559	1.647 – 1.660
Navigation		
L-Band	1.535 – 1.560	1.635 – 1.660
Space research§		
S-Band	2.20 – 2.29	2.025 – 2.120
X-Band	7.25 – 7.75	7.9 – 8.4

***TT&C** = Tracking, Telemetry & Command
§ Includes Earth-observation and interplanetary missions

Encoding, Modulation and Bandwidth

Digital Encoding

Space communications are predominantly digital

⇒ Bit Error Rate (BER) becomes the measure of link quality

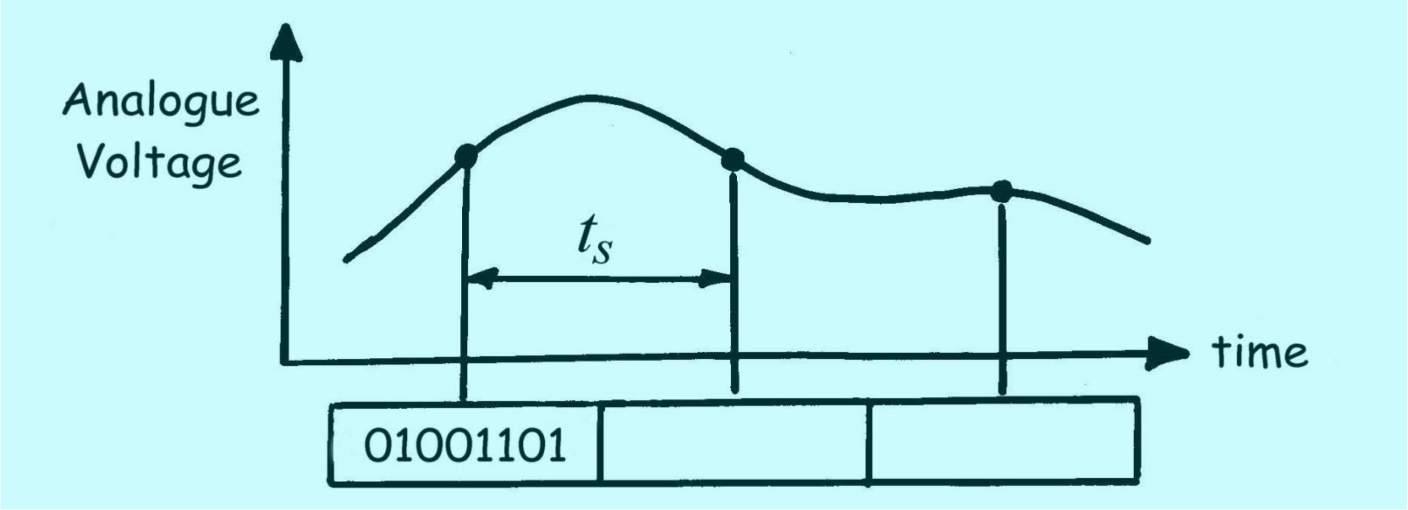
This involves the requirement to convert an analogue signal to a digital bit stream (e.g. telephony)

PCM (Pulse Code Modulation) is a commonly used encoding technique (which is not actually a modulation method!)

Encoding, Modulation and Bandwidth

Digital Encoding

Example: Estimate the digital data rate of an analogue telephone signal using PCM.



- Signal is sampled every t_S seconds, and encoded as an 8 bit word (giving $2^8 = 256$ discrete levels)
- Sampling frequency $$f_S = t_S^{-1} \quad \text{(Hz)}$$

Encoding, Modulation and Bandwidth

Digital Encoding

- Maximum frequency in a human voice ~ 3,400 Hz
- For good quality reproduction we require $f_S \geq 2\, f_{max}$ (Nyquist)
- Therefore $f_S = 8\ \text{kHz}$
- Hence bit rate for one-way telephone circuit is

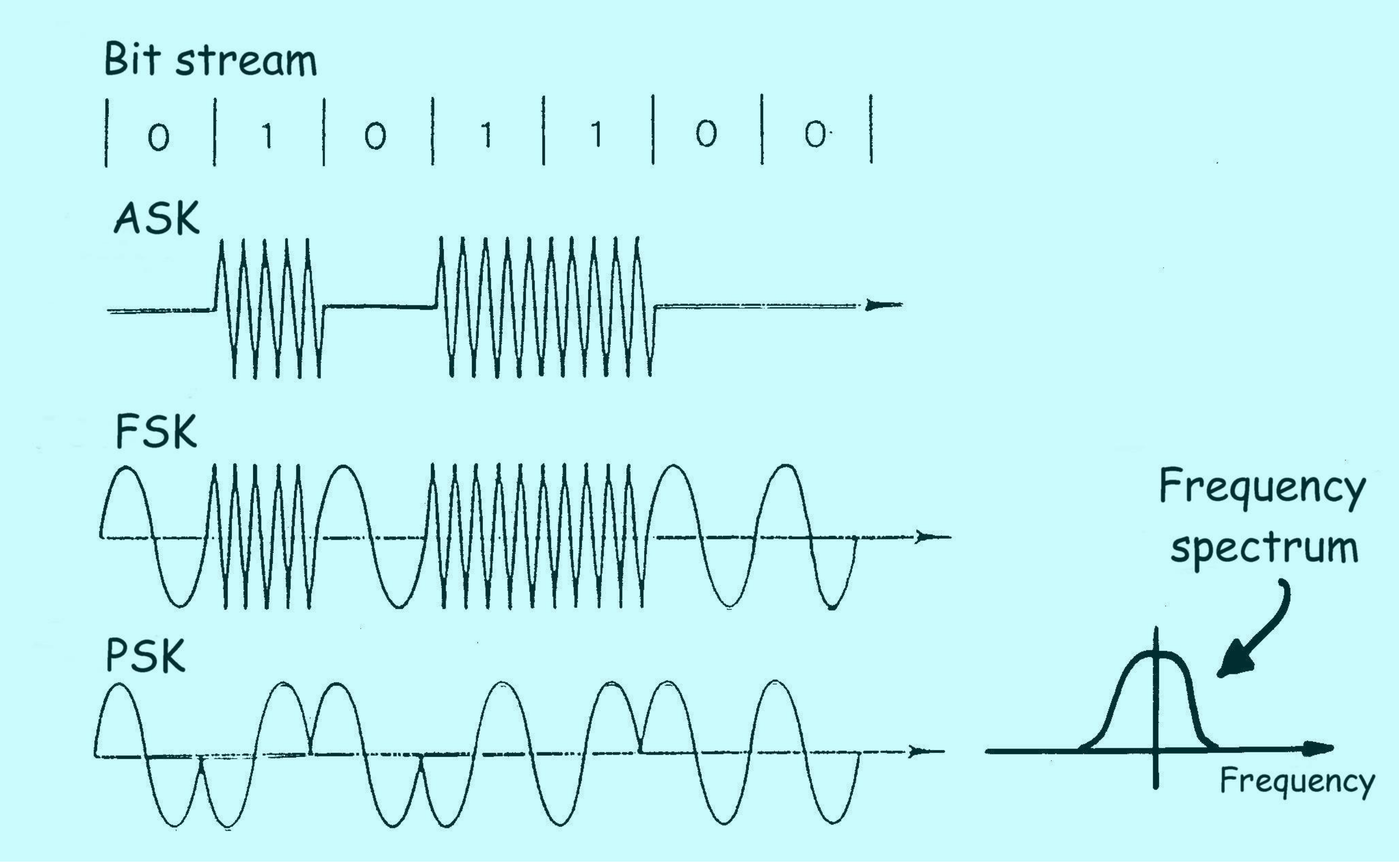
$$R_b = 8000(8) = 64\ \text{kbps}$$

Digital Modulation Techniques

- **The carrier wave** is modulated to carry digital information using:
  - **ASK** (Amplitude Shift Keying)
  - **FSK** (Frequency Shift keying), or
  - **PSK** (Phase Shift Keying)

Encoding, Modulation and Bandwidth

Digital Modulation Techniques



Encoding, Modulation and Bandwidth

Digital Modulation Techniques

- **PSK is the most widely used** form of digital modulation
- **Information transmission** requires frequency bandwidth. This is illustrated by Shannon's Law:

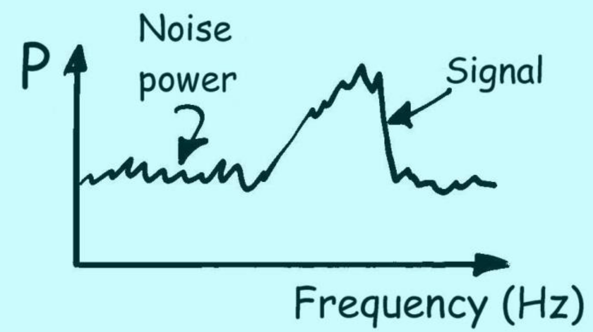
$$R_{\max} = B \log_2 \left(1 + \frac{S}{N} \right) \quad \text{(bps)} \qquad (9.1)$$

where $R_{\max}$ is the maximum data rate (bps),

B is the channel bandwidth (Hz), and S/N is the signal-to-noise power ratio

Noise

- **Noise** is any unwanted interference with the signal:
  - We must be able to recover the signal in a noisy environment
  - The effectiveness of the link is characterised by the signal-to-noise ratio (related to the BER)
- **Sources of noise** include
  - Atmospheric emission and scattering
  - The Sun, Earth and galactic sources
  - Lightning
  - Artificial sources (cars, electrical machinery, etc.)
  - Internal electronic/microwave devices



Power spectrum at the receiver

Noise

- **Sources are characterised** by an equivalent noise temperature T (K) so that the noise power N within a bandwidth B (Hz) is given by

$$N = kTB \quad (\mathrm{W}) \qquad (9.2)$$

where $k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant.

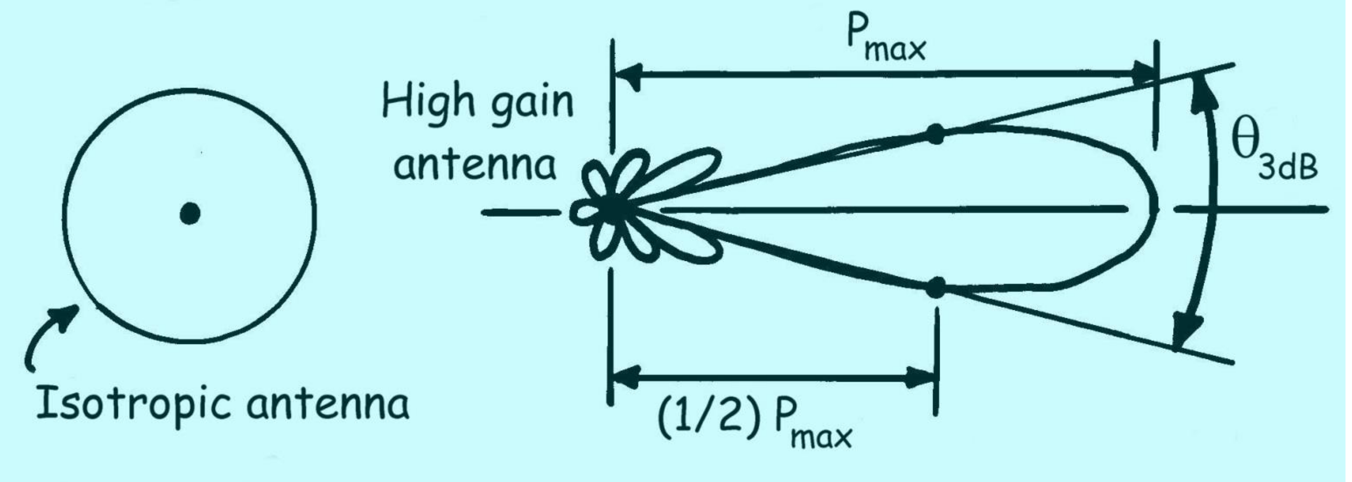
Antenna Gain and Beamwidth

Isotropic Radiator

- Radiates power with equal intensity in all directions
- Gain is defined to be unity (0 dB)

High Gain Antenna

- Concentrates the radiated power in a particular direction (antenna boresight)



Antenna radiation patterns

Antenna Gain and Beamwidth

Beamwidth

- **Beamwidth** is usually defined to be the half-power beamwidth. That is, 3 dB down from maximum boresight power. For a circular parabolic antenna, this is given (empirically) by

$$\theta_{3dB} \approx 72(\lambda / D) \quad \text{(degrees)} \qquad (9.3)$$

where λ is the operating wavelength and D is the dish diameter.

Antenna Gain and Beamwidth

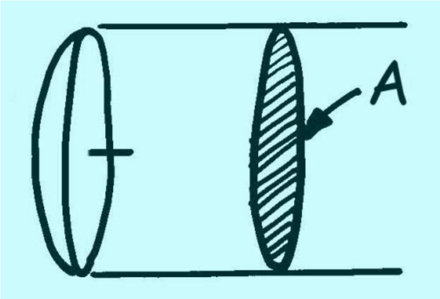
Antenna Gain

- **Antenna gain** is defined by

$$G = \frac{\text{maximum power flux}}{\text{power flux of an isotropic radiator}}$$

for the same transmitted power. In general, antenna gain is given (empirically) by

$$G = \frac{4\pi\, A_{eff}}{\lambda^2} = \frac{4\pi\, A}{\lambda^2}\eta \qquad (9.4)$$



where A_{eff} is the effective aperture area,

A is the projected aperture area, and

η is the antenna efficiency ($0.4 < \eta < 0.8$)

Antenna Gain and Beamwidth

Antenna Gain

For a circular, parabolic antenna of diameter *D* equation (9.4) becomes

$$G = \eta\left(\frac{\pi D}{\lambda}\right)^2, \quad \eta \approx 0.65 \qquad (9.5)$$

Examples of a parabolic dish antenna, operating at C-Band (4 GHz)

– Wavelength $c = f\lambda \;\Rightarrow\; \lambda = \frac{c}{f} = \frac{3\times10^8 \text{ m/s}}{4\times10^9 \text{ Hz}} = 0.075 \text{ m}$

- 1 m dish

$$\theta_{3dB} \sim 5.4^{\circ}, \quad G = 30.6 \text{ dB}$$

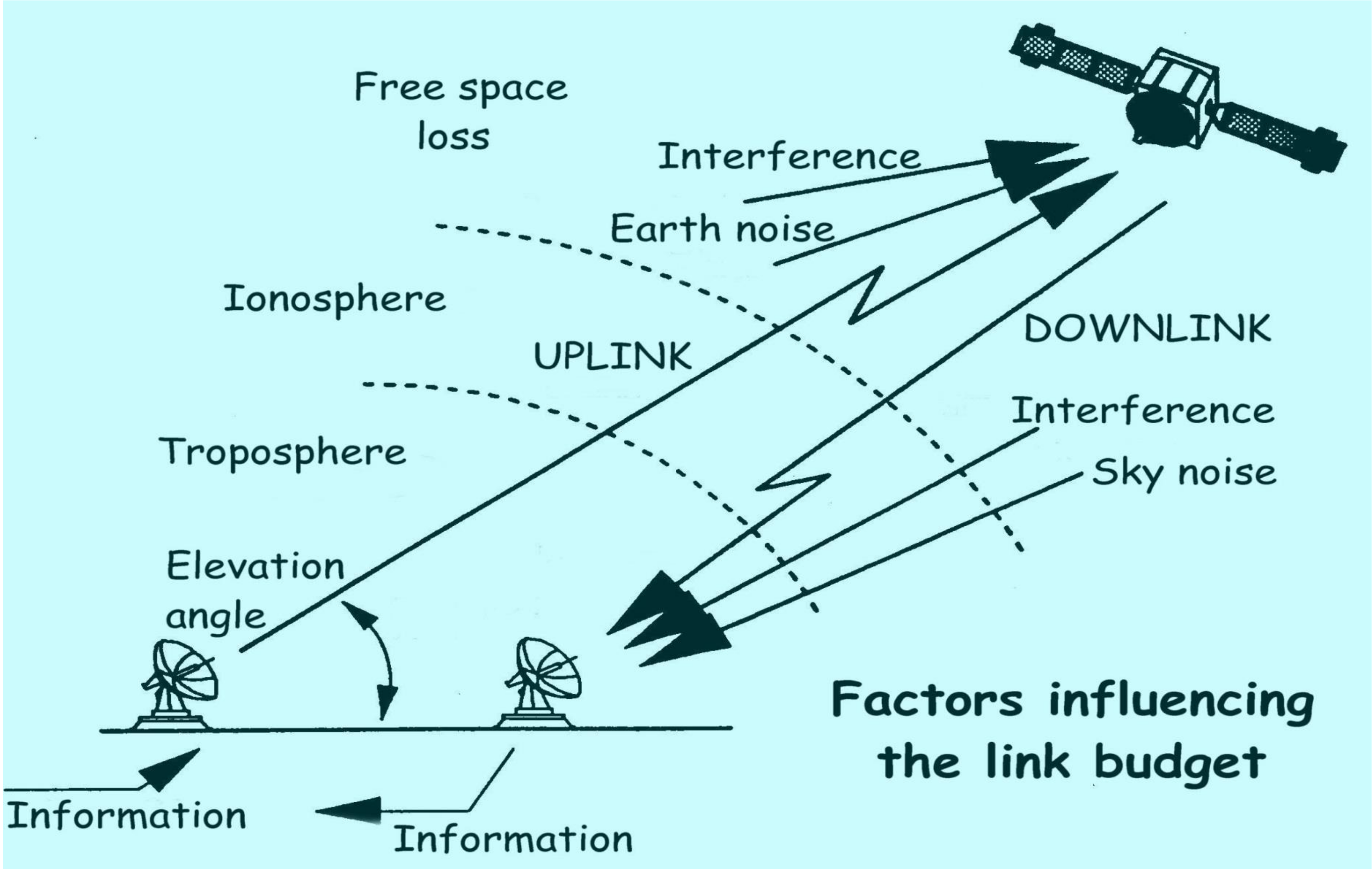
Antenna Gain and Beamwidth

- 6 m dish $\theta_{3dB} \sim 0.9^{\circ}$, $G = 46.1$ dB
- 25.9 m dish (Goonhilly A)

$\theta_{3dB} \sim 0.2^{\circ}$, $G = 58.5$ dB

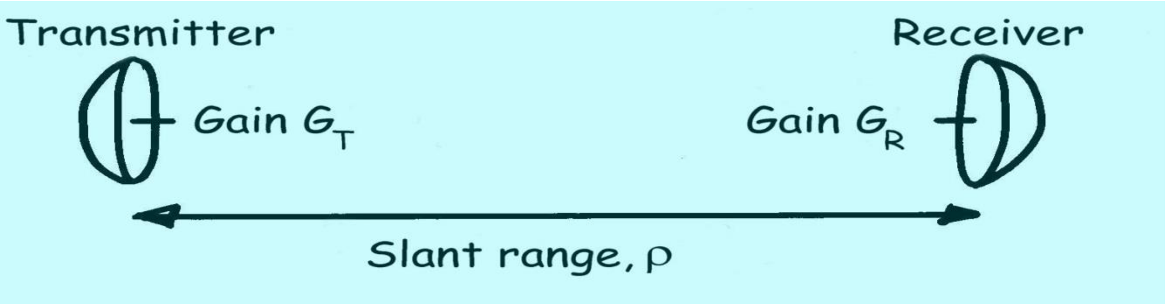
Goonhilly Down, Cornwall

The Communications Link Analysis



The Communications Link Analysis

Link Budget Equation



- If the transmitter were isotropic, power flux at the receiver would be

$$\phi = P_T \big/ (4\pi\rho^2) \qquad (\mathrm{W/m^2})$$

- Taking account of the transmitter gain G_T

$$\phi = P_T G_T \big/ (4\pi\rho^2)$$

- Received power is therefore

$$P_R = \phi \, A_{R,eff} \qquad (\mathrm{W}) \qquad \rightarrow P_R = \frac{P_T G_T}{(4\pi\rho^2)} A_{R,eff}$$

The Communications Link Analysis

Link Budget Equation

- But from equation (9.4) we have

$$G_R = \left(4\pi\ A_{R,eff}\right)\Big/\lambda^2 \quad \rightarrow A_{R,eff} = G_R \lambda^2 \Big/ 4\pi$$

so that

$$P_R = \frac{P_T G_T}{\left(4\pi\rho^2\right)} A_{R,eff} = \frac{P_T G_T}{4\pi\rho^2}\left(\frac{G_R \lambda^2}{4\pi}\right) \equiv \frac{P_T G_T G_R}{L_{FS}}$$

where the free space loss L_{FS} is defined by

$$L_{FS} = \left(\frac{4\pi\rho}{\lambda}\right)^2$$

The Communications Link Analysis

Link Budget Equation

- Introduce additional losses L_A, due to atmospheric absorption, precipitation, depointing, internal (circuit) losses, etc.,

$$P_R = \frac{P_T G_T G_R}{(L_{FS}\ L_A)} \qquad \text{(W)}$$

- Now let $P_R \equiv C$ (carrier power), and introduce noise density N_o at the receiver, given by

$$N_0 = k\ T_R \qquad \text{(W/Hz)}$$

- Then

$$\frac{C}{N_0} = \frac{P_T G_T G_R}{(L_{FS}\ L_A)}\left(\frac{1}{kT_R}\right) = \left(P_T G_T\right)\left(\frac{G_R}{T_R}\right)\left(\frac{1}{L_{FS} L_A}\right)\left(\frac{1}{k}\right)$$

The Communications Link Analysis

Link Budget Equation

- In dBs, this gives

$$10\log_{10}\left(\frac{C}{N_0}\right)=10\log_{10}\left(\left(P_T G_T\right)\left(\frac{G_R}{T_R}\right)\left(\frac{1}{L_{FS}L_A}\right)\left(\frac{1}{k}\right)\right)$$

Therefore the budget equation for the satellite communications link …

$$\underbrace{10\log_{10}\left(\frac{C}{N_0}\right)}_{\text{Carrier Power to Noise density ratio}}=\underbrace{10\log_{10}\left(P_T G_T\right)}_{\text{EIRP}}+\underbrace{10\log_{10}\left(\frac{G_R}{T_R}\right)}_{\text{Ground Station Figure of Merit}}-\underbrace{20\log_{10}\left(\frac{4\pi\rho}{\lambda}\right)}_{\text{Free space loss}}\underbrace{-10\log_{10}L_A}_{\text{Atmospheric losses}}\underbrace{-10\log_{10}k}_{\text{Constant}} \quad (9.6)$$

The Communications Link Analysis

Figures of Merit

Equivalent Isotropic Radiated Power (EIRP)

- This is given by

$$EIRP = P_T G_T \qquad (\mathrm{W}) \qquad (9.7)$$

- If the transmitter were replaced by an isotropic radiator, the EIRP would be the power required by the isotropic radiator to achieve the same power flux at the receiver as the original transmitter.

Receiver G/T ratio

- This is a measure of the sensitivity of the receiver – it can be shown to be directly proportional to the C/N_0 ratio

Link Quality

For a digital link, the link quality is given in terms of the Bit Error Rate (BER), which is the probability that a bit is received incorrectly.

– If R_b is the link data rate (bps), the time to receive one bit of information is

$$t_b = 1/R_b \qquad \text{(seconds)}$$

– Also the energy per bit is given by

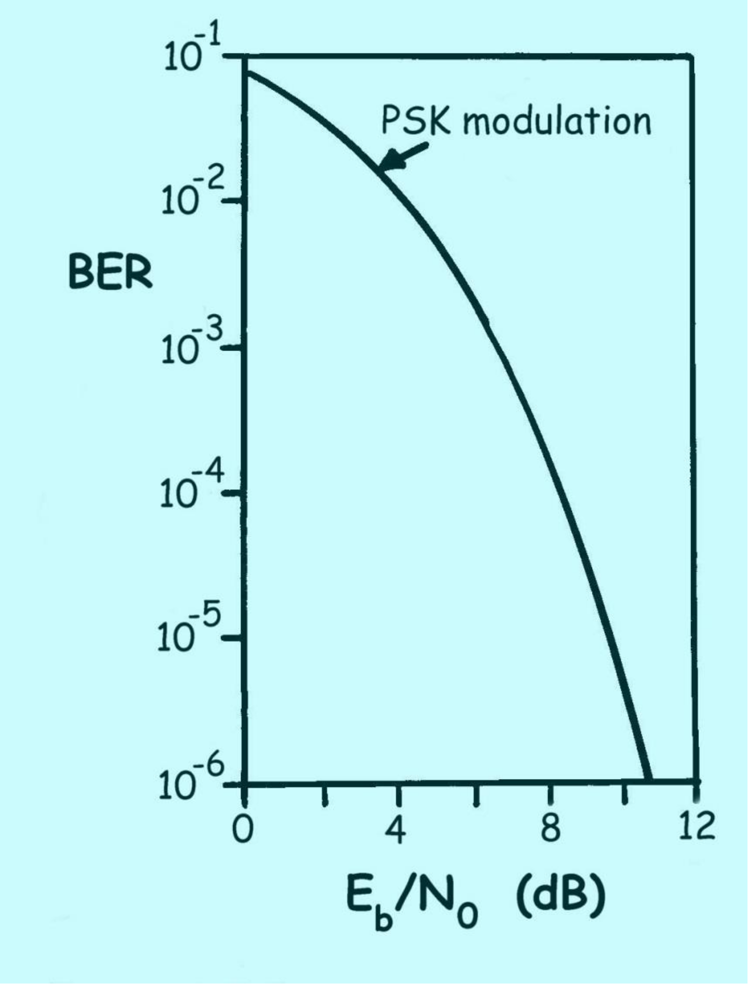
$$E_b = C t_b \quad \rightarrow C = \frac{E_b}{t_b}$$

– Hence we have

$$\frac{C}{N_0} = \frac{E_b}{t_b}\frac{1}{N_0} = \frac{E_b}{N_0}\frac{1}{t_b} \qquad \rightarrow \frac{C}{N_0} = \frac{E_b}{N_0} R_b \qquad (9.8)$$

Link Quality

- For a particular type of modulation (e.g. PSK), E_b/N_0 and BER are related



Example

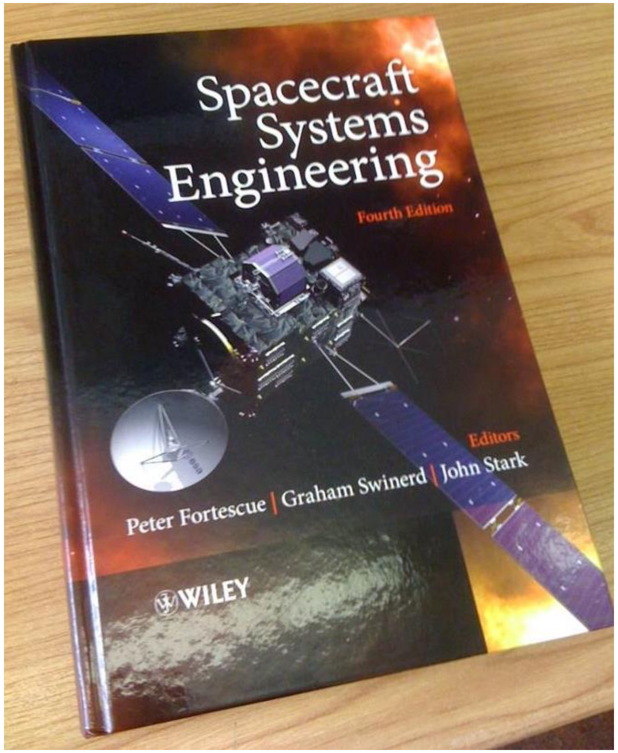
- A geostationary Earth orbit spacecraft broadcasts TV channels at a data rate of 92 Mbps to a user community at a slant range of 38,400 km, with a C-Band downlink frequency of 4 GHz. The user's receiver has a parabolic dish antenna of 0.4 m diameter, and a receiver system noise temperature of 150 K. If a BER of 10^{-6} is required at the receiver and there is an additional loss of 5 dB, estimate the satellite EIRP.
- If the spacecraft transmitting antenna is a 2 m diameter parabolic dish, and the spacecraft transponders are 50% efficient, estimate the transponder electrical power.

Chapter 9 Summary

Key points:

The Communications Subsystem	• Function of the subsystem and examples of missions for which the communications subsystem is the payload • Introduce the decibel and the transmission medium
Atmospheric Windows	• Environmental constraints on the transmission • Useful communication bands and standards
Encoding, Modulation and Bandwidth	• Basic introduction to encoding, modulation and bandwidth • Example to outline these principles
Noise	• Definition, sources and quantification of noise in the communications link
Antenna Gain and Beamwidth	• Introduction to antenna gain and beamwidth • How these values can be calculated using formula's based on empirical data (with examples)
The Communications Link Analysis	• Derivation of the link budget equation • Introduction to each term in the link budget equation and the importance of the EIRP
Link Quality	• How link 'quality' is accounted for in the link budget equation for digital communications
Example	• Link budget equation example

Chapter 9 Summary



Read Chapter 12 of Fortescue, Stark & Swinerd