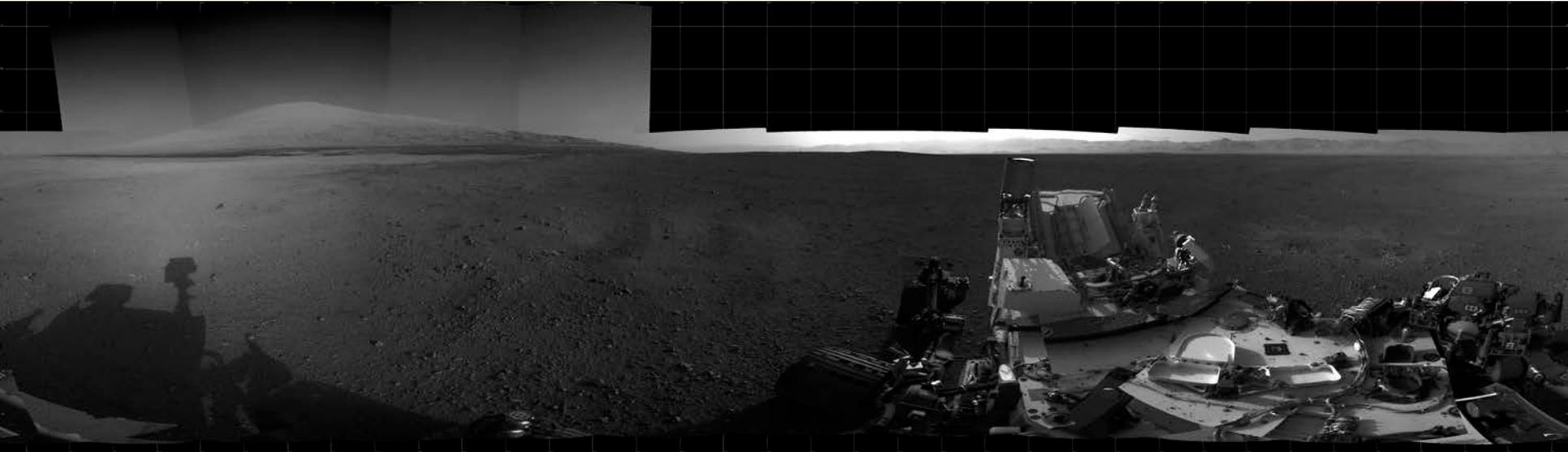




Interplanetary Networking Curiosity Style



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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 Networking Stack
- 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
- Sleep or other activities
- Wake up for 3-4 AM relay pass & commands
 - AM passes frequently used for data management – deleting received data products



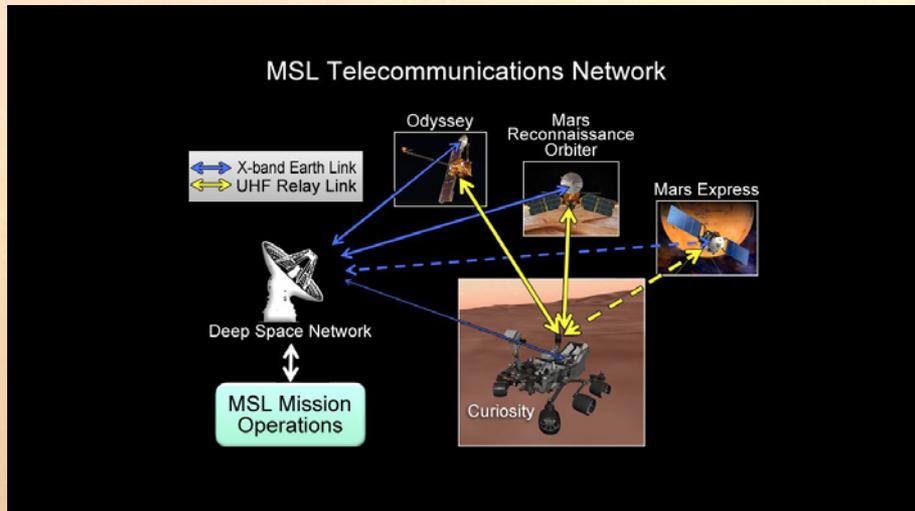
Acronyms & Glossary

- 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

- 3 Deep Network Complexes (Goldstone, CA; Madrid, Spain ; Canberra, Australia)
 - 34-meter and 70-meter dishes
- Mars Relay Satellites
 - Command (forward-link) & telemetry (return-link)
 - May be bent-pipe or store-and-forward
 - Mars Reconnaissance Orbiter (MRO)
 - Odyssey (ODY)
 - Mars Express (MEX – European Space Agency)
 - MEX is a backup – less useful for various reasons



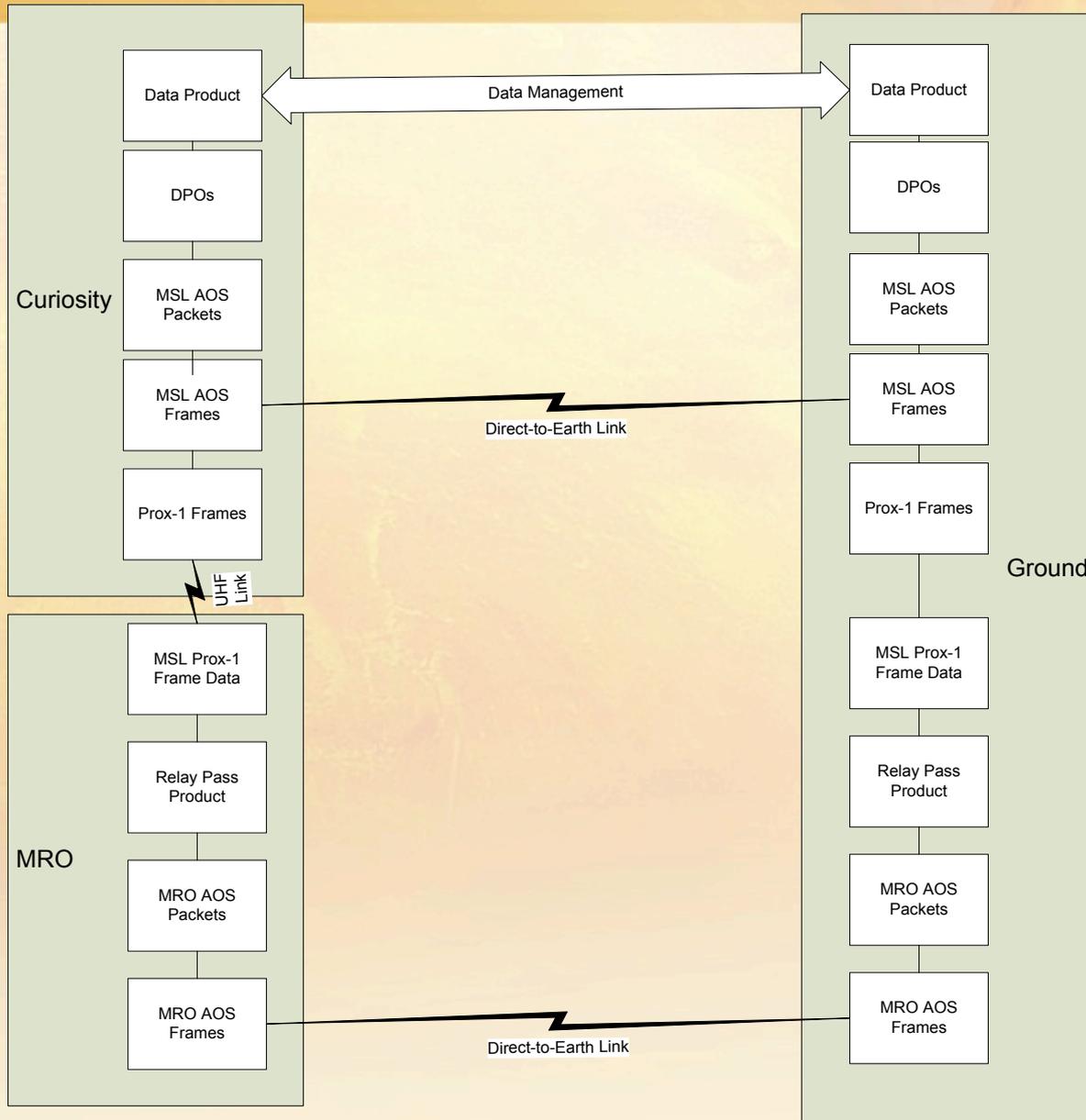


Challenges of communicating with Mars

- Distance
 - Maximum Earth-Mars distance is 401 million km.
 - One-way Light time = 21 minutes
 - Signal strength = $1/(126 \text{ million})$ strength at geo-sync orbit
- Occasional data loss due to space-link noise, station problems, antenna geometry, 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
- Limited contact time, long delay time ->
 - Cannot immediately 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

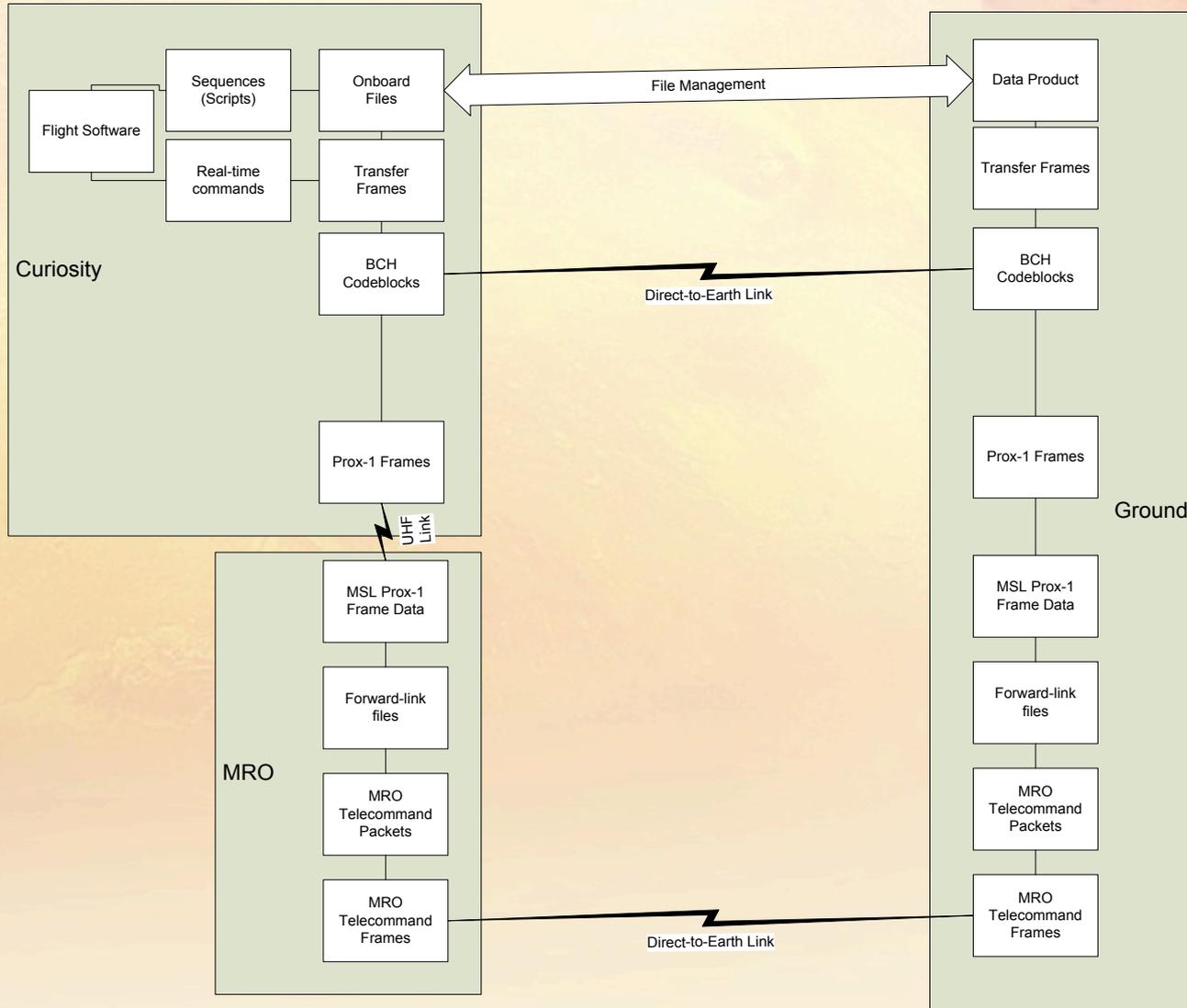


Curiosity Telemetry Networking Stack





Command Networking Stack





bits:

2	1	1	2	10	6	10	8
Ver#	flag	flag	spare	spacecraft identifier	VC ID	frame length	frame sequence

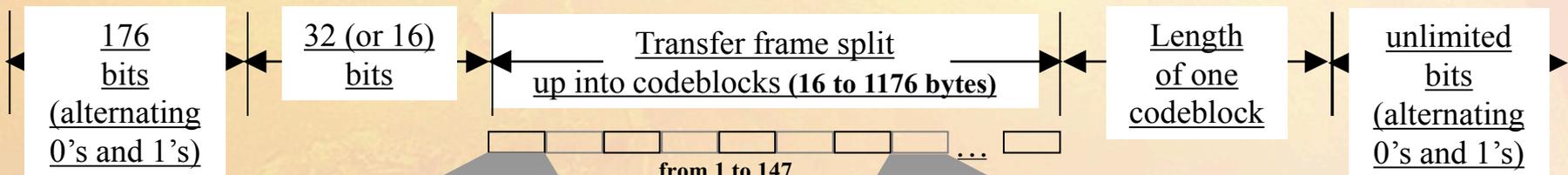
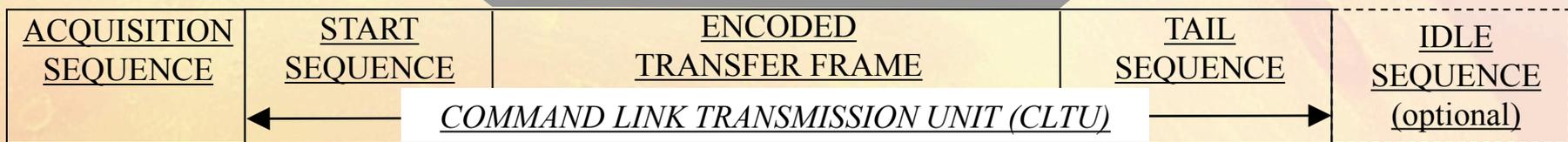
Frame Header

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



from 1 to 147 codeblocks

First Codeblock

Codeblock

Data (56 bits)	EDAC	Fill
Frame Header	Frame Data	

40

16

7

1

Data	EDAC	Fill
------	------	------

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->Earth)
 - 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

- Commands consists of 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)
 - DPOs aligned with packets so partial Data Products can be reconstructed even if parts are missing
- Ground processing of specified DPO types:
 - Telemetry measurements
 - JPG images, science data, health data collected while rover sleeps, etc.
 - Application-specific lossy compression, data decimation
 - Extensive use of XML to define data structure
- 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 millisecc) 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 ~4 Gbytes
 - With science camera storage, 28 Gbytes
 - 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

- Delay Tolerant Networking (DTN) Research Group (DTNRG.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 teleoperation standard will run on top of DTN