Satellite System Engineering

-- Communication Telemetry/Tracking/Telecommand (TT&C)

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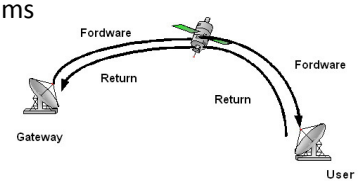
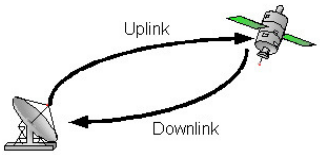
Objectives

- This lesson will discuss the following:
  - Communications subsystem functionalities
  - TT&C links
  - Hardware
  - Architectures
  - Frequency Selection
  - Modulation and Coding
  - Link budget
  - Design process for the comms subsystem
  - Outputs

Communications Systems

- Commercial Satellite Communications Systems
  - Typically in a geostationary orbits
  - Platform + payload
    - Payload transponders
      - Bent-pipe (no processing on-board)
      - Regenerative
    - Platform TT&C subsystem
      - Use part of payload frequency band
  - Limited tracking capabilities

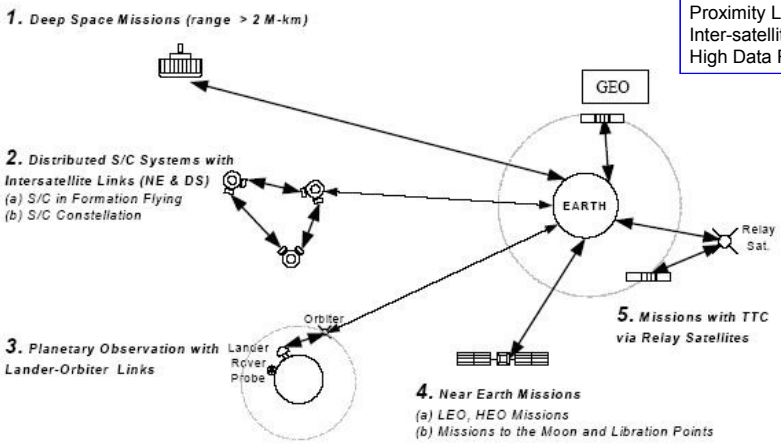




- TT&C Systems for ESA missions
  - Demodulate Telecommands
  - Modulate Telemetry (HK & science data)
  - Tracking of the satellite through radio-metric measurements (range, range rate, Doppler, Delta-DOR,…).

TT&C Links (1/3)

TT&C Links
Proximity Links
Inter-satellite Links
High Data Rate Links

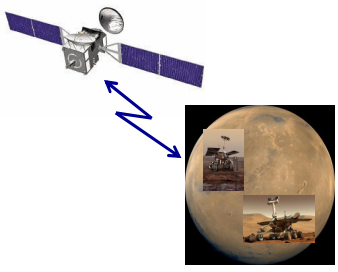


TT&C Links (2/3)

- TT&C links
  - Provide the Tracking, Telemetry and Command functionality of the spacecraft
  - Main equipment: Coherent TT&C transponder
  - Space Research missions (e.g. Planetary, Lagrange and Moon missions)
    - Deep Space missions (distance >2MKm)
    - Cat A missions (distance <2MKm)
  - EESS (Earth Exploration Satellites)
- Inter-satellite link
  - Radio Frequency and Optical Inter-satellite links
    - TDRSS (Tracking and Data Relay Satellite System)
    - Envisat – Artemis Link

TT&C Links (3/3)

- High Data Rate Downlinks
  - Typical for Earth Observation missions
  - Transmission of payload data
  - Equipment: typically telemetry transmitter



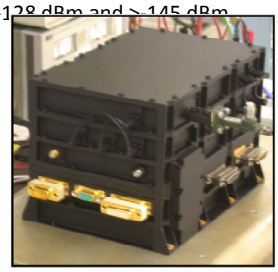
- Proximity Link

-Short-range, bi-directional, fixed or mobile radio links
-Communicate among probes, landers, rovers, orbiting constellations and orbiting relays.
-Equipment: Transceiver/transponder

Hardware

TT&C Transponder

- Transmitting, receiving and coherency capabilities.
  - Coherency: the downlink frequency is coherent with the uplink frequency, i.e. it is determined by a fixed turn around ratio (e.g. X-band turn around ratio 749/880) allowing two way Doppler measurements.
- Types of transponders:
  - Deep Space: high receiver sensitivity (very low received power at satellite), e.g. receiver sensitivity <-145 dBm
  - Near Earth (EESS, Moon mission): reduced receiver sensitivity (high rx power at satellite), e.g. >-128 dBm
  - Near Earth (Lagrange missions): receiver sensitivity typically <-128 dBm and >-145 dBm



Transceiver

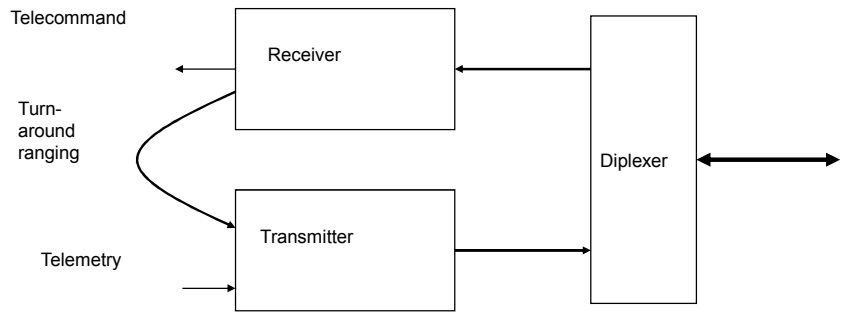
- Transmitting and receiving capabilities
- Non-coherent

Transmitter

- Only transmitting capabilities

Transponder

Typical Transponder Top Level Functions

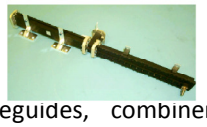


RF components

Filters

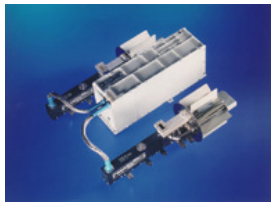
- Typical filters are Low Pass and Band Pass Filters
- OMUX (Output Multiplexer)
  - Filters and combines different channels for transmission
- Diplexer
  - Separates the uplink and downlink signals and provides isolation
  - Used typically in TT&C architectures to use single antenna for both up-and downlink

RFDU (Radio Frequency Distribution Unit)

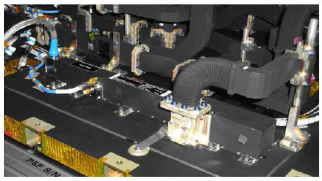


- Connect the antenna with the transponder/amplifier.
- Include: switches (coaxial/waveguides), cables, waveguides, combiners, splitters,…

Amplifiers



- SSPA (Solid State Power Amplifiers)
  - Highly reliable
  - Limited in RF power
  - Lighter and smaller
  - Efficiency ~20-30%
- TWTA (Travelling Waveguide Tube Amplifier)
  - High RF power achievable
  - Highly efficient (>60%)
  - Bulky

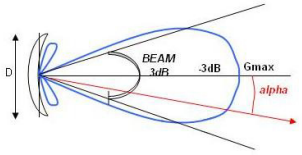


Typical: SSPA are typically used for power levels up to maximum 20 W

Antennas

Depending on the gain provided they are classified as:

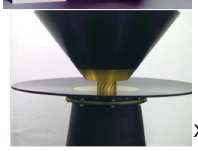
- LGA (Low Gain Antenna)
- MGA (Medium Gain Antenna)
- HGA (High Gain Antenna)



- The higher the antenna gain is the narrower the beamwidth.
- TT&C Antennas implement Right Hand Circular Polarisation (RHCP)/Left Hand Circular Polarisation (LHCP)
- Different types
  - Horn
  - Dish
  - Patch
  - Helix
  - Phased Array
  - Isoflux


X-band Horn

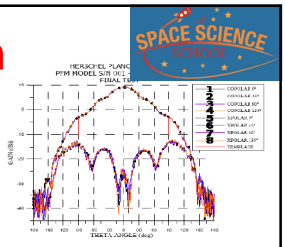
GAIA Phased Array

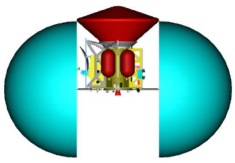

X-band Isoflux

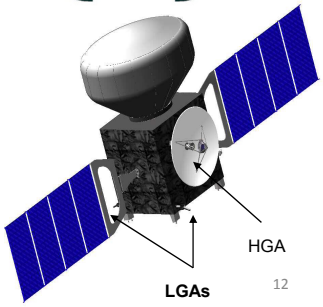

S-band Conical Helix

Antenna Configuration

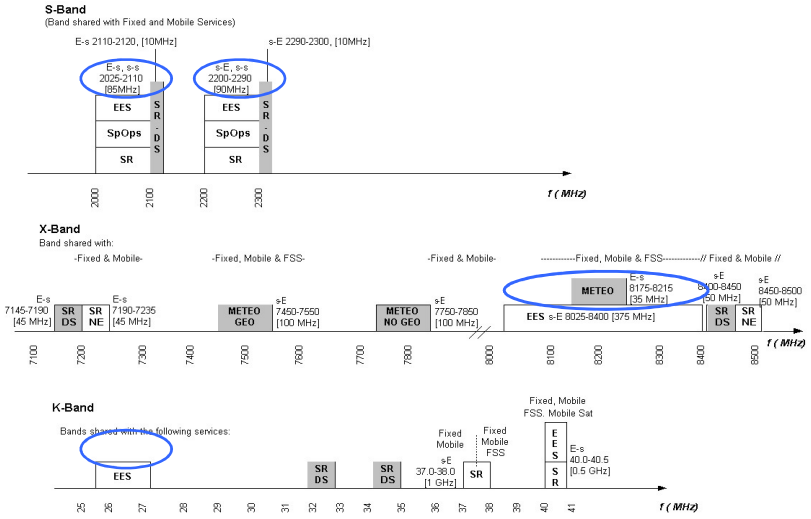
- Ensure communications during all mission phases
- LGA (Low Gain Antenna)
  - Used during LEOP (Low Earth Orbiting Phase)
  - Used during loss of S/C attitude
  - Typically main antenna used for LEO satellites (e.g. EES missions)
- MGA (Medium Gain Antenna)
  - Used during cruise phase → MGA (does not require accurate pointing)
  - Support medium/high data rates
- HGA (High Gain Antenna)
  - On-station operations (high data rates/large distances)
  - Require accurate pointing (very narrow beamwidth)







Frequency Selection



Frequency bands info is available in the ECSS-E-ST-50-05C: RF and Modulation Standard

Discussion on Frequency Selection (1/2)

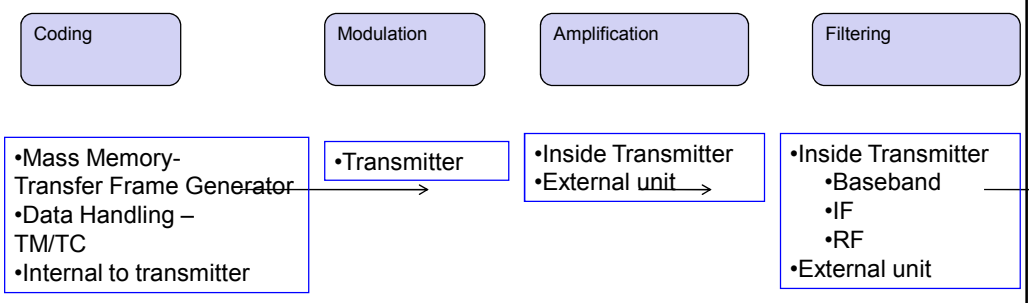
- Each service has associated certain frequencies
- Frequency bands' constraints are related usually to the TM links
- Near Earth, S-band allocation
  - Suffers from congestion
  - Max occupied bandwidth limited to 6 MHz

- EESS X-band (8025-8400 MHz)
  - Suffers from congestion
  - Allocation for high data rate links
  - Use of bandwidth efficient modulation schemes
  - There are occupied BW restrictions in the way of a Spectral mask that must be met
  - Strong requirement on protection of the adjacent band (Deep Space 8400-8450 MHz)

Discussion on Frequency Selection (2/2)

- Space Research X-band (8450-8500 MHz)
  - Maximum occupied bandwidth limited to 10MHz (cfr GAIA)
- 26 GHz band (25.5-27 GHz)
  - Allocated to Space Research Near Earth missions and EESS high data rate links.
- Space Research (category B)
  - 8400-8450 → Spectral mask to be met
  - Maximum occupied bandwidth limited to 8 MHz
- No limitations in the other bands.
- Increasing the frequency
  - Higher antenna gains (on-board/on-ground) -> more accurate pointing required
  - Higher path losses
  - Higher attenuation losses

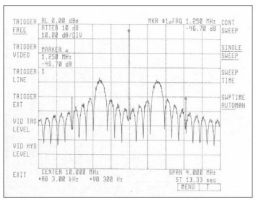
Functional Architecture



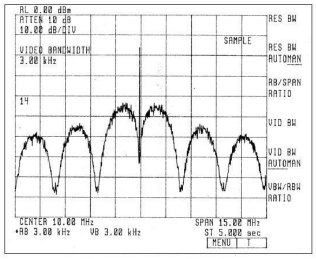
Modulation Schemes - TM Signal

Modulation: is the process by which an input signal varies the characteristics of a radio frequency carrier

- Residual carrier schemes are easier when different signals are transmitted over using the same frequency (e.g. telemetry and ranging signal)
- Phase Modulation with Residual Carrier
  - NRZ/BPSK/PM (sinewave)
  - NRZ/BPSK/PM (squarewave) → Deep Space missions
  - SPL/PM (bi-phase encoding)



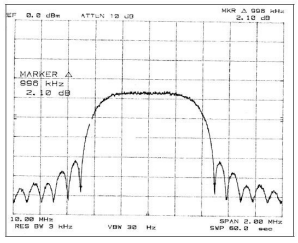
NRZ/BPSK/PM (sinewave)



SPL/PM

Modulation Schemes - TM Signal

- Suppressed Carrier Modulation Schemes
  - Filtered OQPSK
  - GMSK (for all bands except 8025-8400 MHz)
  - TCM 8PSK (only for the EESS band 8025-8400 MHz)
  - Note: Current Ranging is not compatible with suppressed carrier modulation schemes



Ranging and Range Rate

Spacecraft Navigation (Orbit Determination)

Currently used Ranging signal

- Consists of a sinewave phase modulated by a series of codes for ambiguity resolution
- Phase modulated into a carrier
- Frequency tone is selectable between100KHz-1.5MHz offset from the carrier frequency

PN Regenerative Ranging (proposed for Bepi Colombo)

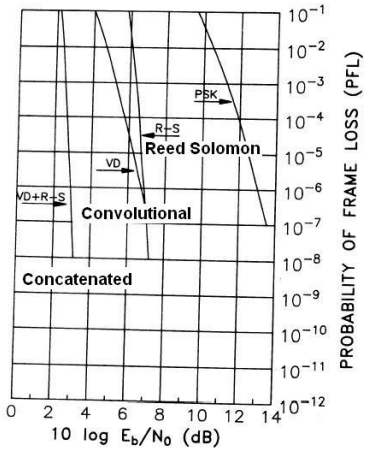
- Better performance by regenerating the ranging signal on-board (removing the noise in the uplink)
- Up to 30 dB increased in S/No
- Missions with low signal to noise ration could benefit from it (Deep Space)

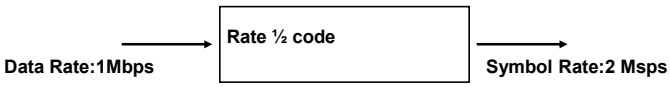
Delay → Distance (Range)
Differential Delay → Angular position
Frequency Shift (Doppler)→ Radial velocity
Frequency Change Rate (Doppler Rate)→ Radial Acceleration
Integrated Doppler →Radial Range Rate

ECSS-E-50-02A: Ranging and Doppler Tracking Standard

Coding

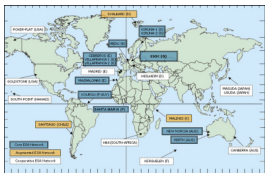
- Protection of the data at the expense of redundant bits. Quality criteria:
  - BER: Bit Error Rate
  - FER: Frame Error Rate
- Select the coding based on:
  - Bandwidth expansion
  - Required Eb/No for a target BER/FER
- Coding schemes:
  - RS (255, 223)
  - Convolutional rate ½
  - Concatenated conv and RS
  - Punctured conv codes rates 2/3,3/4, 5/6, 7/8
  - Turbo codes rates: ½, 1/4





Ground Stations Considerations

- Comms design shall be compatible with the network of ground stations (e.g. ESA/ESTRACK, NASA DSN)
- Different ground stations are used for the different mission operational phases. Ensure link budget for all G/S
- Main Parameters:
  - Transmission: EIRP (Effective Isotropic Radiated Power)
  - Reception: G/T (Gain over Noise Ratio)



Typical ground station antennas diameters for TT&C are:

- 15 m antennas → LEOP operations, EESS satellites
- 35 m antennas → Lagrange points and Deep Space
- 70 m NASA antenna → contingency cases in Deep Space missions

Telemetry Downlink Antennas (typical at high latitudes for EES missions)

- 7.3, 11 m, 13 m, 15m

Data Strategy

- Data rate definition:
  - For the different phases of the mission
  - For different Ground Stations antenna diameters
  - Depending on the on-board antenna (LGA/MGA/HGA)
  - Calculate the link budgets for all cases

Example: Lagrange mission - Herschel-Planck

Symbol Rate	On-board Antenna	On-ground Antenna	Mission Phase	Modulation Scheme
Low rate1: 1 ksps	LGA	Kourou 15m	LEOP/Safe mode	NRZ/BPSK/PM
Low rate2: 11 ksps	LGA	New Norcia 35 m	LEOP/ Cruise	NRZ/BPSK/PM
Medium rate: 344 Ksps	MGA	New Norcia 35m/ Kourou 15m	On station (compatible with RNG)/Cruise	SPL/PM
High rate: 3.4 Msps	MGA	New Norcia 35m	On-station	GMSK

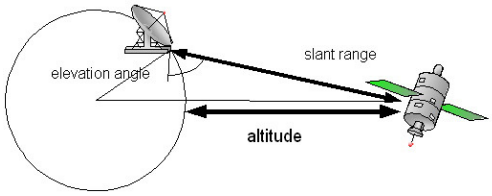
- Consider the visibility of the ground station to calculate the data volume transmitted.

Link Budget

- Calculate link budget for worst case to ensure the link under all conditions, both for Uplink and Downlink
- Margins to be calculated for:
  - Carrier Recovery
  - TC Recovery/ TM Recovery
  - Ranging Recovery

Link Budgets are calculated to meet > 3 dB margin (nominal case)

- Link budget parameters
  - Data Rates
  - Modulation & Coding
  - Ground Station
  - On-board Tx power
  - On-board antenna gain
  - Elevation angle
    - Near Earth missions → minimum elevation angle 5º
    - Deep Space missions → minimum elevation angle 10º
  - Propagation → especially important for high frequencies (K-band)



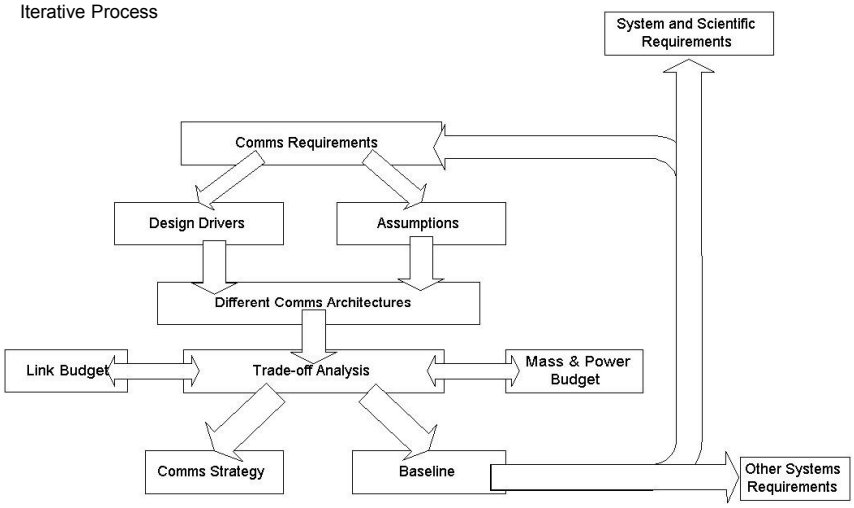
Major criteria for Design

- Compatibility and Interoperability
  - Compliant to standards to ensure compatibility and cross-agency support
- Heritage
  - Reuse of flight proven hardware in order to reduce the schedule and cost.
  - Reduces the technology risk
- Lessons Learnt
  - Keeping track of past and future European and non-European missions
  - Past experience is indispensable
- Performance
  - Specifications of minimum performance to close link budget with > 3 dB margin.
  - Compliance with Power Flux Density (PFD) requirements and protection of the Deep Space and astronomy bands for interference mitigation purposes(*)
- Reliability
  - Avoid single point failures
  - Redundancy concept

(*) ITU: International Telecommunication Union

Design Process

Iterative Process



Outputs

- Definition of frequency
- Definition of the TT&C architecture
- Definition of the modulation and signal coding
- Estimation of the required power (EIRP)
- Equipment list
- Estimation of the power consumption & duty cycle
- Estimation of the total mass
- Configuration
- Requirements to other subsystems