Interplanetary Networking Curiosity Style

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Overview

- A typical day in the life of a Mars rover
- Assets for communicating with Mars
- Challenges of communicating with Mars
- Curiosity Protocol Stacks
- Communication Standards
- Command Error Detection, Correction Methods
- Telemetry Techniques
- Relay Techniques
- Downlink Data Types
- Data Product Prioritization
- Downlink Data Management
- The Future of Interplanetary Networking

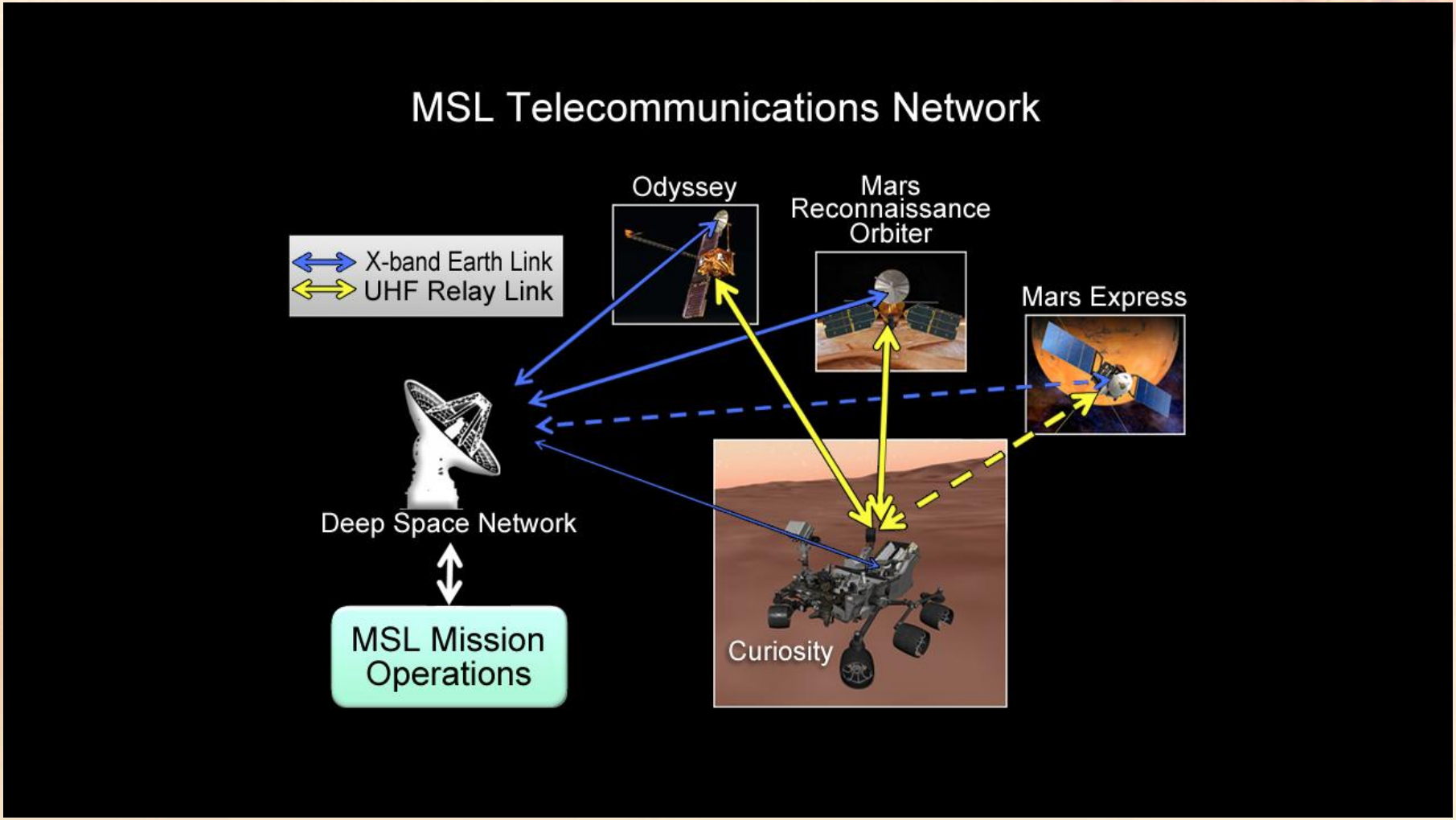
A typical day in the life of a rover

- Rover energy is limited so it sleeps during some portions of the Martian day (Sol)
- Wake up 10 AM local Mars time, receive orders direct from Earth (DFE)
- Do science, drive, etc. 11-3 PM
- Send data back via relay satellites 3-4:30 PM
  - PM data is used to make decisions about next-Sol activities
  - Earth operations works through Mars night to make plans for next command window
- Do science, drive, etc.
- Sleep till 3 AM
- Wake up for 3-4 AM relay pass & commands
  - AM passes primarily non-decisional science data. Forward link may be used for data management – deleting received data products
- Sleep till 10 AM

Acronyms & Glossary

- CCSDS – Consultative Committee for Space Data Systems – standards body for space communications
- Telemetry, downlink, return-link – any data returned from a spacecraft to Earth. Return-link is telemetry returned by relay
- Command, uplink, forward-link – any data transmitted from Earth to a spacecraft. Forward-link is commands sent by relay.
- Sequence – a series of timed commands, in a simplified scripting language.
- AOS – Advanced Orbiting Systems - a series of CCSDS standards
- Data Product – a structured set of telemetry data. A well-defined file.
- Data Product Object (DPO) – record component of a data product
- MSL – Mars Science Laboratory – Curiosity rover

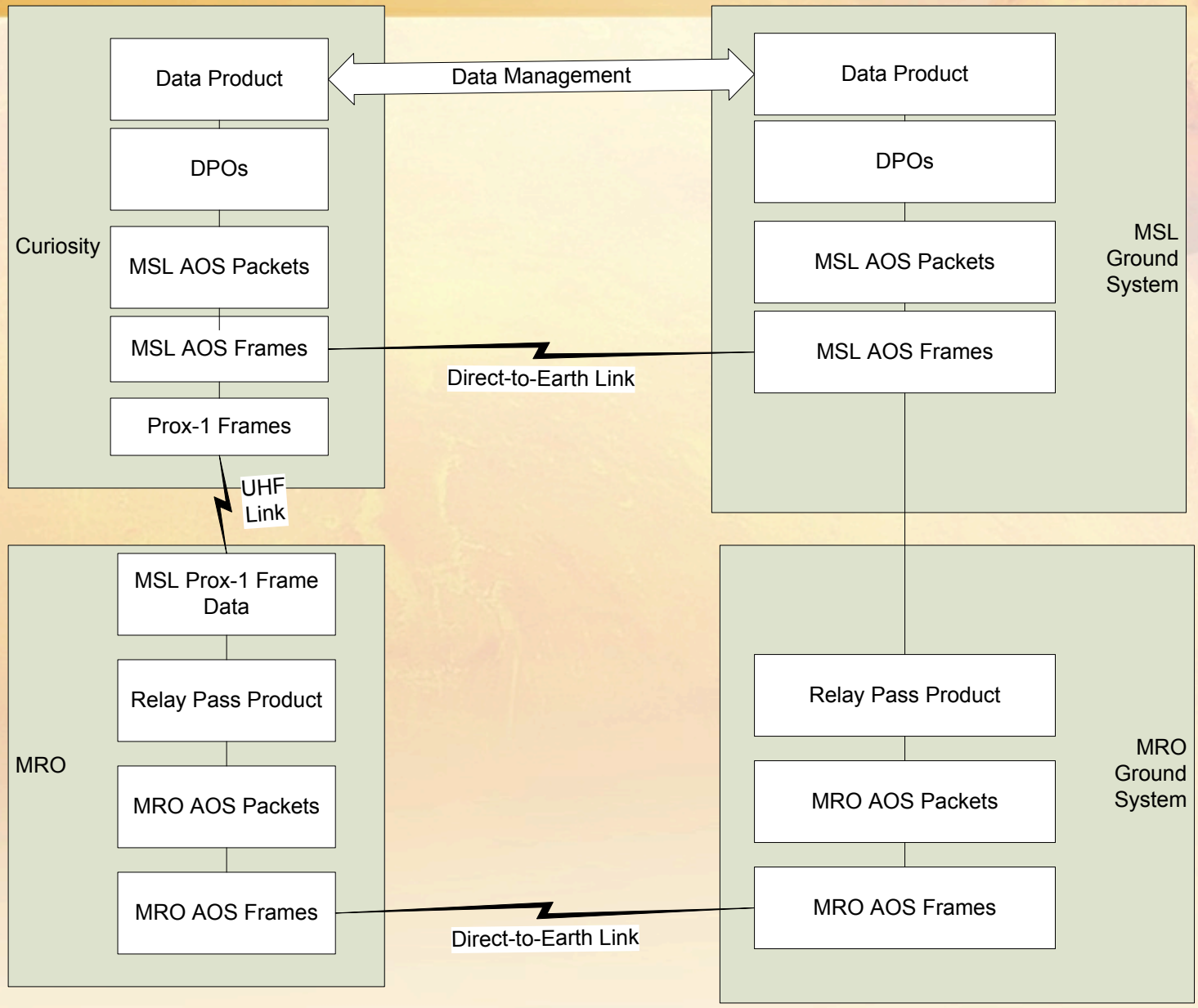
Assets for Communicating with Mars



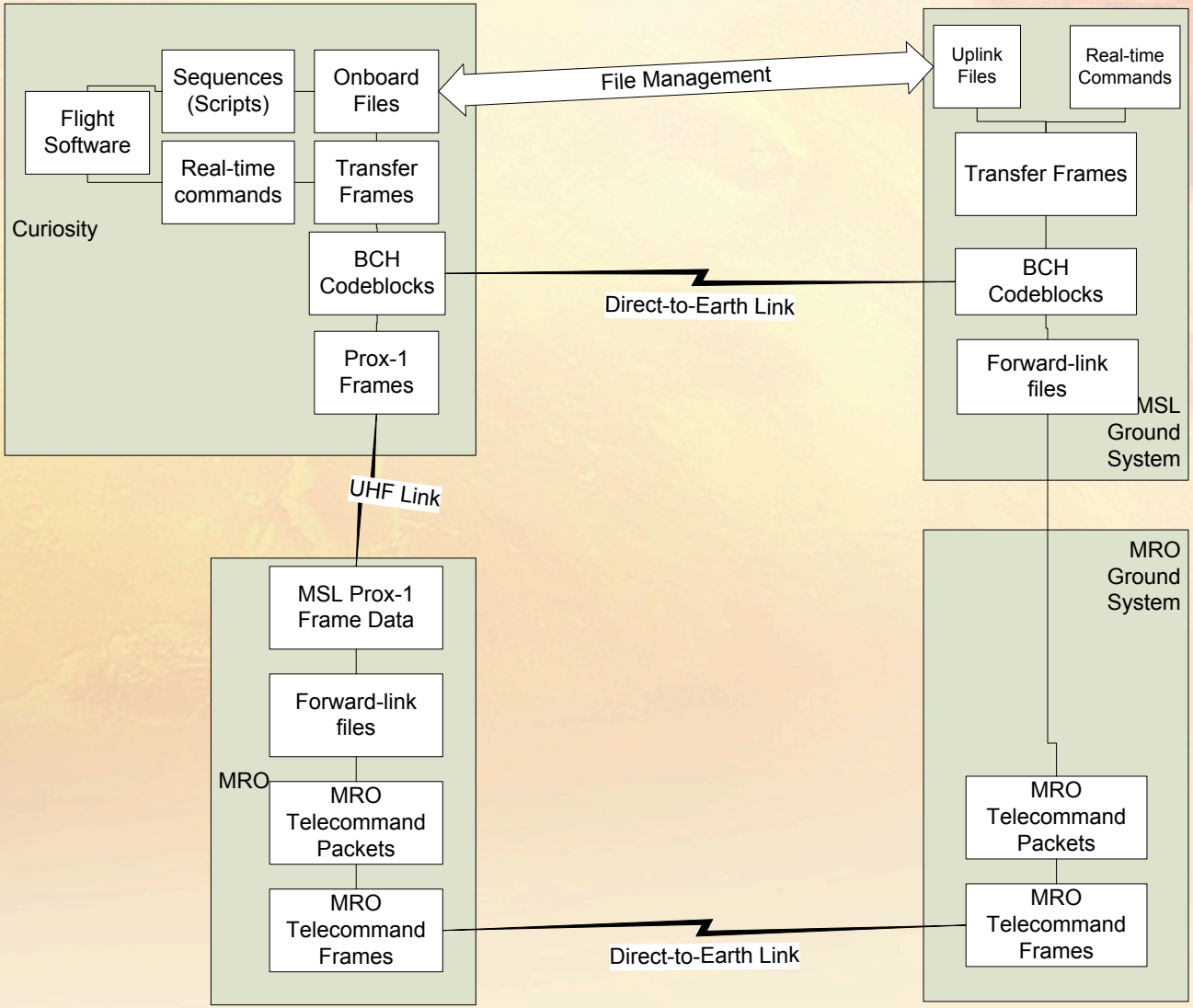
Challenges of communicating with Mars

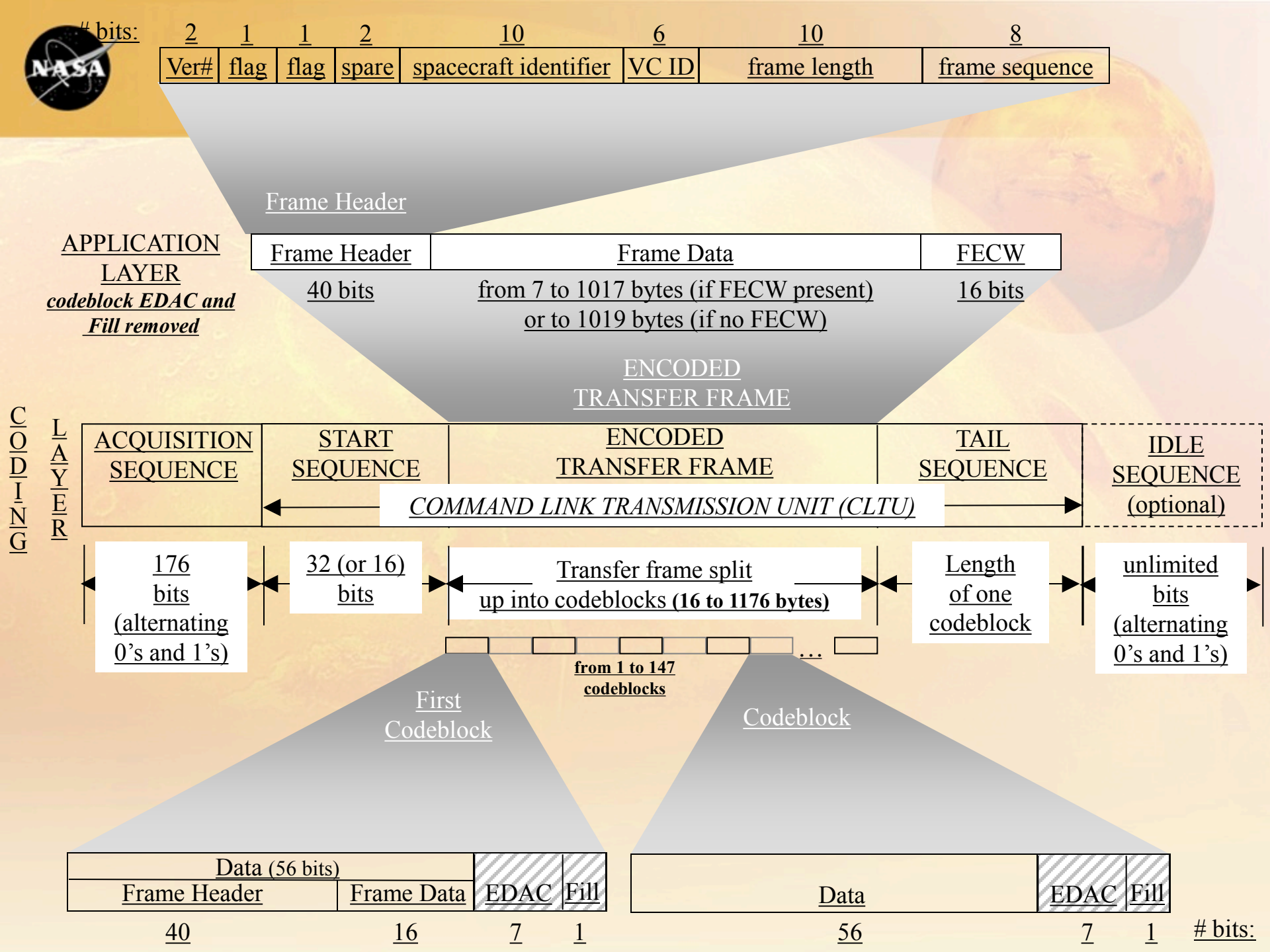
- Distance
  - Maximum Earth-Mars distance is 401 million km.
    - One-way Light time = 21 minutes
    - Signal strength = 1/(126 million) strength at geo-sync orbit
- Occasional data loss due to space-link noise, station problems, antenna geometry, spacecraft behind Mars, etc.
- Limited contact time and downlink
  - 2-4 relay contacts/sol, 15 minutes/pass
    - MRO flies over ~3 AM/PM local Mars time
    - ODY flies over ~4 AM/PM local Mars time
  - Best case 80 mbytes/pass, 125 mbytes/sol
- Orbiters also have other priorities – science, Opportunity rover
- Limited contact time, long delay time ->
  - Earth cannot immediately request retransmit if data is lost or uncorrectable
  - Project design emphasizes error detection, correction, loss tolerance since can't depend on immediate retransmit
- Telemetry designed to be usable even if some parts missing

Curiosity Telemetry Networking Stack



Command Protocol Stack




bits:
2
1
1
2
10
6
10
8
Ver#
flag
flag
spare
spacecraft identifier
VC ID
frame length
frame sequence
Frame Header
APPLICATION LAYER
codeblock EDAC and Fill removed
Frame Header
Frame Data
FECW
40 bits
from 7 to 1017 bytes (if FECW present)
or to 1019 bytes (if no FECW)
16 bits
ENCODED TRANSFER FRAME
CODING LAYER
ACQUISITION SEQUENCE
START SEQUENCE
ENCODED TRANSFER FRAME
TAIL SEQUENCE
IDLE SEQUENCE (optional)
COMMAND LINK TRANSMISSION UNIT (CLTU)
176 bits (alternating 0's and 1's)
32 (or 16) bits
Transfer frame split up into codeblocks (16 to 1176 bytes)
Length of one codeblock
unlimited bits (alternating 0's and 1's)
from 1 to 147 codeblocks
First Codeblock
Codeblock
Data (56 bits)
Frame Header
Frame Data
EDAC
Fill
Data
EDAC
Fill
40
16
7
1
56
7
1
bits:

Communication Standards

Standards defined by CCSDS – Consultative Committee on Space Data Systems (ccsds.org)

- AOS – Advanced Orbiting Systems Space Data Link Protocol
  - Space Packet Protocol
  - Time Code Formats
  - Telecommand Synchronization and Channel Coding
  - Telecommand Space Data Link Protocol
  - Communication Operation Procedure
- Proximity-1 (Prox-1) – Relay Operations
  - Forward-link (commands->Relay->Mars)
  - Return-link (telemetry->Relay->Earth)
- CCSDS File Delivery Protocol (CFDP) – MRO
  - MSL uses a custom file protocol for better tolerance of missing pieces

Command Error Correction, Detection Techniques

- Individual real-time commands and file uploads including sequences (simple script language)
- Errors are detected and corrected at several layers:
  - Command frames have a leading sequence marker – ensure that radio is locked on data, not noise
  - 56-bit blocks with BCH coding – single-error correction, double-error detection
  - Blocks assembled into variable-length frames, with lengths up to 1kbytes. Check frame header contents.
  - Frames are numbered in sequence numbers –
    - detect if frames are missing.
  - Fill in missing frame numbers w/ tandem repeats
  - Assemble file from multiple frames, with checksum and length checks.
  - Sanity checks on file contents
- Quarter-megabyte max file size; concatenate onboard
- Convolutional coding (7,1/2) on Relay forward link

Telemetry Packaging

- Some real-time telemetry -> current spacecraft status
- Most surface telemetry data packaged as Data Products (~600 types)
  - Structured data sets (think: files)
  - Stored in non-volatile memory file system (saved through sleep cycles)
  - Made up of self-identifying Data Product Objects (DPOs)
  - At transmission, DPOs aligned with packets so partial Data Products can be reconstructed even if parts are missing
- Ground processing of specified DPO types:
  - All data transmitted as binary; XML definitions in ground system to interpret data
  - Telemetry measurements
  - JPEG images, science data, health data collected while rover sleeps, etc.
  - Thumbnails & successive compression
  - Application-specific lossy compression, data decimation
- Lossless data compression coming in Nov delivery

Telemetry concepts

- Telemetry is sent in fixed-length frames (~1 kbyte) with attached sync marker (ASM)
  - ASM at fixed separation allows DSN to verify sync on data, not noise.
  - Each frame has a sequence number.
- Variable-length packets, with length field, span multiple frames.
  - Allows packaging variable-size data into fixed-size frames.
- Data products are packaged into packets with type, time.

Telemetry Error Detection, Correction Techniques

- Frames are the unit of error loss & detection. Entire frame rejected if uncorrectable
- DSN detects if frame ASMs are at correct bit separation
- Frame coding & error detection
  - Turbo coding on direct-to-Earth
  - CRC error checking on relay data
- Frame sequence numbers – detect missing frames
- Check that packet lengths match frame pointers
- Multiple sequence number, checksum, length checks when reassembling data products
- Can process partial data products, with explicit knowledge of what is missing
- Ground can command retransmission of missing parts (with several days latency)

Relay Techniques

- MRO & Odyssey relay orbiters are close enough (<2 millisec) to allow retransmission
- Reliable prox-1 standard uses frame sequence numbers to detect missing data, request retransmission
- Adaptive data rate – MRO
  - UHF Radio (Electra) measures return-link signal/noise, commands MSL transmit rate to optimize bandwidth
- Relay communications with MRO have been near-perfect. Some data loss with Odyssey.

Data Product Storage and Prioritization

- Onboard data product storage: engineering computer ~4 Gbytes
  - 24 Gbytes in science cameras
  - Up to 300k DPs at a time
    - Including virtual links to science camera storage
  - 100-300 sols of onboard storage
    - Mission is downlink-limited not storage-limited
    - Emphasis on most efficient use of downlink, especially for next-sol decisions
    - Low priority data may be stored onboard for months
- Ground operations can prioritize DPs, assign to particular pass types.

Downlink Data Management

- Ground tools maintain knowledge of Data Products onboard Curiosity – sent or unsent
- Ground can command:
  - Partial retransmissions to complete partial products
  - Delete fully received products
  - Reprioritize unsent products
- Spacecraft generates a Data Product Summary Report (DPSR)
  - Products sent, not yet sent, deleted
  - Can generate complete report or delta since last report

The Future of Interplanetary Networking

- Interplanetary Networking Special Interest Group (www.ipnsig.org)
- RFCs: Bundle Protocol (BP), Licklider Transmission Protocol (LTP), Bundle Security Protocol (BSP)
- CCSDS Blue Books for DTN protocols
- JPL's implementation of BP/LTP/BSP
  - Demonstrated on Deep Impact Spacecraft – '08
    - LTP automated retransmission over multi-day round trips
  - In continuous use for science download on ISS since '09, will be used for ISS operations starting in 2013
  - Planned for use in International Solar System Internet
- RAPID robot teleoperation standard will run on top of DTN