Spacecraft Telecommunication Systems – Part 1/2

The Transmission and Reception of Data and Commands

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Introduction (1/2)

- Long range (hundreds of billions of kilometers)
- Potentially large relative velocity between transmitter and receiver
  - Doppler shift
  - Receivers may require frequency-tracking loops
- Limited coverage – assume a 300km orbit
  - One ground station that can track at 5° above horizon
  - ~6.5 minutes at best, even for a zenith pass
- Spacecraft can acquire voluminous amounts of data
- Data downlink: many fewer opportunities
  - Therefore, downlink rate >> acquisition rate
- Earth’s troposphere and ionosphere absorb energy
Introduction (2/2)

- **Hardware**
  - Typically, power, mass, and volume limits
  - Led to the development of low power, low mass electronics

- **Environmental stresses**
  - Mechanical shock
  - Acoustic and vibration
  - Radiation
  - Thermal extremes
    - Choice of internal location
    - Antenna design

- Telecommunications interfaces – directly or indirectly – with every other spacecraft subsystem
Command System (1/2)

- Allows instructions and data to be sent to the spacecraft
  - Immediate action, or
  - Stored and executed later

- Command types
  - Relay commands
    - Like a switch closure; simply on/off
    - Initiate a complex operational sequence
  - Data commands
    - Provide data upon which the spacecraft acts
    - Data commands have a particular structure
    - Complex operations may require many data commands
      - May also require relay commands to configure the spacecraft
    - Need to consider ground station visibility
      - Autonomous mission management
Command System (2/2)

- Hardware components
  - Bipolar transistors
    - Use the most power, but resistant to radiation
  - n-type metal oxide semiconductors (NMOS)
  - Complementary metal oxide semiconductors (CMOS)
    - Higher speed and low power consumption
    - More sensitive to radiation
  - Radiation hardening
    - Often required
    - Radiation causes degradation long-term
    - Shielding has limited effect
      - Shields low energy particles
      - High energy particles do the damage

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Hardware Redundancy

- Simplest
  - Two completely parallel systems
  - Not practical or foolproof

- More sophisticated
  - Redundancy at the subsystem level
  - Cross-strapping: a given subassembly can be powered by multiple strings

- Redundancy management
  - A science unto itself
  - Pitfalls
    - Irreversible switchovers
    - Untested modes
    - Is the system truly redundant?
Autonomy

- Made possible by increasing computer power and denser memory
- Allows the use of high level commands instead of detailed command sequences
  - EG, : “Apply x\Delta V in a certain direction”
  - Computer autonomously computes and executes the command
- More complex
  - Larger variety of spacecraft states and modes
  - Impossible to test every conceivable mode
  - Requires very thoughtful design
  - Usually means more test time in the schedule
- Mars Polar Lander
Command Subsystem Elements

- Antenna
- Receiver
- Modulation
- Command processor
- Telemetry subsystem
- Onboard processors
- Onboard storage
- Modulation methods
Command System Block Diagram

Receiver → Command Processor → Power Switching Unit → Spacecraft Systems

Command Decoder

Clock → Onboard Computer → Onboard Storage
Antennas

- For LEO missions, uplink antenna will normally be omnidirectional, low gain
  - Easier to communicate with a moving spacecraft
  - Constantly changing aspect angle

- Deep space missions require directional, high gain antennas
Receivers

- Amplifies and demodulates the signal, filters out noise and EMI, and sends the information on to command decoder and processor
- Tuned radio frequency (TRF)
  - Radio frequency amplifier
  - Tuned for a specific frequency
- Superheterodyne
  - Received signal is shifted to a lower frequency than that at which it was transmitted
  - Two or three shifts are common
    - Signal is amplified and filtered at each stage
  - More sensitive to weak signals
  - Allows better rejection of unwanted signals
Modulation

- Types of modulation
  - Amplitude modulation (AM)
  - Frequency modulation (FM)
  - Phase modulation (PM)

- Trade space
  - Signal-to-noise ratio (SNR)
  - Graceful degradation
  - Available RF bandwidth
  - Data rate
  - Compatibility with ground station

- FM and PM
  - Can operate at a lower SNR
  - Require greater bandwidth
  - Suffer from threshold effect

- AM
  - Requires high SNR
  - Doesn’t suffer from threshold effect

- Electromagnetic interference (EMI)
  - Can drive frequency selection to avoid EMI
Command Processor

- Functional block of code in a multipurpose processor
- Interprets commands
- Checks commands for validity
  - Parity bits
  - Error detection and correction (EDAC) schemes
- Today’s central processor is a coordinator
  - Allows for a distributed architecture
  - Equal or more computational power in subsystems
Telemetry

Function
- Prepares data for transmission to the ground
  - Spacecraft health information
  - Experimental results
  - Observations

Signal conditioning
- Make data acceptable to telemetry system
  - Amplification
  - Attenuation
  - Filters remove bias and noise
  - Notch filters remove high intensity signals at specific frequencies
  - Dynamic range compression (compatible with telemetry system)
  - Analog-to-digital conversion (ADC)
    - Will be errors in the ADC and in the ultimate DAC
    - A noisy signal can fool the ADC
    - Digital quantization can result in data falling between quantization levels
Multiplexing

- Required if processing more than one type of data

Types of multiplexing

- Frequency-division multiplexing (FDM)
  - Allocates the various data streams to separate portions of the bandwidth

- Time-division multiplexing (TDM)
  - Assigns sets of bits from different data streams within a data frame as a function of time

- Code-division multiplexing
  - Data is sent in parallel over the same bandwidth, but encoded
Aliasing

- Artifact of poor data reconstruction
- Nyquist rate
  - A signal must be sampled at twice the maximum frequency contained in the signal
  - In practice, a factor of two is too low
  - A sampling factor of five or greater is more realistic
Onboard Processors

- Early onboard “computers” were basically timers
- Spacecraft have benefitted from the increasing computing power and storage capability evolving from the computer industry
- Distributed systems are the norm today
  - Central computer coordinates and directs traffic
  - Subsystem microprocessors are equally as powerful as the central processor
- The environment of space is a burden
  - Thermal extremes and cycling
  - Hard vacuum
  - Vibration
  - EMI
- Not surprisingly, less computer power costs more
- Parts
  - Space qualified (class S)
    - Expensive
    - Long delivery times
  - Class B parts
    - Functionally equivalent to class S without the screening and burn-in
  - Radiation hardness
Onboard Storage

- Data storage on the ground has steadily gotten denser and cheaper (MB/$)

- Space applications are different
  - Radiation
  - Temperature extremes
  - Desire to avoid moving parts
  - Lack of human interaction

- Overwhelming choice: solid-state memory
  - Evolving rapidly
  - Adequate systems are readily available
    - 2 Tb with 10 I/O channels, radiation hardened
Modulation

- Method used to encode a “baseband” information bearing signal upon an RF carrier signal, $S(t)$
  
  \[ S(t) = A(t)\cos[\omega(t) + \Phi(t)] \]
  
  - $A =$ amplitude
  - $\omega =$ frequency
  - $\Phi =$ phase angle

- Modulation schemes
  - AM varies amplitude (rarely used)
  - FM varies frequency
  - PM varies phase

- PCM – pulse code modulation
  - Samples the signal and quantizes it
  - Formed into a serial binary bit stream
  - Digital bit stream “keys” the carrier to represent a 1 or a 0
    - Amplitude-shift, frequency-shift, or phase-shift
    - BASK, BFSK, BPSK