



ClearSpace-1
Active Debris Removal

Telecommunication Subsystem Design

Hannes Bartle

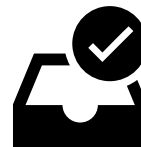
EE-584 Spacecraft Design and Systems
Engineering

Lecture 7

4/11/2024

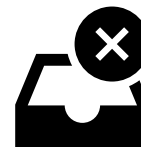
In this lecture:

- System level view of spacecraft communication systems
- Subsystem design process
- Link budget analysis
- Rough-Order-of-Magnitude (ROM) intuition about certain metrics
- Lots of cool pictures of spacecrafts



Not in this lecture:

- Details of RF engineering (amplifier metrics, mixers, filters, etc)
- Details on Information Theory (Error correction codes)
- Higher level communication protocols (e.g. TCP/IP, CCSDS, CSP, ...)
- Ground Segment architectures (next week)
- On-board data communication interfaces (next week)



2020-today: PhD Student Electromagnetics/Antenna Design



2020-2024: Telecom & Radar System Engineer



2017-2019: M.Sc. Electrical Engineering



2014-2017: B.Eng. Aerospace Engineering

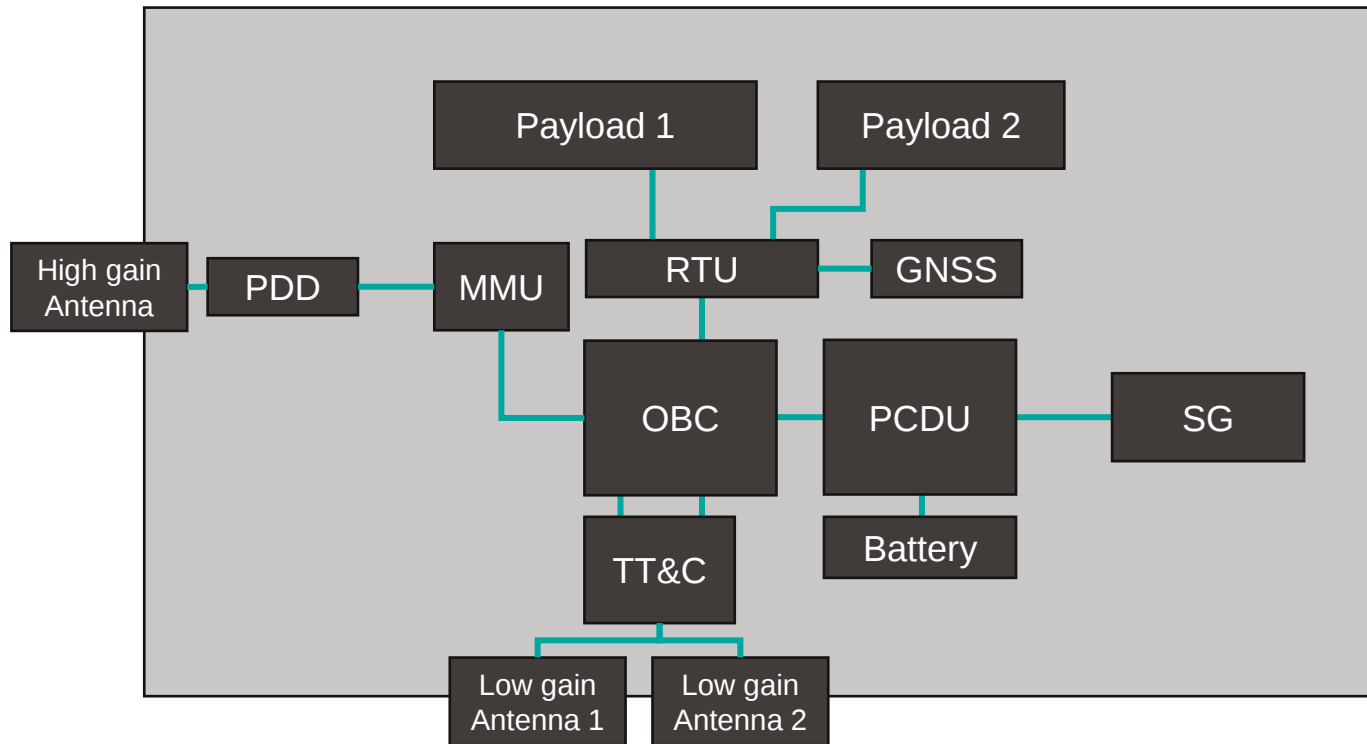




Sentinel-6A
SAR Sea-level Monitoring

System Overview

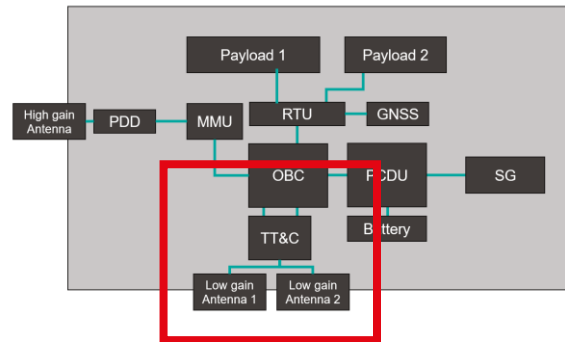
Typical Earth Observation/Space Science architecture



Communication Systems

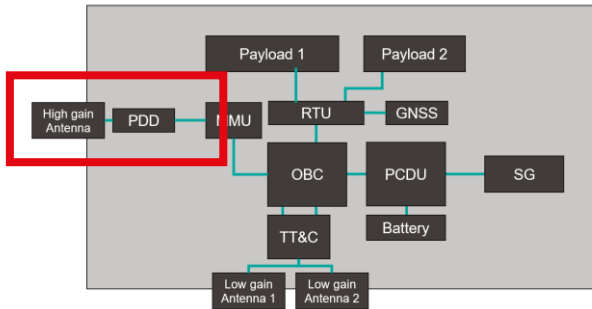
Telemetry, Tracking & Control (TT&C)

- General commanding of the satellite
- Housekeeping and status information
 - Temperatures
 - Power states
 - Battery
 - Mechanisms states
 - etc
- Tracking
 - Tracking/Ranging functionality to determine position of spacecraft
 - Especially important when now GNSS available, i.e. interplanetary missions
- Without Tracking Capability: TM/TC



Properties:

- Generally uses low gain antennas for quasi-isotropic coverage
- Relatively low data rates in kbps range
- Highly reliable hardware



Payload Data Downlink

- Downlink of large bulk data
 - Images
 - Video
- Either from mass memory or directly from payload
- High data rates
 - 10-100Mbps for CubeSat
 - 100-1000Mbps for SmallSats
 - >10Gbps for big earth observation missions
- Either traditional RF link or Optical (Laser)

EO/Science Spacecraft System

Sentinel-6A

- Synthetic Aperture Radar
- Sea-surface height measurements
- Measure the temperature and humidity in the troposphere and stratosphere



E0/Science Spacecraft System

Flying Laptop

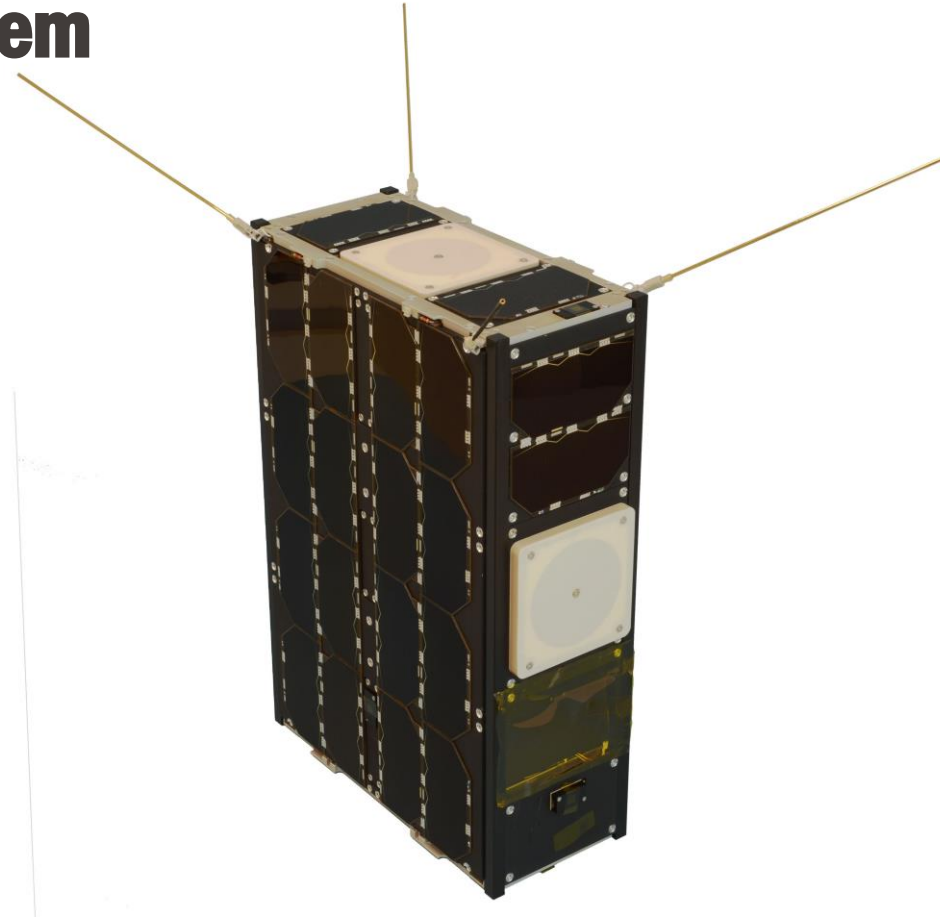
Technology Demonstration
Multispectral Imagery



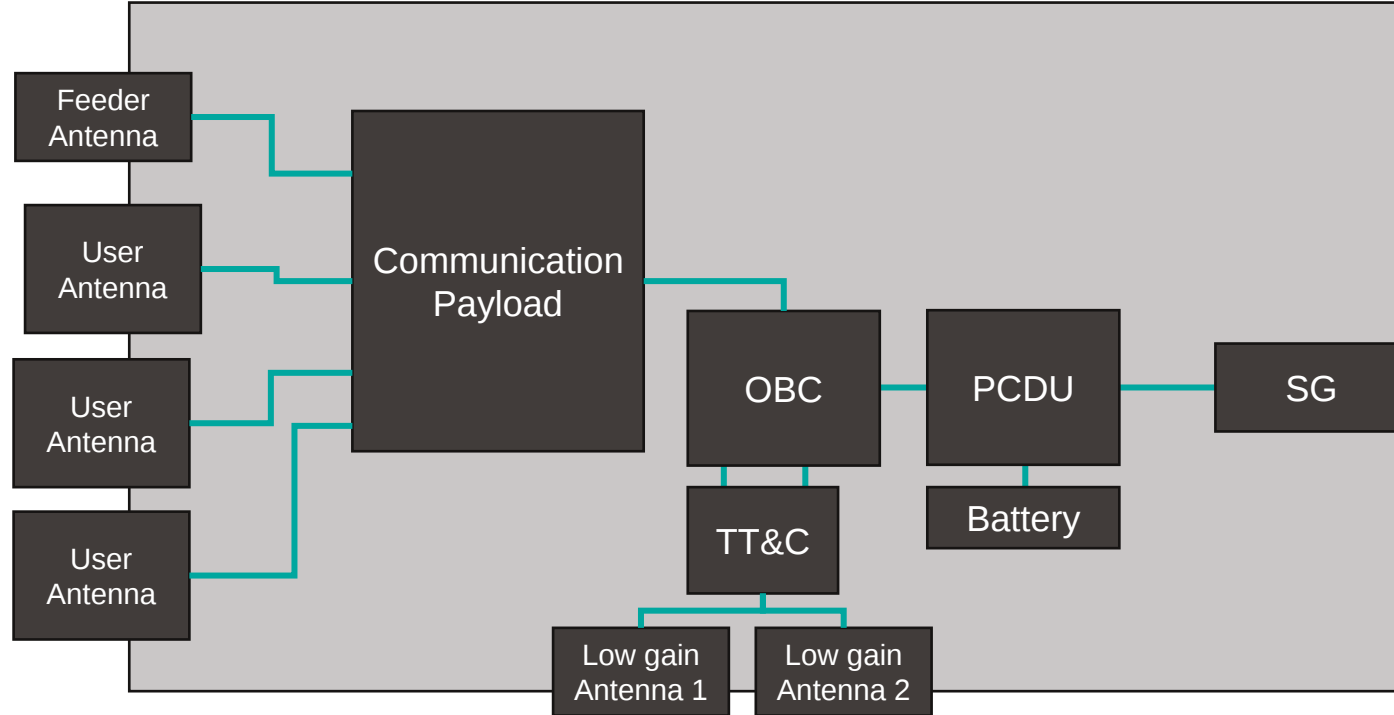
E0/Science Spacecraft System

GOMX-4a

Multi-purpose imagery (land)
Vegetation



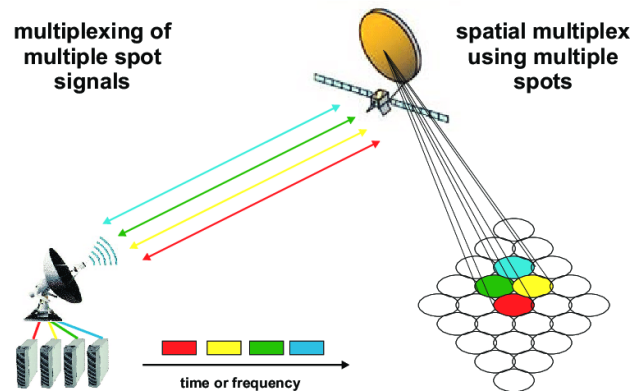
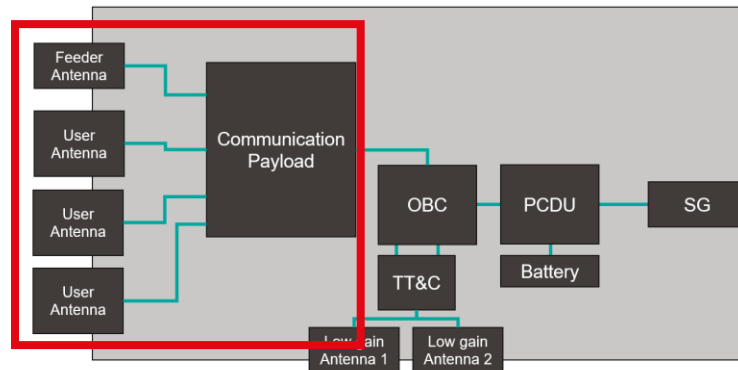
Typical Communication satellite architecture



Communication Satellite System

Communication payload

- High performance Multiplexer/Demultiplexer/Router
- One or multiple feeder links
- Up to several hundreds user beams
- Capacity 100-1000Gbps (single satellite)



Communication Satellite System

NSS-12

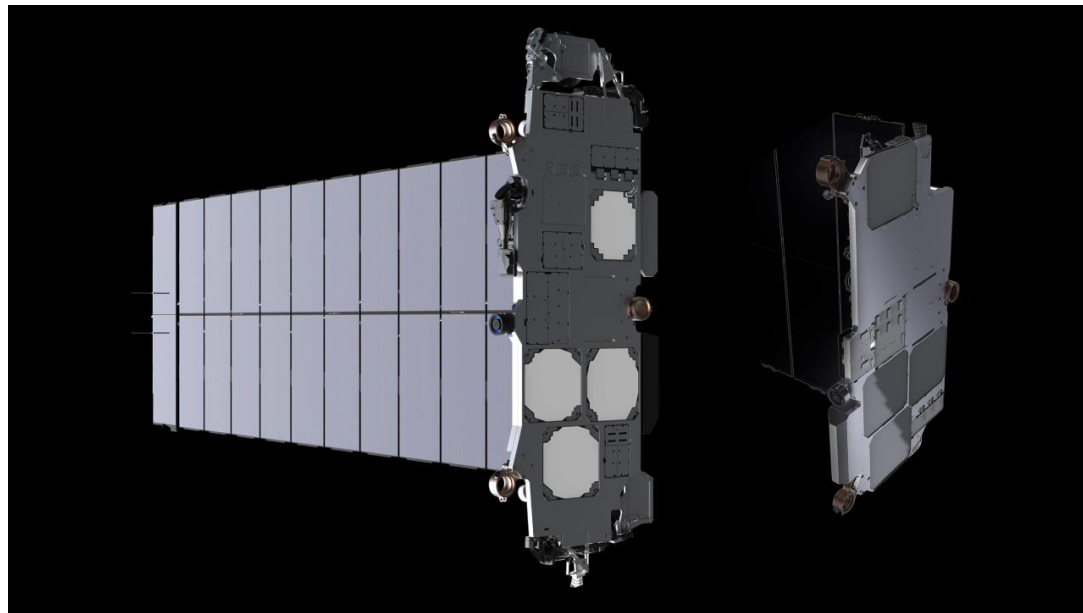
- Ku-Band internet/TV Broadcast
- Several parabolic reflector antennas

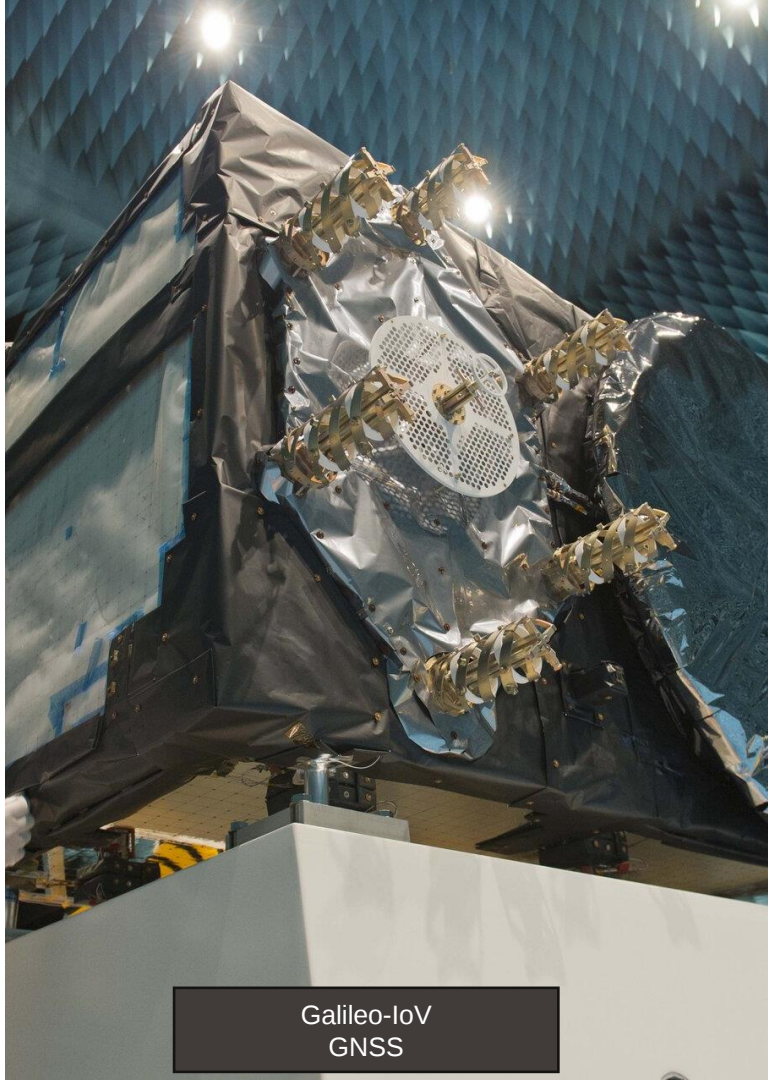


Communication Satellite System

Starlink

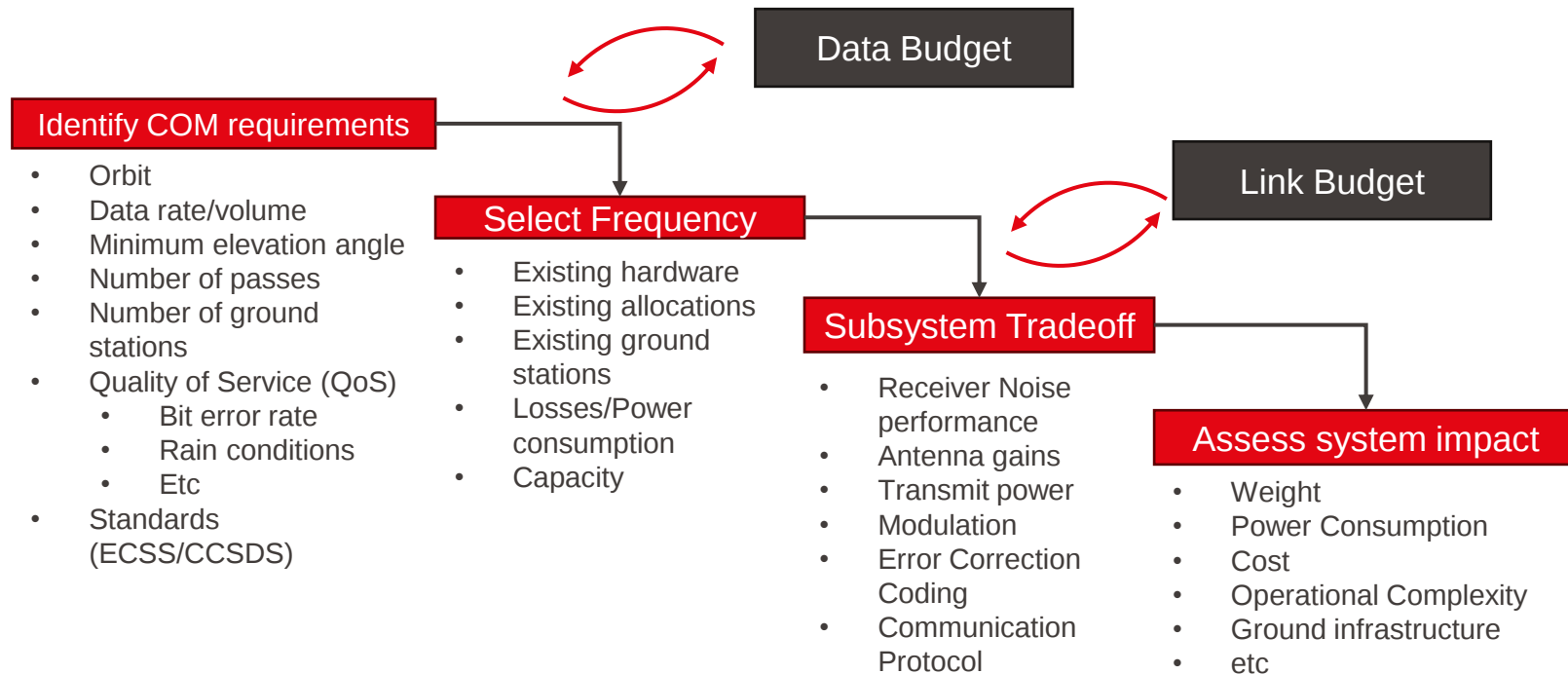
- Ku/Ka-Band
- Intersatellite links
- Phased Array antennas





System Design Process

Communication System Design Process

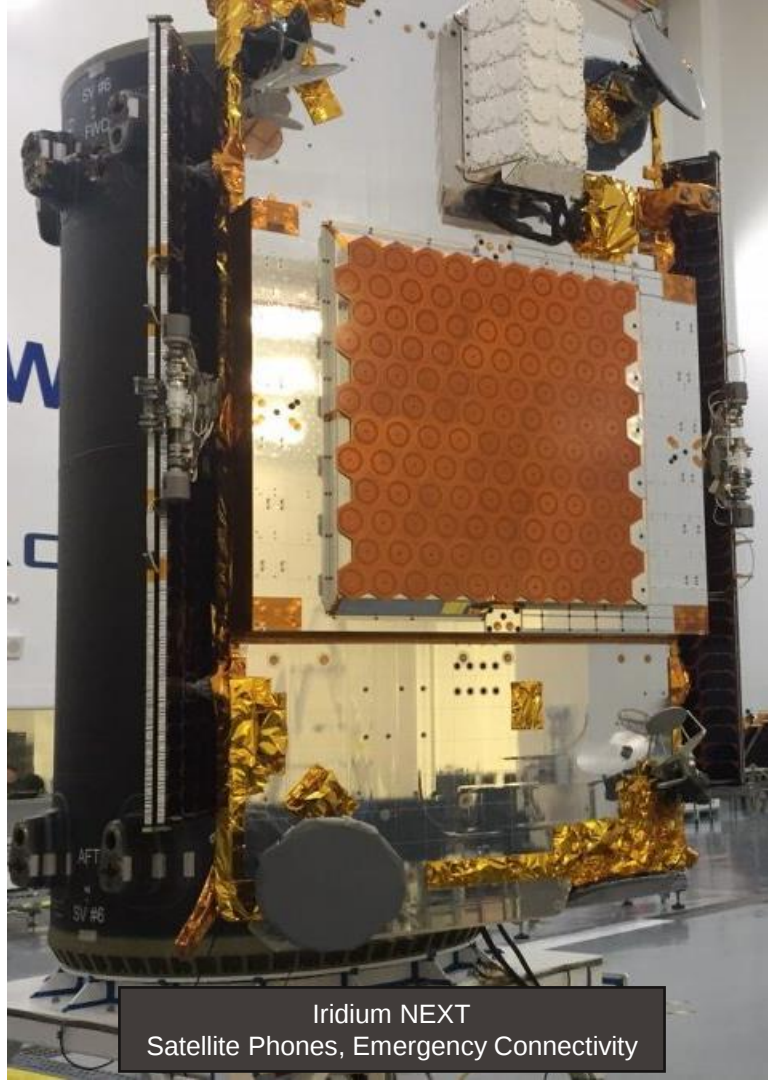




O3b Satellite
Broadband Internet, Maritime

System Data Budget

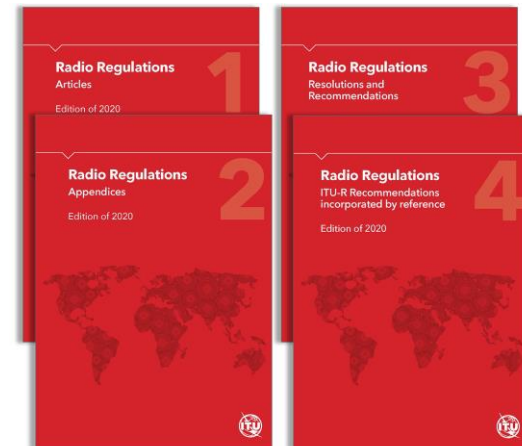
- How much data is produced?
- How often does a Ground Station pass occur?
- How many Ground stations are used?
- How long is a pass (avg)?



Iridium NEXT
Satellite Phones, Emergency Connectivity

Frequencies

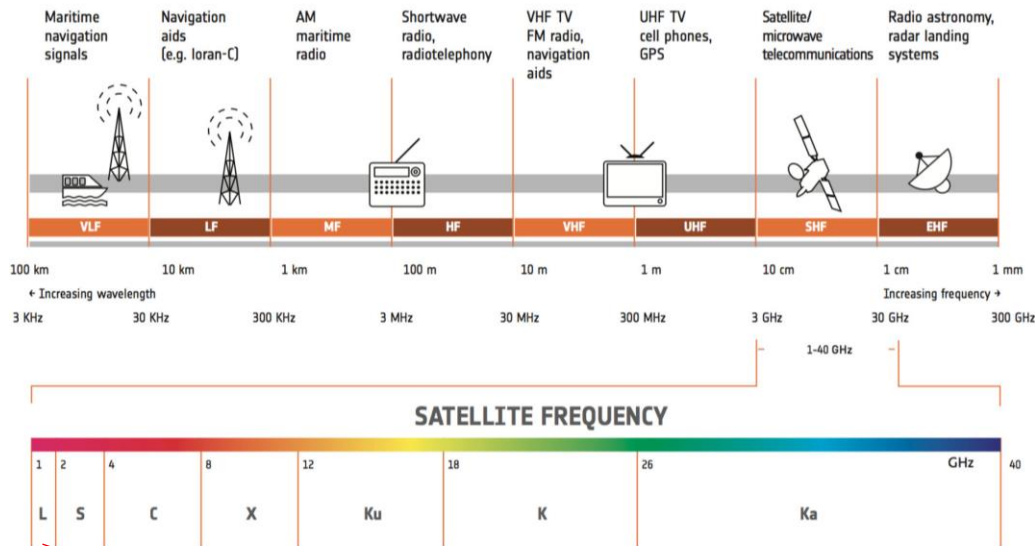
- Frequency Spectrum coordinated by
- Frequencies are assigned to Services:
 - Earth Exploration Satellite Service (EESS)
 - Space Operation Satellite Service (SOS)
 - Space Research Service (SRS)
 - Amateur Satellite Service (ASS)
 - Etc



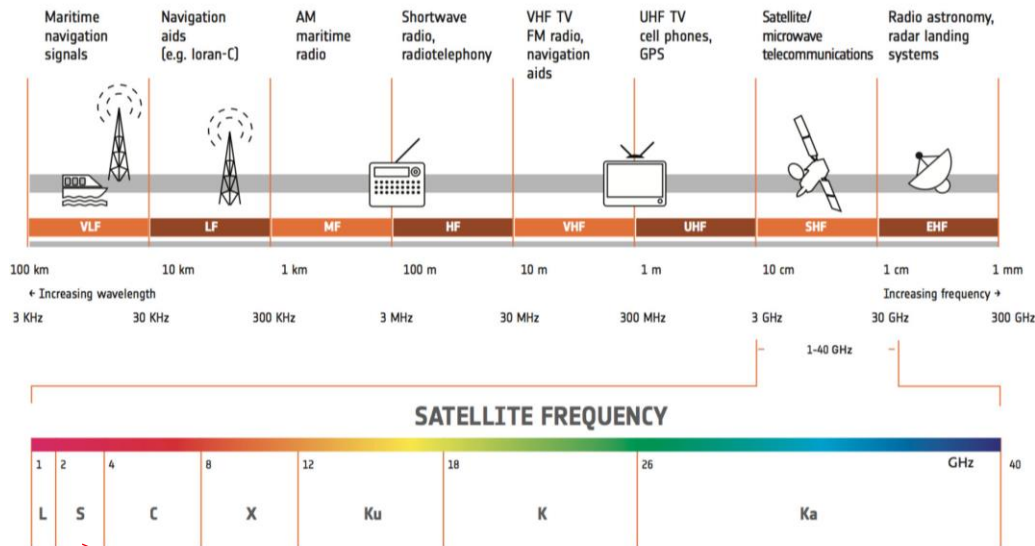
1 710-2 170 MHz

Allocation to services		
Region 1	Region 2	Region 3
1 710-1 930	FIXED MOBILE 5.384A 5.388A 5.388B 5.149 5.341 5.385 5.386 5.387 5.388	
1 930-1 970 FIXED MOBILE 5.388A 5.388B 5.388	1 930-1 970 FIXED MOBILE 5.388A 5.388B Mobile-satellite (Earth-to-space) 5.388	1 930-1 970 FIXED MOBILE 5.388A 5.388B 5.388
1 970-1 980	FIXED MOBILE 5.388A 5.388B 5.388	
1 980-2 010	FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) 5.351A 5.388 5.389A 5.389B 5.389F	
2 010-2 025 FIXED MOBILE 5.388A 5.388B 5.388	2 010-2 025 FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) 5.388 5.389C 5.389E	2 010-2 025 FIXED MOBILE 5.388A 5.388B 5.388
2 025-2 110	SPACE OPERATION (Earth-to-space) (space-to-space) EARTH EXPLORATION-SATELLITE (Earth-to-space) (space-to-space) FIXED MOBILE 5.391 SPACE RESEARCH (Earth-to-space) (space-to-space) 5.392	
2 110-2 120	FIXED MOBILE 5.388A 5.388B SPACE RESEARCH (deep space) (Earth-to-space) 5.388	
2 120-2 160 FIXED MOBILE 5.388A 5.388B 5.388	2 120-2 160 FIXED MOBILE 5.388A 5.388B Mobile-satellite (space-to-Earth) 5.388	2 120-2 160 FIXED MOBILE 5.388A 5.388B 5.388
2 160-2 170 FIXED MOBILE 5.388A 5.388B 5.388	2 160-2 170 FIXED MOBILE MOBILE-SATELLITE (space-to-Earth) 5.388 5.389C 5.389E	2 160-2 170 FIXED MOBILE 5.388A 5.388B 5.388

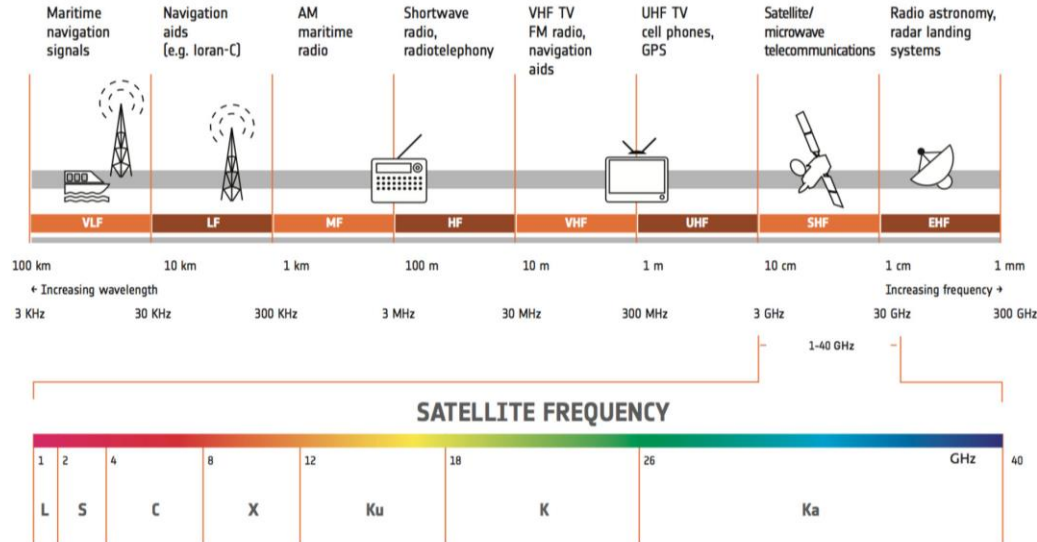




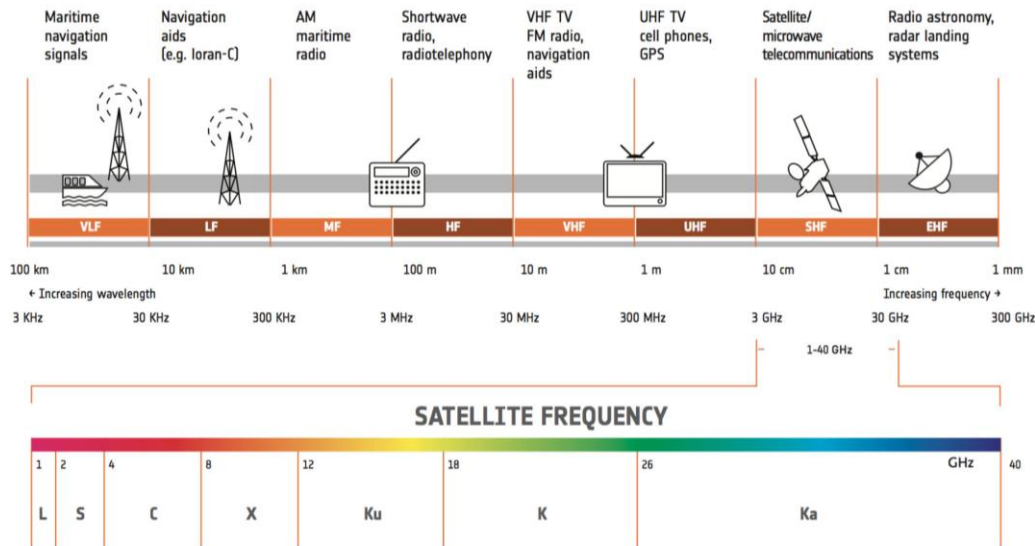
- GNSS
- Mobile Satellite Service
- Emergency Services



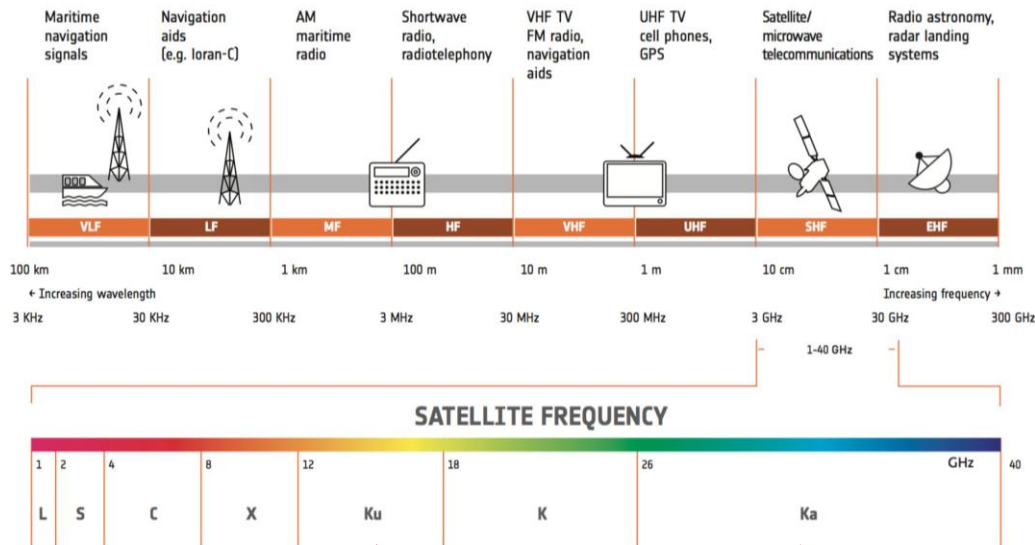
- LEO Spacecraft TM/TC
- Deep Space TT&C



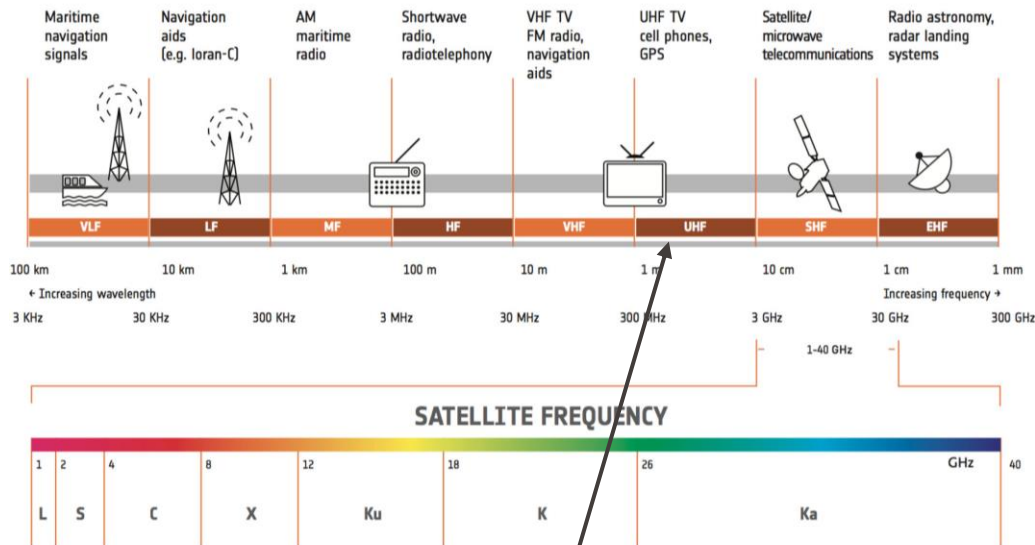
- Heritage GEO communication satellites
- 5G LEO constellations



LEO Earth Observation Downlink



- LEO+GEO communication satellites
- Intersatellite links



Most amateur satellites

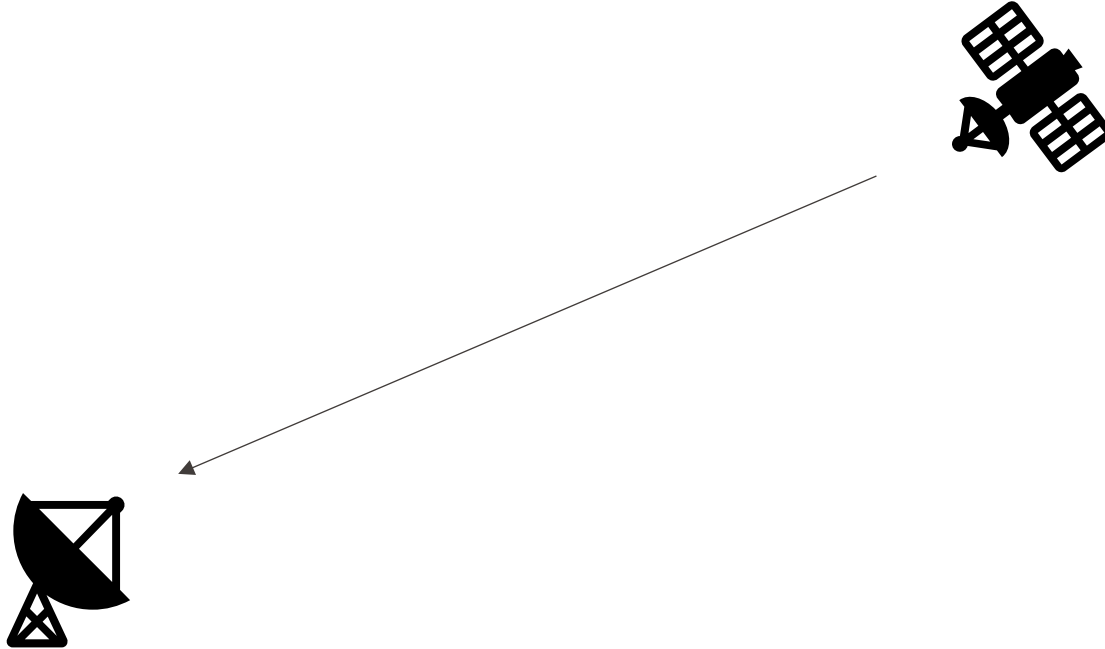


Teleport
Leuk/Loèche, Valais

Link Budget

Link Budget Equation

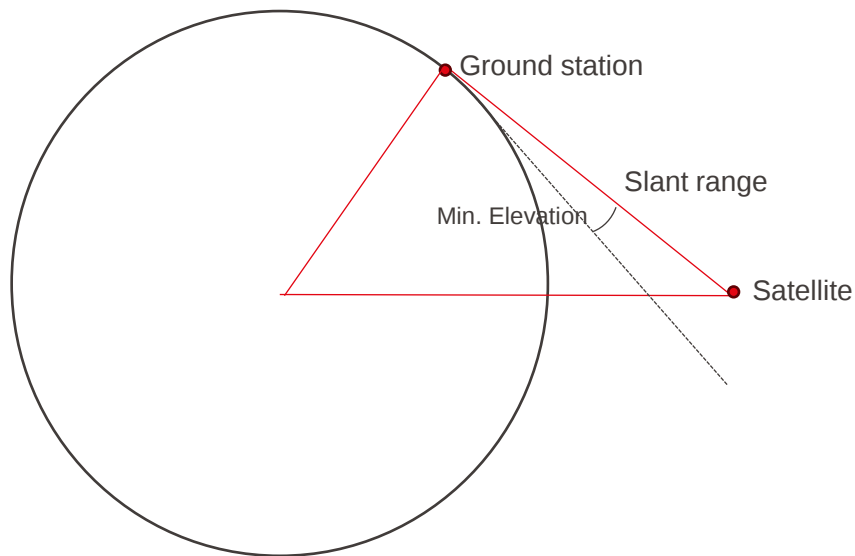
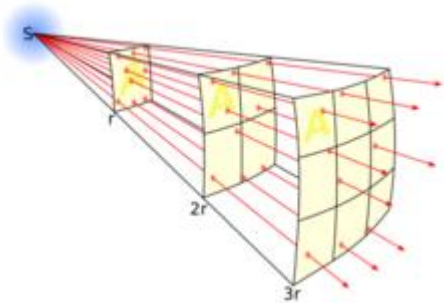
$$P_r =$$



$$P_r = P_t - L_t + G_t - L_{\text{FSPL}} - L_{\text{atm}} - L_{\text{pol}} - L_{\text{rain}} + G_r$$

Attenuation due to spatial spreading of power

$$L_{\text{FSPL}} = \left(\frac{4\pi r}{\lambda} \right)^2$$



600km Orbit & 5deg min Elevation:

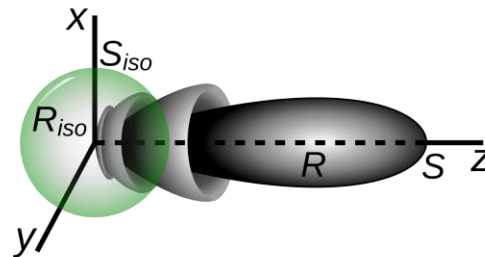
→ Max Slant range: 2330km

→ FSPL at 2.2GHz: **167dB**

$$P_r = P_t - L_t + G_t - L_{\text{FSPL}} - L_{\text{atm}} - L_{\text{pol}} - L_{\text{rain}} + G_r$$

How **directive** is the antenna?
How **efficient** is the antenna?

$$G = \eta D$$



Quasi-isotropic: <3dBi
Hemispherical: ~6dBi
Directional: >10dBi

Parabolic dish antennas:

$$G = \eta \left(\frac{\pi d}{\lambda} \right)^2$$

Aperture Efficiency ~55-70%



$$P_r = P_t - L_t + G_t - L_{\text{FSPL}} - L_{\text{atm}} - L_{\text{pol}} - L_{\text{rain}} + G_r$$

Antennas have a specific polarization (Direction of E-field of radiated wave)

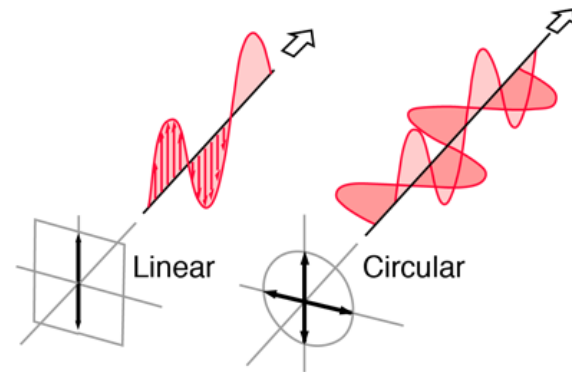
Linear:

- Potentially affected by Faraday rotation in the atmosphere
- Transmitter and Receiver antenna need to be aligned
 - Otherwise polarization loss

Circular:

- No Faraday rotation effect
- Spacecraft orientation (i.e. antenna alignment) doesn't matter

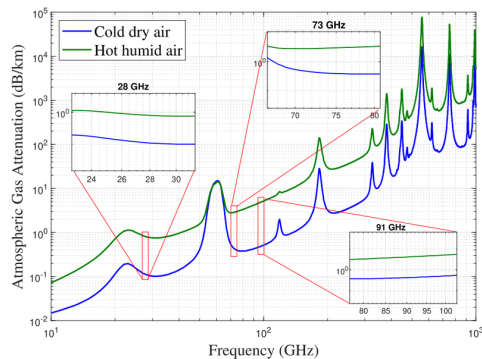
→ Most spacecraft antennas use circular polarization



$$P_r = P_t - L_t + G_t - L_{\text{FSPL}} - L_{\text{atm}} - L_{\text{pol}} - L_{\text{rain}} + G_r$$

Attenuation due to gases and humidity in atmosphere

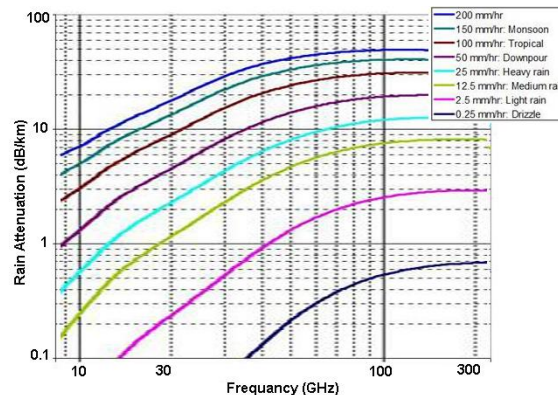
→ Only relevant for high frequencies
>20GHz



ITU Recommendation P.676-13

Attenuation due to rain

- Depends on GS location
- Depends on Service Availability (90%, 95%, 99%)



ITU Recommendation P.838-3

Observing a signal means introducing noise

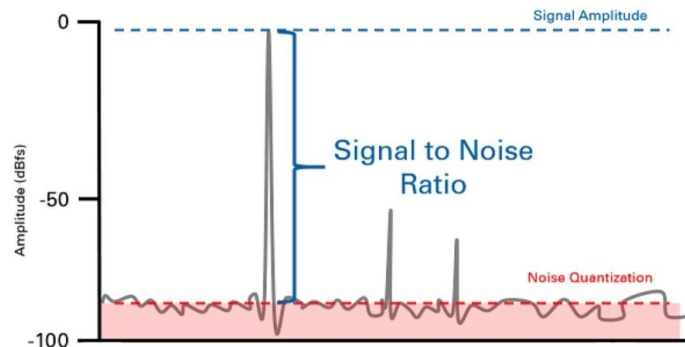
$$N = k_B T_{sys} B$$

B: Bandwidth of receiver window

- Needs to be large enough to let all “useful” signal through
- Shouldn't be any larger as noise will be increased
- Dedicated filtering necessary at receiver

T_{sys} : Equivalent System Noise Temperature

k_B : Boltzmann's constant

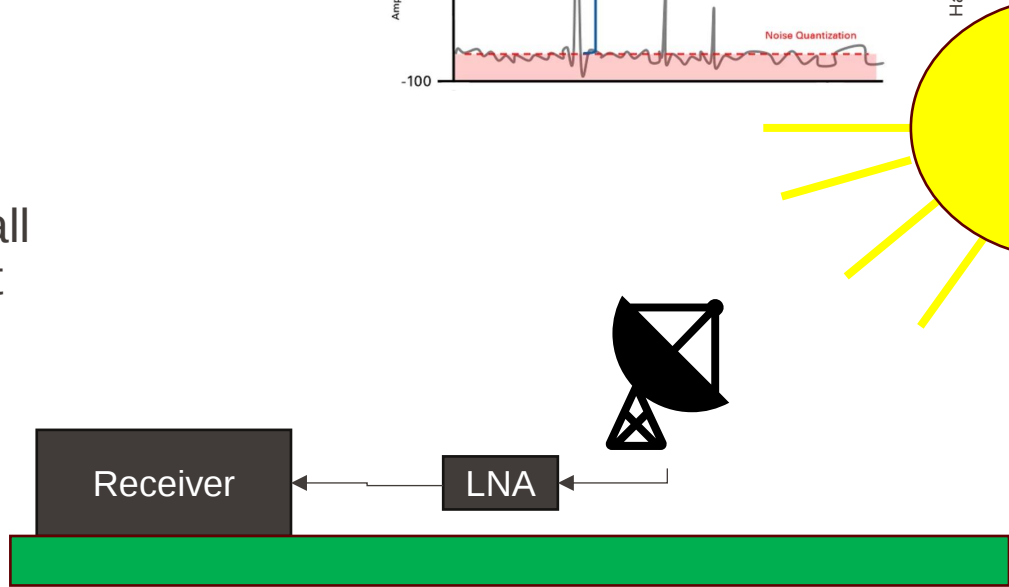
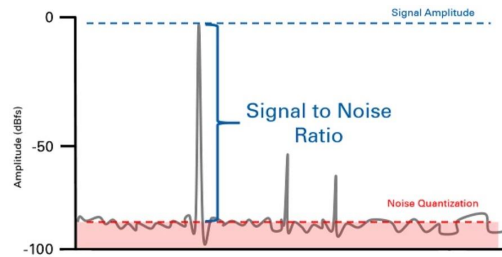


$$N = k_B T_{sys} B$$

System Noise Temperature

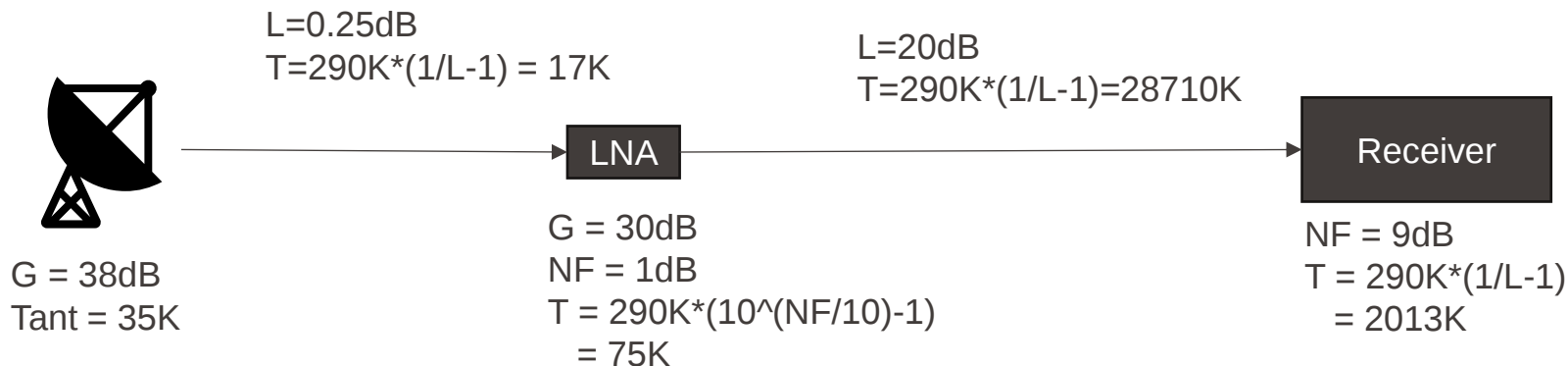
- Artificial metric to account for all components in the system that introduce noise
- Not a physical temperature
- Main components:
 - Antenna Temperature
 - Receiver chain
- Derived by Friis Noise Formula:

$$T_{sys} = T_{ant} + T_{cable} + T_{LNA} + \frac{T_{cable}}{G_{LNA}} + \frac{T_{Rx}}{G_{LNA} L_{cable}}$$



Noise Example

$$T_{sys} = T_{ant} + T_{cable} + T_{LNA} + \frac{T_{cable}}{G_{LNA}} + \frac{T_{Rx}}{G_{LNA}L_{cable}}$$



Resulting System Noise temperature:

$T_{sys} = 340\text{K}$

Combined with receiver antenna gain into the Receiver Figure of Merit (G/T):

$G/T = 12.68\text{dB/K}$

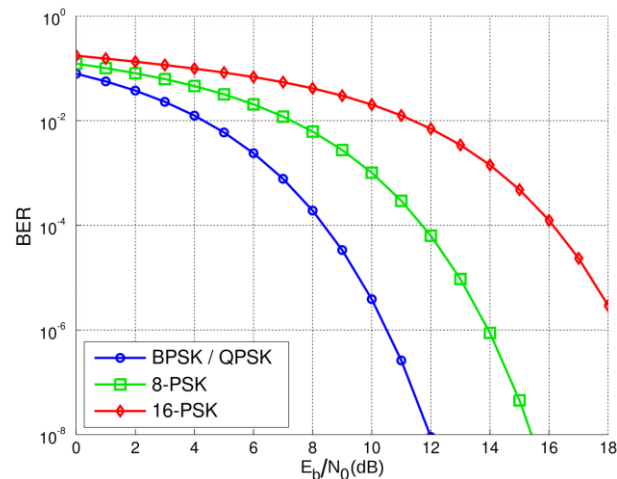
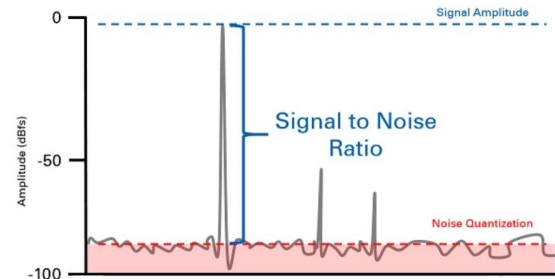
SNR determines if data can be recovered or not

$$SNR = \frac{C}{N} = \frac{P_r}{N}$$

Energy per bit relative to the noise spectral density is more useful (independent of bandwidth B):

$$\frac{E_b}{N_0} = \frac{C}{N} \frac{B}{R} = \frac{P_r}{k_B T_{sys}} \frac{1}{R}$$

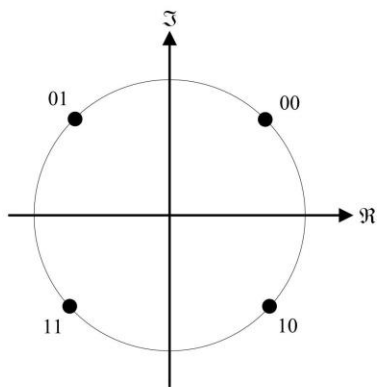
Different modulation schemes have different required E_b/N_0 for a certain **Bit-Error-Rate**



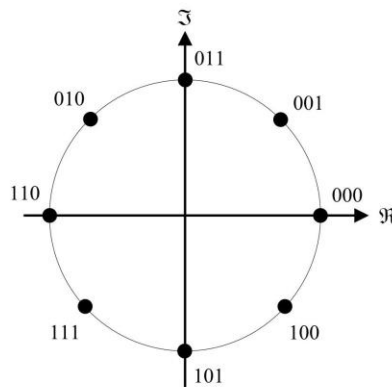
In order to send data, analog or digital, a RF carrier signal needs to be **modulated**:

- Amplitude
- Phase
- Frequency
- Combination of the above

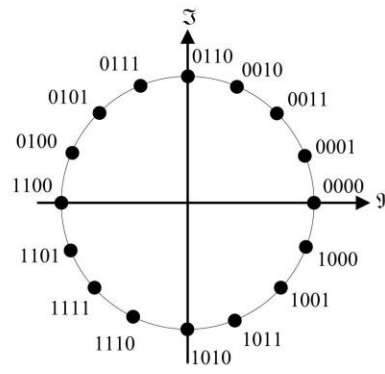
- Higher order modulations use several states to encode more than one bit
- For the **same symbol rate** they achieve a **higher data rate**



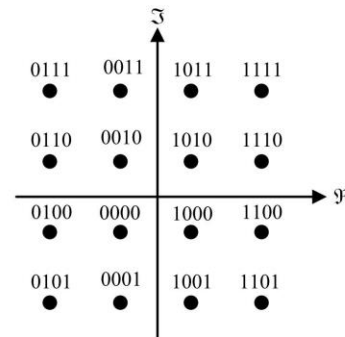
(a) QPSK



(b) 8-PSK

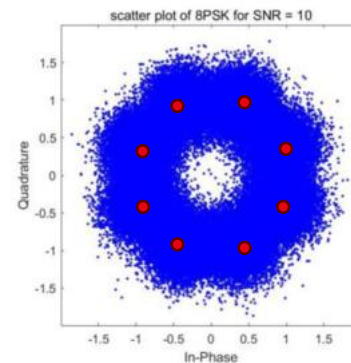
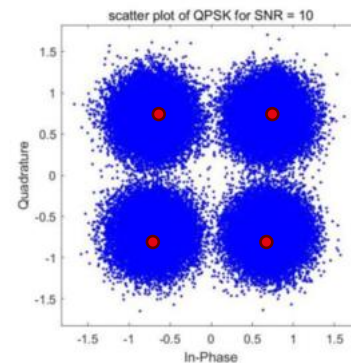
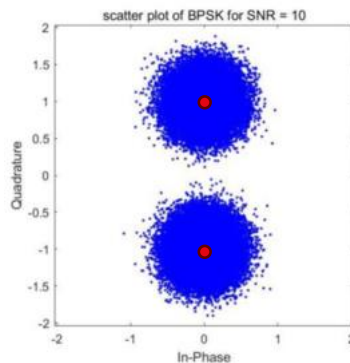
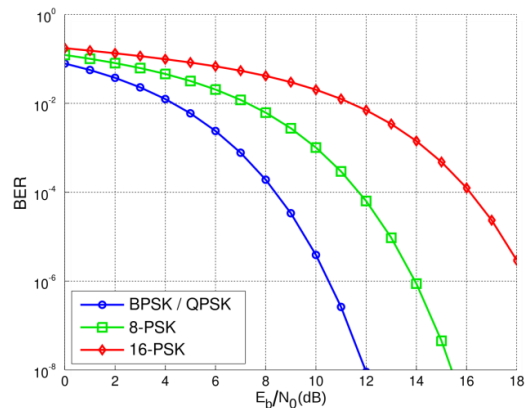


(c) 16-PSK



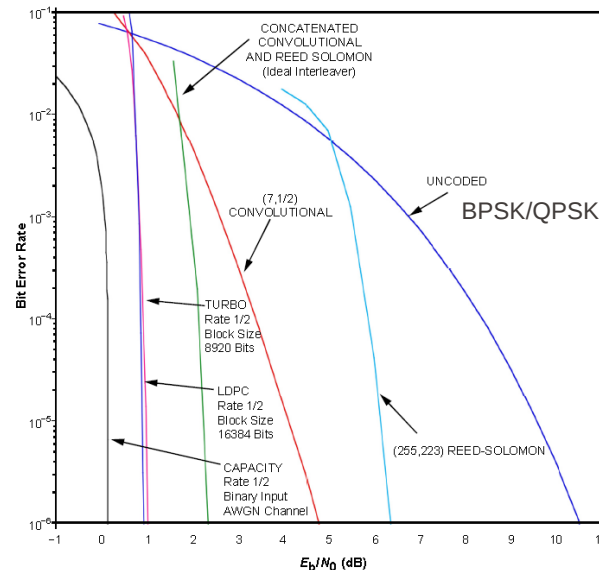
(d) 16-QAM

- How likely do we make mistake in receiving data?
→ Bit-Error Rate
- Determines Quality of Service required for specific application



Modulation	E_b/N_0 for BER = 10^{-5} (dB)	Spectrum Utilization (bps/Hz)	Advantages	Disadvantages
BPSK	9.6	1.0	Good BER performance. Good use of spectrum.	Susceptible to phase disturbances.
DPSK	10.3	1.0	Not susceptible to phase disturbances.	Higher E_b/N_0 required.
QPSK	9.6	2.0	Excellent use of spectrum.	More susceptible to phase disturbances.
FSK	13.3	0.5	Not susceptible to phase disturbances.	Higher E_b/N_0 required. Poor use of spectrum.
8FSK	9.2	0.375	Good BER performance. Not susceptible to phase disturbances.	Poor use of spectrum.
BPSK and QPSK Plus R-1/2 Viterbi Decoding	4.4	0.5 and 1.0	Excellent BER performance.	Higher complexity. Reduced use of spectrum.
BPSK Plus RS and Viterbi Decoding	2.7	0.44	Best BER performance.	Most complex. Reduced use of spectrum.
8FSK Plus R-1/2 Viterbi Decoding	4.0	0.188	Excellent BER performance. Not susceptible to phase disturbances.	Poor use of spectrum. High complexity.
MSK	9.6	1.5	Low adjacent channel interference.	Higher complexity.
BPSK/PM ($\Delta\phi = 1.0$ rad sinewave)	13.8	$\sim \frac{R}{2f_c}$	Carrier transmitted for Doppler measurement.	Requires extra power and bandwidth.

- Different modulations have different required E_b/N_0 for given BER
- Required E_b/N_0 can be lowered by adding an **error correction code**
- Similar to parity bits/checksum
- Detects errors AND can correct some of them
- Better codes (lower E_b/N_0) generally means **higher implementation complexity**
- FEC introduces overhead



- Even if worst case estimates are used, parameters are randomly distributed
- Link margins ensure robust communication
- Commonly used margins:
 - Amateur Satellite: 10dB
 - TT&C for EO satellite: 3-6dB
 - Payload Downlink for EO satellite: 3dB



LEO sat observing Rolex
Building, ChatGPT

Link Budget Examples

Mission:

- Live video feed of EPFL Campus from LEO Orbit
- 400km orbit
- Ground Sample Distance (GSD) 1m
- 4K@60fps
- Use 1.7m dish on top of ELB building
- S-band TMTC
- X-band Payload Data Downlink

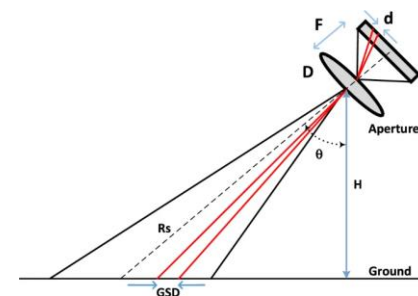


Berlin SpaceTech (BST) LEOS-50



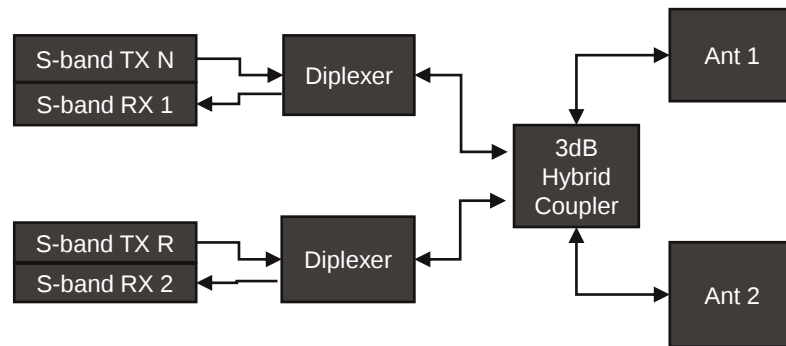
$$\text{GSD} = \frac{dH}{F}$$

$$\begin{aligned} \text{GSD} &= 1\text{m} \\ \text{Pixel Size} &\sim 7\mu\text{m} \\ \rightarrow F &= 2.8\text{m} \end{aligned}$$



LEO Example TMTC System

- Cold Redundant Transmitter
- Hot Redundant Receiver
- Diplexing filter splits TX/RX frequencies to avoid self interference
- Two quasi-isotropic antennas to maximize coverage when tumbling
- 3dB hybrid to split/combine signal between redundant antennas and redundant RX/TX pairs



LEO Example TMTC System



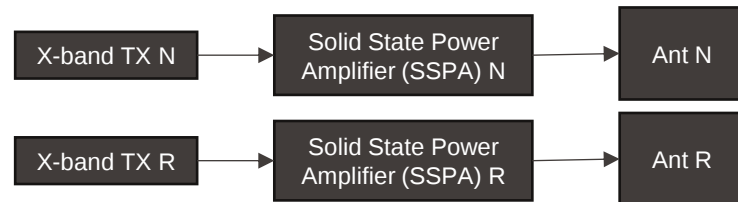
SSTRC300
STT Systemtechnik GmbH



Turnstile Crossed-Dipole Antenna
STT Systemtechnik GmbH

LEO Example PDD System

- Cold Redundant chains
- Directive antennas

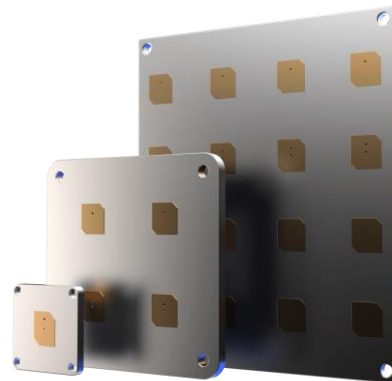


LEO Example PDD System

XONOS
Syrlinks



X-band patch antenna array
EnduroSat



LEO Example Data Budget

TMTC Data budget

- Assuming only one contact per day (TMTC and PDD at the same time)
- 10min communication window
- Live camera is very tricky to operate and calibrate because of high resolution/frame rate
- 32kbps uplink
- 512kbps downlink

LEO Example Data Budget

PDD Data budget

- 4k@60fps
- 12-bit colour resolution

Data generation rate:

$$3840 \times 2160 \times 12 \times 60 = 5.9 \text{ Gbps}$$

Live downlink means

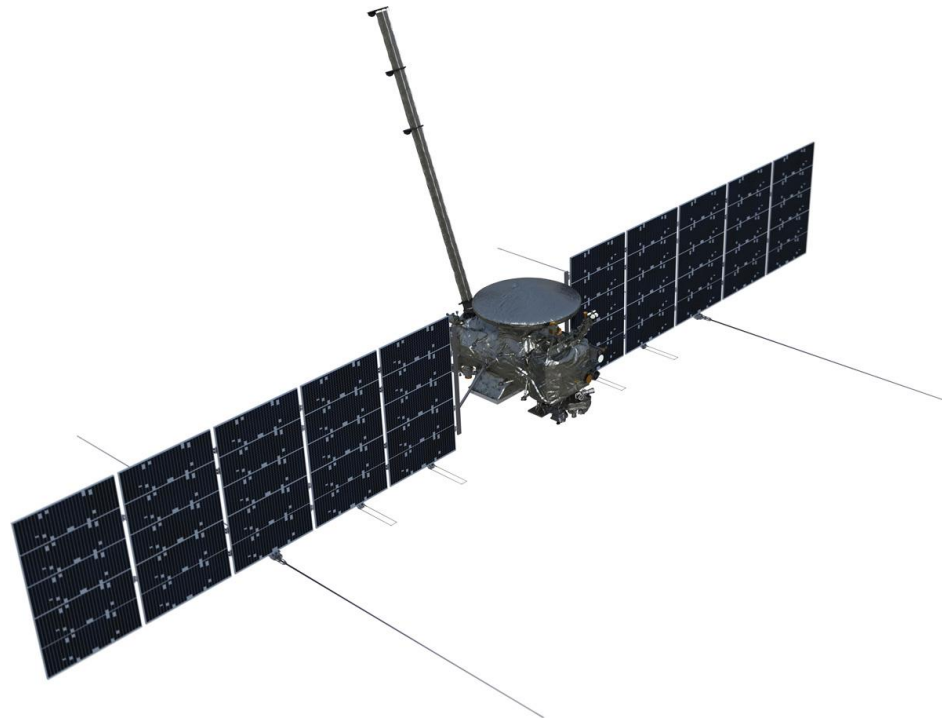
→ Data generation rate = Useable downlink data rate

- 600km Orbit
- 5deg min Elevation
- TT&C in S-band Up and Downlink
 - Uplink 32kbps
 - Downlink 512kbps
 - Quasi-isotropic coverage in case satellite is tumbling
- PDD in X-band
 - Downlink 5.9Gbps
 - Directional antenna, spacecraft steering towards ground

Excel Link Budget Table

EuropaClipper

- Launched 14.10.2024
- Investigate Jupiter moon Europa's ice crust and subsurface water oceans
- Potential for life?



- X-band TMTC system
 - 10bps (Emergency) to 100kbps (during Cruise)
- Ka-band Payload data system
 - 50kbps to 1Mbps
- All links with TurboCode
- Several Low gain, medium gain and high gain antennas

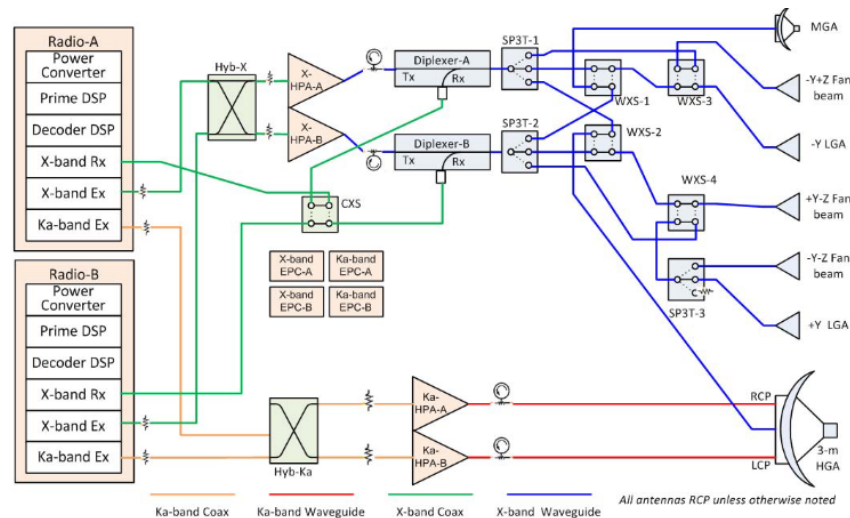


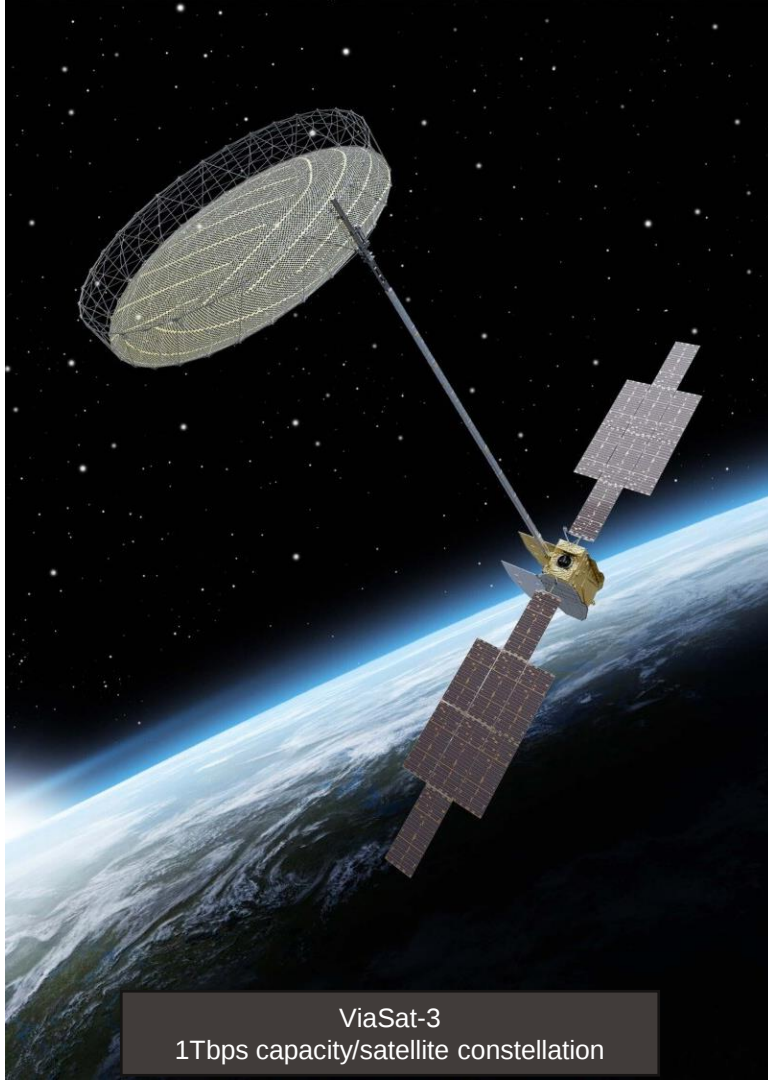
Fig. 1. Europa Clipper telecommunication system block diagram.

References:

- [1] D. Srinivasan, C. Sheldon and M. Bray, "Telecommunications systems for the NASA Europa missions," 2017 IEEE MTT-S International Microwave Symposium (IMS), Honolulu, HI, USA, 2017, pp. 394-397
- [2] Haskins, Christopher B. and Wesley P. Millard. "Multi-band software defined radio for spaceborne communications, navigation, radio science, and sensors." 2010 IEEE Aerospace Conference (2010): 1-9.

Deep Space Example

Excel Link Budget Table



ViaSat-3
1Tbps capacity/satellite constellation

Further Reading

- Systems Engineering for Telecom Subsystems
 - Yuen, J. H. (Ed.). (1983). **Deep Space Telecommunications Systems Engineering**. Springer US. <https://doi.org/10.1007/978-1-4757-4923-6>
 - Fortescue, P., Swinerd, G., & Stark, J. (Eds.). (2011). **Spacecraft Systems Engineering**. Wiley. <https://doi.org/10.1002/9781119971009>
 - Maral, G., Bousquet, M., & Sun, Z. (2020). **Satellite Communications Systems**. Wiley. <https://doi.org/10.1002/9781119673811>
- More theory on communication systems w.r.t spacecraft
 - Liu, J. (2015). **Spacecraft TT&C and Information Transmission Theory and Technologies**. In Springer Aerospace Technology. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-662-43865-7>

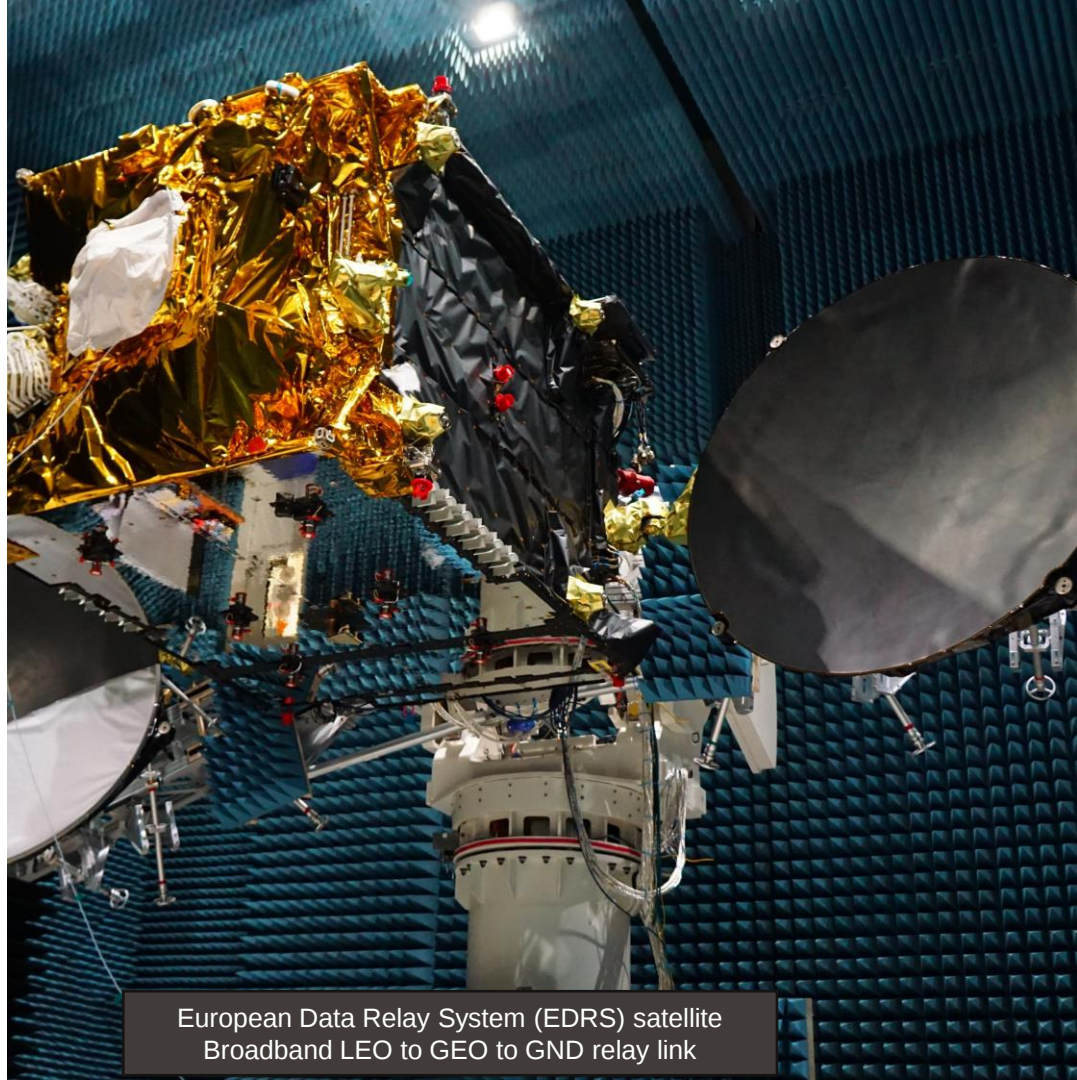
- **Consultative Committee for Space Data Systems (CCSDS) standards**

- CCSDS 131.0-B-5 TM Synchronization and Channel Coding
- CCSDS 231.0-B-4 TC Synchronization and Channel Coding
- CCSDS 232.0-B-4 TC Space Data Link Protocol
- CCSDS 132.0-B-3 TM Space Data Link Protocol

→ De facto standard for most commercial spacecraft and ground stations

- Link budget information/State-of-the-art/Current systems
 - <https://www.eoportal.org/>

- ESA Ladybird guide to spacecraft communications
 - https://www.esa.int/Education/ESA_Academy/



European Data Relay System (EDRS) satellite
Broadband LEO to GEO to GND relay link

Thank you !

Questions?

hannes.bartle@epfl.ch

ELB037