AEROSPACE

GROUND SYSTEM ARCHITECTURES WORKSHOP

Tutorial J
CCSDS Course
February 24, 2025

CCSDS Course – GSAW 2025

February 2025 | Robert Ritter | 703-652-7858 | rritter@imi-technology.com
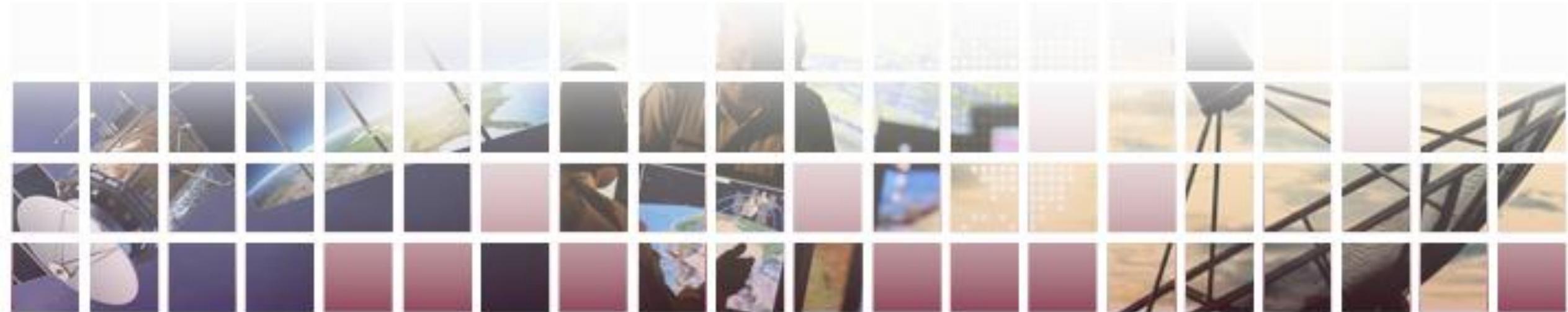
- Introductions
- Overview –
  - Network Considerations
  - Challenges of Space vs Terrestrial
- System Engineering Area
  - SANA, Security
- Space Onboard Interface Services
  - Application Support Services, Wireless, Flight Software
- Space Link Services
  - Physical Layer (RF Links)
  - Data Link Layer (Coding, Framing, and Virtual Channels)
  - Optical Communications
- Cross Support Services
  - SLE, CSTS
- Internetworking Services
  - Network Layer (Packet Protocols)
  - Transport Layer (IP, SCPS-TP, DTN)
  - File Transport (FTP, CFDP, SCPS-FP)
  - Data Compression
- Other Considerations – USLP (or when CCSDS runs out of space…)
- Mission Operations and Information Management Services
  - XTCE, SOLM, GEMS, GMSEC
- References

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Introduction CCSDS Video

- https://youtu.be/XdGeaJE7yEk (ESA)

- https://youtu.be/xnMTNcRBDvU (NASA)

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Let's talk IP for a moment (Some transports don't work well in Space)

- UDP
  - Constant data streaming
  - No acknowledgement required
  - **No error control**
  - Suitable for streaming voice and video (un-compressed), where timing is more critical than noise or dropout
- TCP
  - Guaranteed delivery and packet ordering
  - Acknowledgement required to advance the data window. When the data window is full, data flow stops
  - **Susceptible to slow throughput due to high latency and errors in transmission**
  - Multiple clients increase bandwidth and memory usage

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- Telemetry now requires diverse routing
    - End-to-end, multi-hop, store-and-forward operation.

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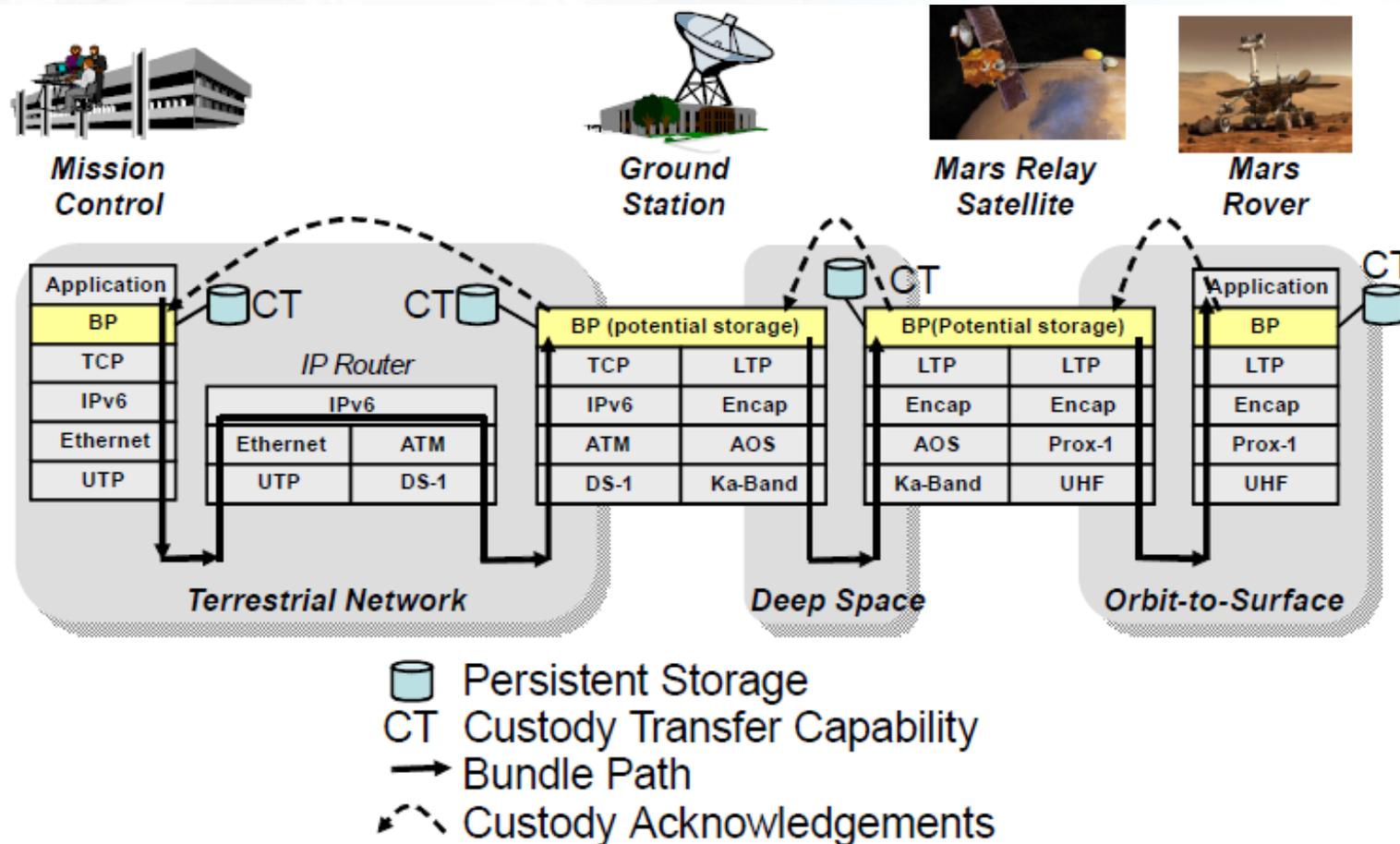
Constraints and Considerations for Space

- Timeliness of Delivery
- Data Integrity
- Channel-to-Channel Coherence
- Time of Arrival and Time-Difference of Arrival
- Packet or Bit Jitter (especially with crypto systems)
- RF clock-drift/power-variance/Noise/Doppler vs. Network delay/variation/congestion
- Security

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# Some Clever Enhancements to RF Links

- Power Limits

- New Modulation Schemes

- Adapting to Link Conditions

- Coding Methods for Framed and Unframed Data

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Some Clever Enhancements to Data on Networks

- Error Detection with Selective Negative Acknowledgement
    - With selective retransmission, reordering, etc.
- Forward Error Correction
- Though Sometimes, Don't-Care is Acceptable

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- Standards that Span High-Latency, Error-Prone Links
  - Define Telemetry & Command Formats
  - Define Ground Transport Protocols
  - Working on Control & Status Standards
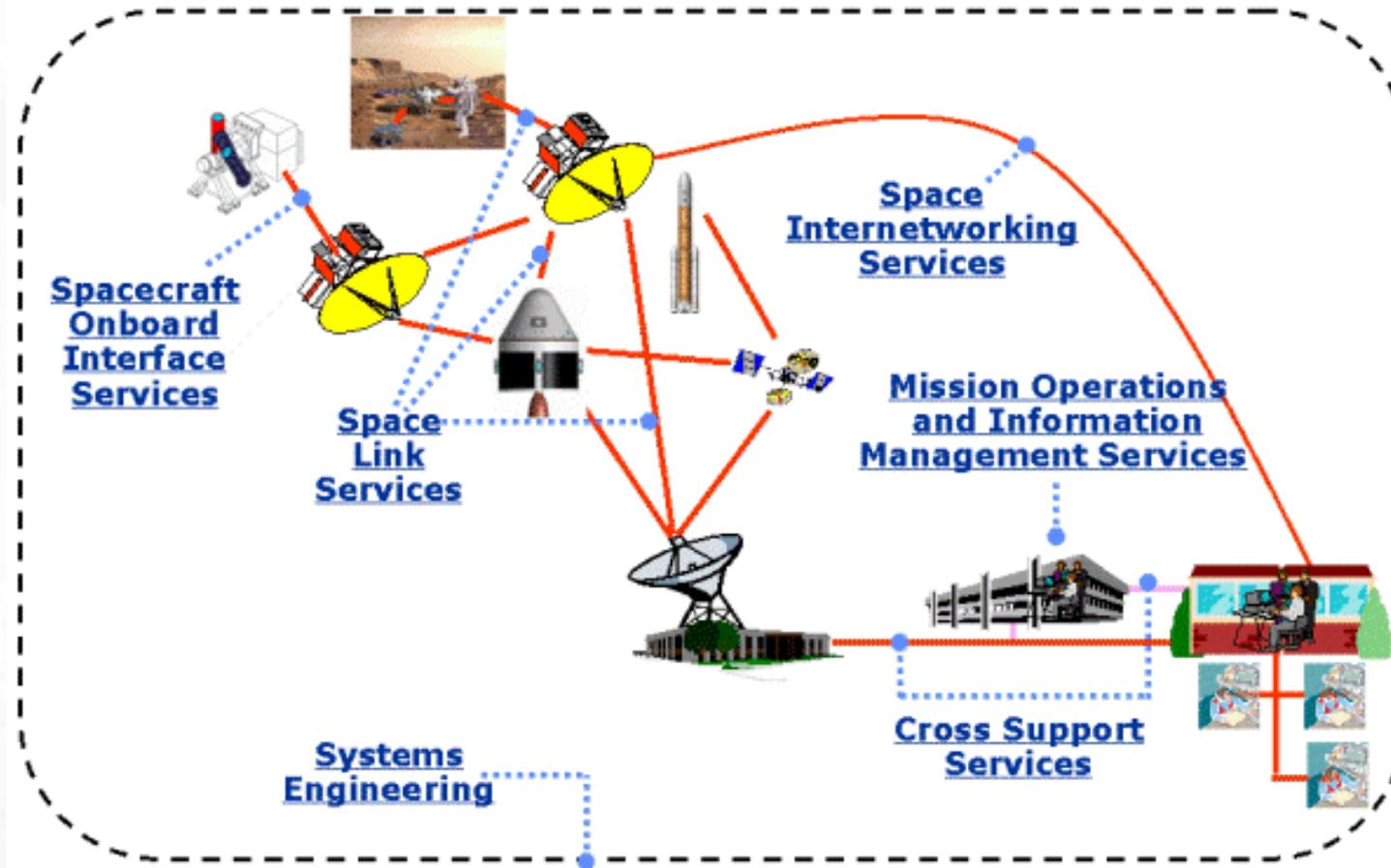
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- Benefits are Typical Of Using Any Standard
  - These Standards are Focused on Space!
  - Reduced Cost
    - Reduces Nonrecurring & Recurring Costs
    - Fewer Project-Unique Development Efforts
    - More Commercial Off-the-Shelf Hardware
    - Proven Technology Results in Shorter System Test Periods
  - Reuse of Knowledge & Technology
    - Less Training or Retraining of Personnel
    - Promotes Understanding of Exchanged Data
  - Interoperability
    - Common Protocols Allow for Interoperability with Other Facilities
    - Shared Primary/Backup Roles
    - Leverage Development Efforts on Other Programs

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- Consultative Committee for Space Data Systems
  - Key Members are the Major Space Agencies
  - Recommendations Span RF Links to Ground Transports
  - Related Areas for Ground Standards Include
    - Cross Support Services (SLE, Service Management)
    - Mission Operations and Information Management Services
  - Recommendations can be Used Together or Separately

- 1981 – NASA and ESA met and formed a working group to address space data standards with particular interest in Packet Telemetry and Packet Telecommand
- 1982 – The CCSDS was officially formed
- 1991 – CCSDS joined the ISO Technical Committee 20, for Aircraft and Space
- 2003 – CCSDS organized in the IETF Model with the following Working Group "Areas" of discipline
- 2017 – CCSDS Runs out of "Space" - Unified Space-Data Link Protocol

Sami Asmar:
CCSDS Secretariat and Chair, CCSDS Management Council

Adrian Hooke
Founder

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Member Agencies

–Agenzia Spaziale Italiana (ASI)/Italy.

–Canadian Space Agency (CSA)/Canada.

–Centre National d'Etudes Spatiales (CNES)/France.

–China National Space Administration (CNSA)/People's Republic of China.

–Deutsches Zentrum für Luft- und Raumfahrt (DLR)/Germany.

–European Space Agency (ESA)/Europe.

–State Space Corporation (ROSCOSMOS) /Russia

–Instituto Nacional de Pesquisas Espaciais (INPE)/Brazil.

–Japan Aerospace Exploration Agency (JAXA)/Japan.

–National Aeronautics and Space Administration (NASA)/USA.

–UK Space Agency/United Kingdom.

Observer Agencies

–Austrian Space Agency (ASA)/Austria.

–Belgian Federal Science Policy Office (BFSPO)/Belgium.

–Central Research Institute of Machine Building (TsNIIMash)/Russian Federation.

–China Satellite Launch and Tracking Control General, Beijing Institute of Tracking and Telecommunications Technology (CLTC/BITTT)/China.

–Chinese Academy of Sciences (CAS)/China. –Chinese Academy of Space Technology (CAST)/China.

–Commonwealth Scientific and Industrial Research Organization (CSIRO)/Australia.

–Danish National Space Center (DNSC)/Denmark.

–Departamento de Ciência e Tecnologia Aeroespacial (DCTA)/Brazil.

–Electronics and Telecommunications Research Institute (ETRI)/Korea.

Observer Agencies (cont.)

—European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)/Europe.
–European Telecommunications Satellite Organization (EUTELSAT)/Europe.
–Geo-Informatics and Space Technology Development Agency (GISTDA)/Thailand.
–Hellenic National Space Committee (HNSC)/Greece.
–Indian Space Research Organization (ISRO)/India.
–Institute of Space Research (IKI)/Russian Federation.
–KFKI Research Institute for Particle & Nuclear Physics (KFKI)/Hungary.
–Korea Aerospace Research Institute (KARI)/Korea.
–Ministry of Communications (MOC)/Israel.
–National Institute of Information and Communications Technology (NICT)/Japan.
–National Oceanic and Atmospheric Administration (NOAA)/USA.
–National Space Agency of the Republic of Kazakhstan (NSARK)/Kazakhstan.
–National Space Organization (NSPO)/Chinese Taipei.
–Naval Center for Space Technology (NCST)/USA.
–Scientific and Technological Research Council of Turkey (TUBITAK)/Turkey.
–South African National Space Agency (SANSA)/Republic of South Africa.
–Space and Upper Atmosphere Research Commission (SUPARCO)/Pakistan.
–Swedish Space Corporation (SSC)/Sweden.
–Swiss Space Office (SSO)/Switzerland. –United States Geological Survey (USGS)/USA.

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Why Cooperate?
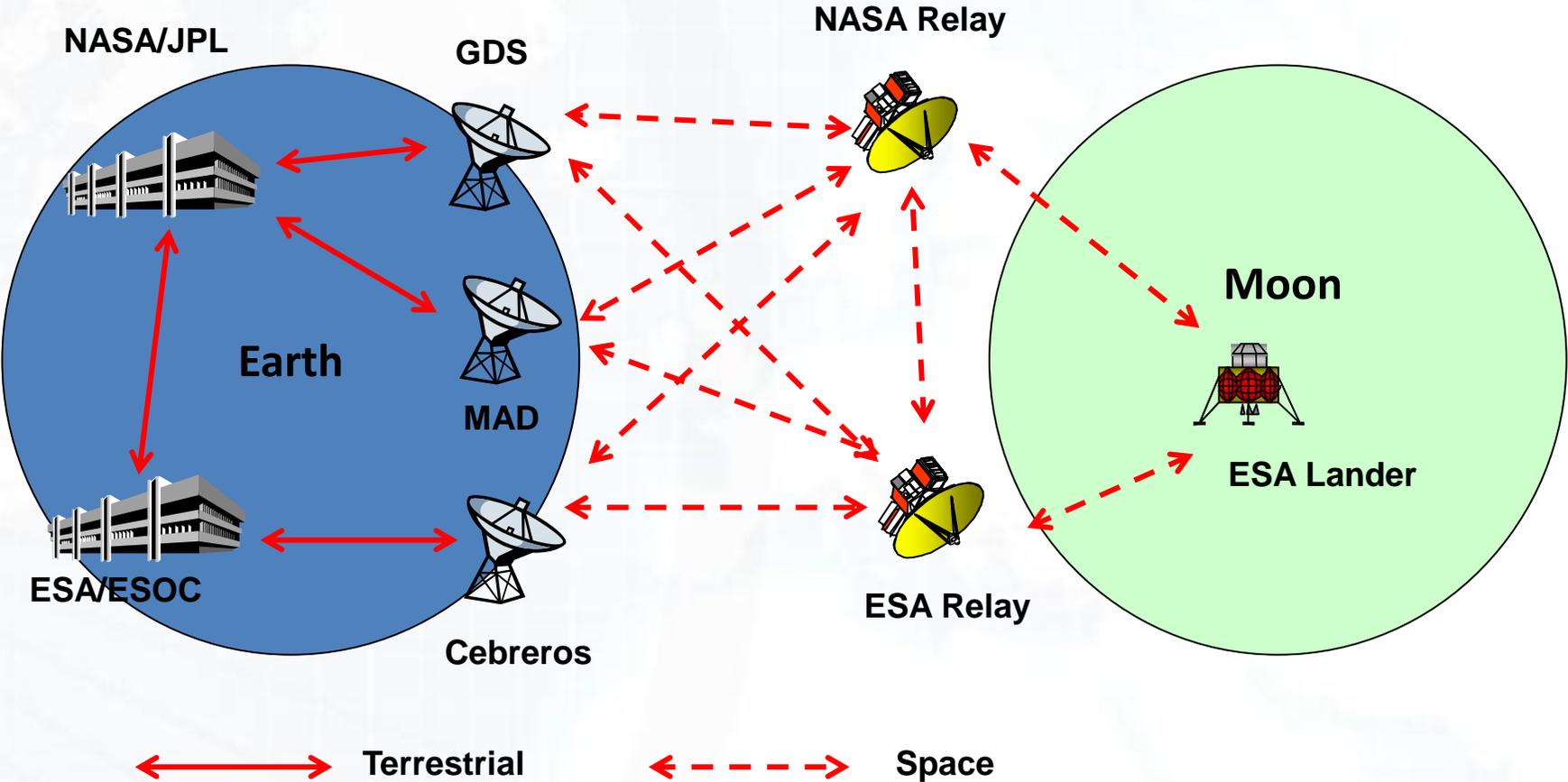
- Your source for everything new and exciting!!!

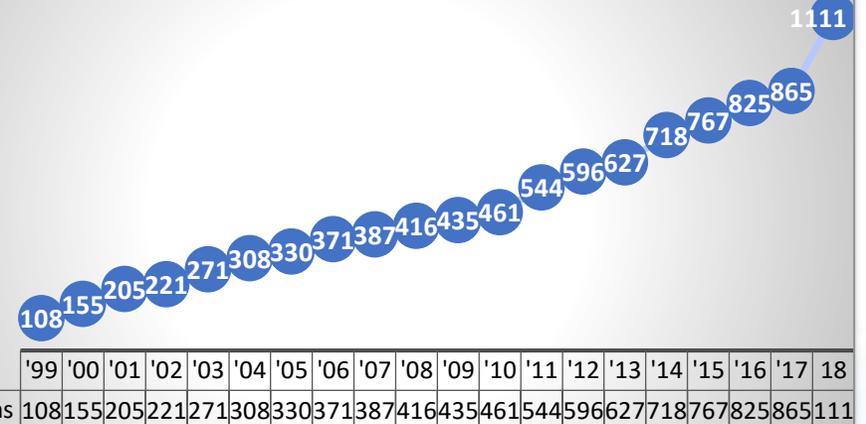**Active Publications**
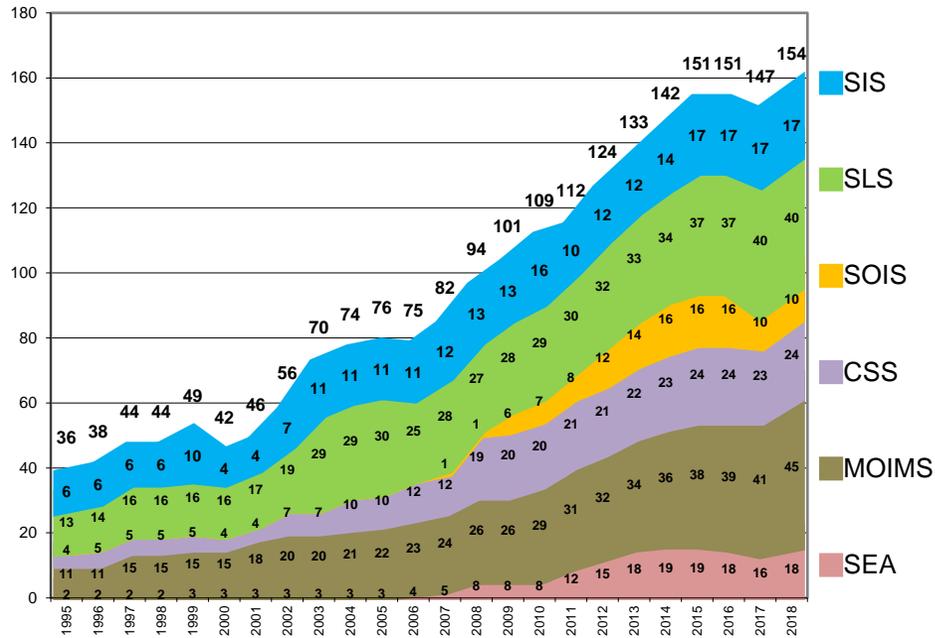
Currently Active Publications:

154 *Normative (Blue & Magenta)*: **95**
Informative (Green): **59**

Downloadable for free from www.ccsds.org

All major pubs since 1982: ~370
(Some were historical mission needs
or superseded technologies)

Cumulative Missions

1,111 space missions have adopted and used various CCSDS standards

	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	18
Missions	108	155	205	221	271	308	330	371	387	416	435	461	544	596	627	718	767	825	865	111

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CCSDS – the business side

- Large technical meetings are held twice per year
  - Typically once in U.S., once in Europe
  - Next one is TBD
  - About 200 people split across about 20 working groups

- Lots of effort throughout the year
  - Working groups hold telecons and work on documents
  - Documents are reviewed at working group, agency, and leadership levels
  - Editors finalize and publish the new standards and updates
  - Once published, some documents are provided to ISO for further release
  - CCSDS engineering and management councils meet regularly to discuss issues

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Concept of "Recommendations"

- CCSDS defines over 100 standards
  - From spacecraft to mission ops, all everything in between
  - Many can connect to each other to create an apparent reference architecture

- Saying your "follow CCSDS standards" or are required to "be CCSDS compliant" does not mean you adhere to all the standards

- Instead, the standards are a collection of possible proven formats, specifications, and methods for addressing specific space-domain challenges. Some may even overlap each other.

- Chose what you like, don't worry about the others.
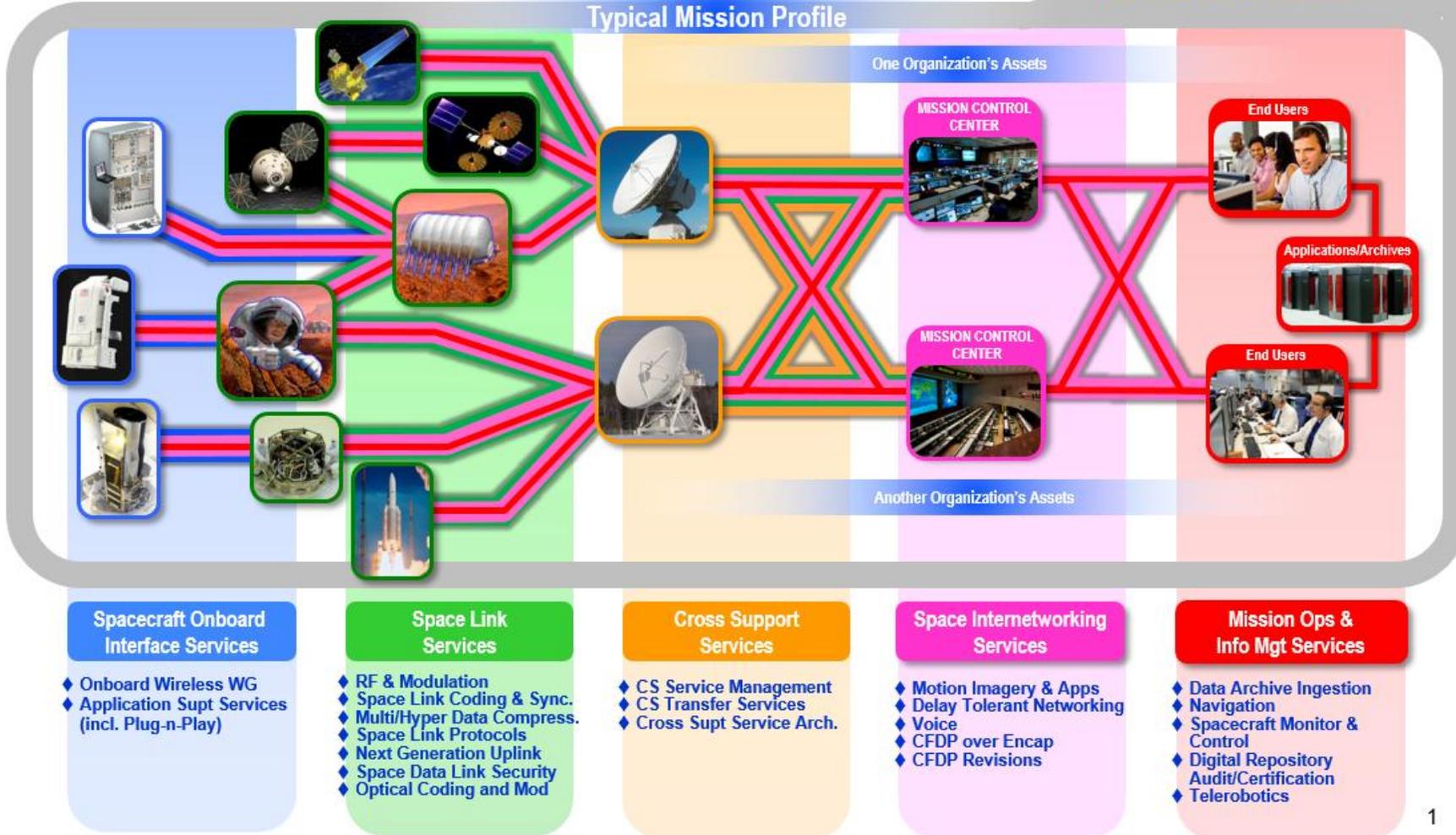
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CCSDS Overview
End-to-End Architecture

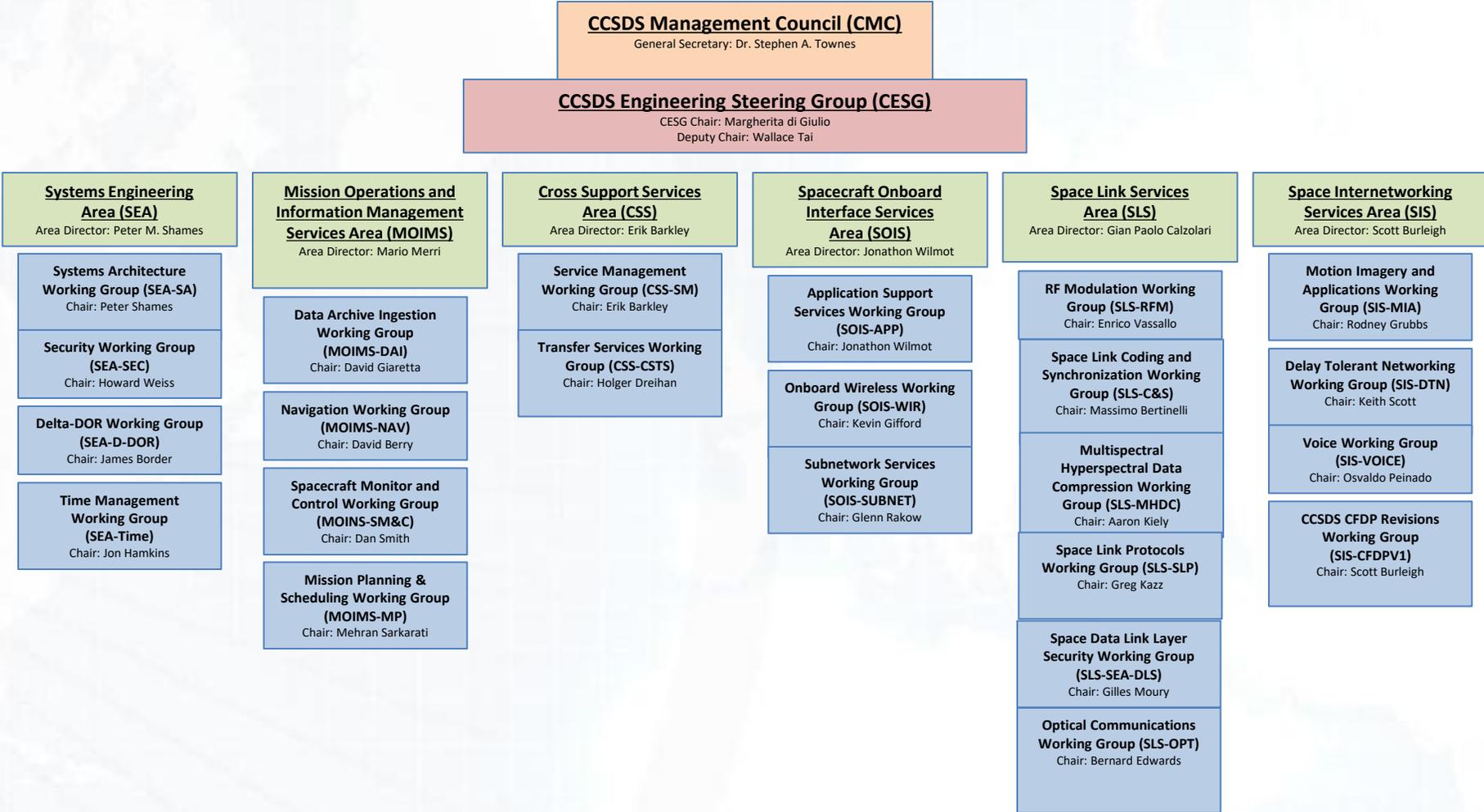**Six Technical Areas, Twenty-Six Teams**
- ◆ Working Group (producing standards)
- ◆ Birds-Of-a-Feather stage (pre-approval)
- ◆ Special Interest Group (integration forum)

Systems Engineering
- ◆ Security
- ◆ Delta-DOR
- ◆ Timeline Data Exchange
- ◆ XML Standards and Guidelines

Typical Mission Profile

One Organization's Assets

MISSION CONTROL CENTER

End Users

Applications/Archives

MISSION CONTROL CENTER

End Users

Another Organization's Assets

Spacecraft Onboard Interface Services	Space Link Services	Cross Support Services	Space Internetworking Services	Mission Ops & Info Mgt Services
◆ Onboard Wireless WG ◆ Application Supt Services (incl. Plug-n-Play)	◆ RF & Modulation ◆ Space Link Coding & Sync. ◆ Multi/Hyper Data Compress. ◆ Space Link Protocols ◆ Next Generation Uplink ◆ Space Data Link Security ◆ Optical Coding and Mod	◆ CS Service Management ◆ CS Transfer Services ◆ Cross Supt Service Arch.	◆ Motion Imagery & Apps ◆ Delay Tolerant Networking ◆ Voice ◆ CFDP over Encap ◆ CFDP Revisions	◆ Data Archive Ingestion ◆ Navigation ◆ Spacecraft Monitor & Control ◆ Digital Repository Audit/Certification ◆ Telerobotics

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CCSDS Structure

CCSDS Management Council (CMC)
General Secretary: Dr. Stephen A. Townes

CCSDS Engineering Steering Group (CESG)
CESG Chair: Margherita di Giulio
Deputy Chair: Wallace Tai

Systems Engineering Area (SEA)
Area Director: Peter M. Shames

- **Systems Architecture Working Group (SEA-SA)**
  Chair: Peter Shames
- **Security Working Group (SEA-SEC)**
  Chair: Howard Weiss
- **Delta-DOR Working Group (SEA-D-DOR)**
  Chair: James Border
- **Time Management Working Group (SEA-Time)**
  Chair: Jon Hamkins

Mission Operations and Information Management Services Area (MOIMS)
Area Director: Mario Merri

- **Data Archive Ingestion Working Group (MOIMS-DAI)**
  Chair: David Giaretta
- **Navigation Working Group (MOIMS-NAV)**
  Chair: David Berry
- **Spacecraft Monitor and Control Working Group (MOIMS-SM&C)**
  Chair: Dan Smith
- **Mission Planning & Scheduling Working Group (MOIMS-MP)**
  Chair: Mehran Sarkarati

Cross Support Services Area (CSS)
Area Director: Erik Barkley

- **Service Management Working Group (CSS-SM)**
  Chair: Erik Barkley
- **Transfer Services Working Group (CSS-CSTS)**
  Chair: Holger Dreihan

Spacecraft Onboard Interface Services Area (SOIS)
Area Director: Jonathon Wilmot

- **Application Support Services Working Group (SOIS-APP)**
  Chair: Jonathon Wilmot
- **Onboard Wireless Working Group (SOIS-WIR)**
  Chair: Kevin Gifford
- **Subnetwork Services Working Group (SOIS-SUBNET)**
  Chair: Glenn Rakow

Space Link Services Area (SLS)
Area Director: Gian Paolo Calzolari

- **RF Modulation Working Group (SLS-RFM)**
  Chair: Enrico Vassallo
- **Space Link Coding and Synchronization Working Group (SLS-C&S)**
  Chair: Massimo Bertinelli
- **Multispectral Hyperspectral Data Compression Working Group (SLS-MHDC)**
  Chair: Aaron Kiely
- **Space Link Protocols Working Group (SLS-SLP)**
  Chair: Greg Kazz
- **Space Data Link Layer Security Working Group (SLS-SEA-DLS)**
  Chair: Gilles Moury
- **Optical Communications Working Group (SLS-OPT)**
  Chair: Bernard Edwards

Space Internetworking Services Area (SIS)
Area Director: Scott Burleigh

- **Motion Imagery and Applications Working Group (SIS-MIA)**
  Chair: Rodney Grubbs
- **Delay Tolerant Networking Working Group (SIS-DTN)**
  Chair: Keith Scott
- **Voice Working Group (SIS-VOICE)**
  Chair: Osvaldo Peinado
- **CCSDS CFDP Revisions Working Group (SIS-CFDPV1)**
  Chair: Scott Burleigh

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Books of Many Colors

BLUE BOOKS RECOMMENDED STANDARDS

Normative, and sufficiently detailed (and pre-tested) that they can be used to implement interoperable systems.

MAGENTA BOOKS RECOMMENDED PRACTICES

Normative, but at a level that is not implementable for interoperability. Reference architectures, APIs, operational practices, etc.

GREEN BOOKS INFORMATIVE DOCUMENTS

Not normative. These may be foundational for Blue Books and Magenta Books, describing their applicability, overall architecture, ops concept, etc.

ORANGE BOOKS EXPERIMENTAL

Normative, but may be very new technology that does not yet have consensus of enough agencies to standardize.

RED BOOKS DRAFT STANDARDS/PRACTICES

Drafts of future Blue Books or Magenta Books that that are in agency review.

YELLOW BOOKS ADMINISTRATIVE

Procedures, test reports, etc.

SILVER BOOKS RETIRED

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CCSDS Benefits

- Protocols Optimized for the Space Domain
  - Command Structure
    - Frame and packets for complex payload
    - Onboard FEC decode with low processing power
  - Telemetry
    - Frame and packet structure for diverse payload functions and easy demux
    - Easy transition to IP on ground
    - Low spacecraft power requirement to encode data with strong FEC
      - RS, LDPC, Convolutional
  - Optimized file transport layer for on-board stored data transfer
  - Optimized IP packet encapsulation
  - COTS equipment for on-board and ground equipment
- Standard Ground Protocol (SLE)
  - Standard data encapsulation, timing, quality metrics, security, etc.
  - Standard commanding with scheduling, authentication, verification

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Where do CCSDS Standards Apply?

Focus On The Data Formats

Focus On Key Interfaces Within The Architecture

Space Systems

External User

Missions Applications

Remote Ground Facility

RF/IF Equipment

Comm Equipment

Control Center

Comm Equipment

TLM & CMD Front-Ends

Missions Applications

TT&C Applications

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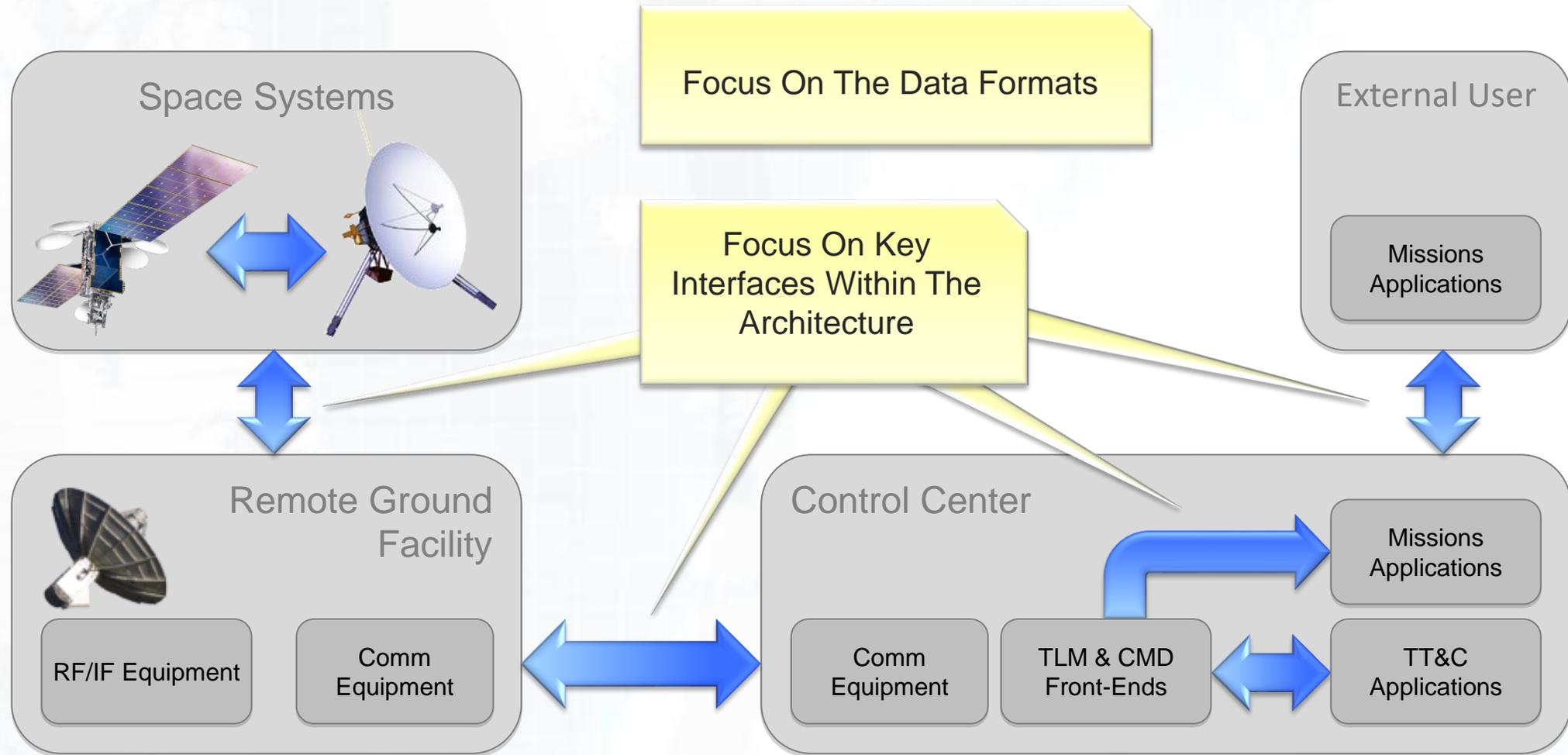
CCSDS Modeled after OSI

- Open Systems Interconnection (OSI)
- Utilize a Layered Approach
- Each Layer can be used Independently
- Each Layer Serves the Layer Above

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Data in the CCSDS Layers

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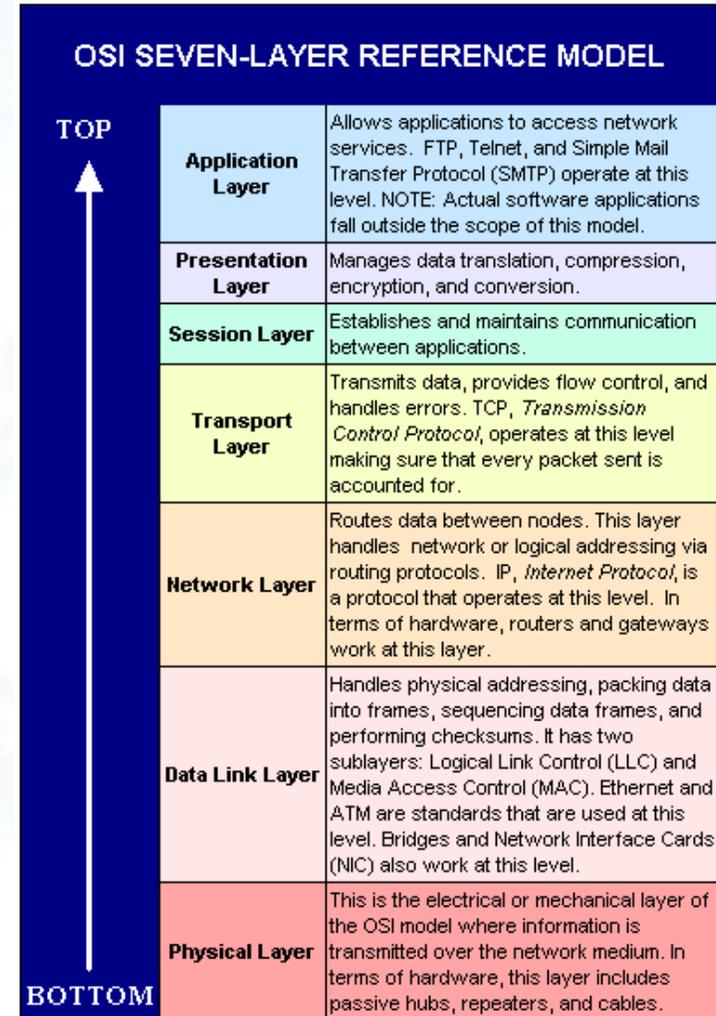
The CCSDS Stack

- We will touch on many of these through the remainder of the course
- We encourage you to learn more

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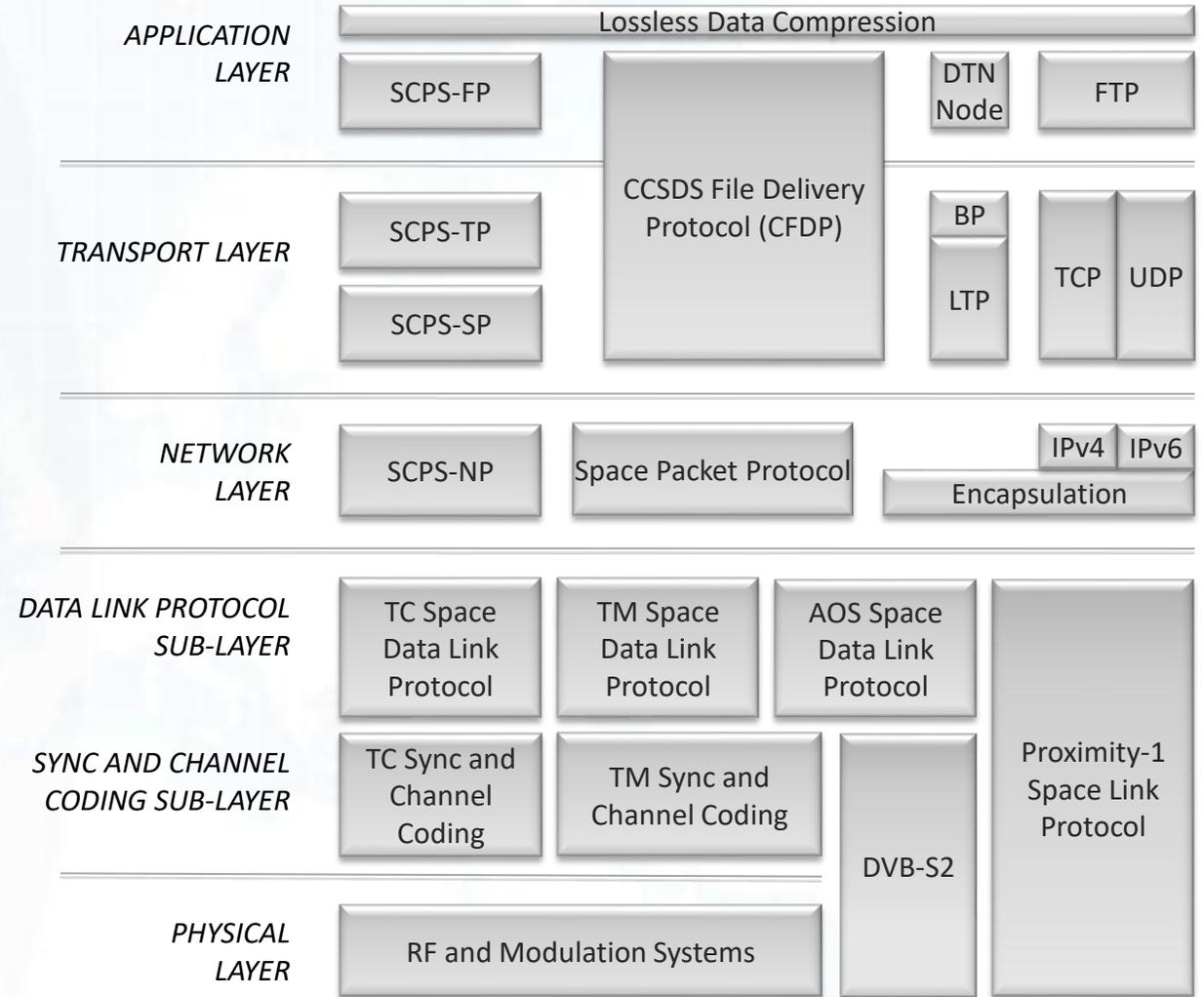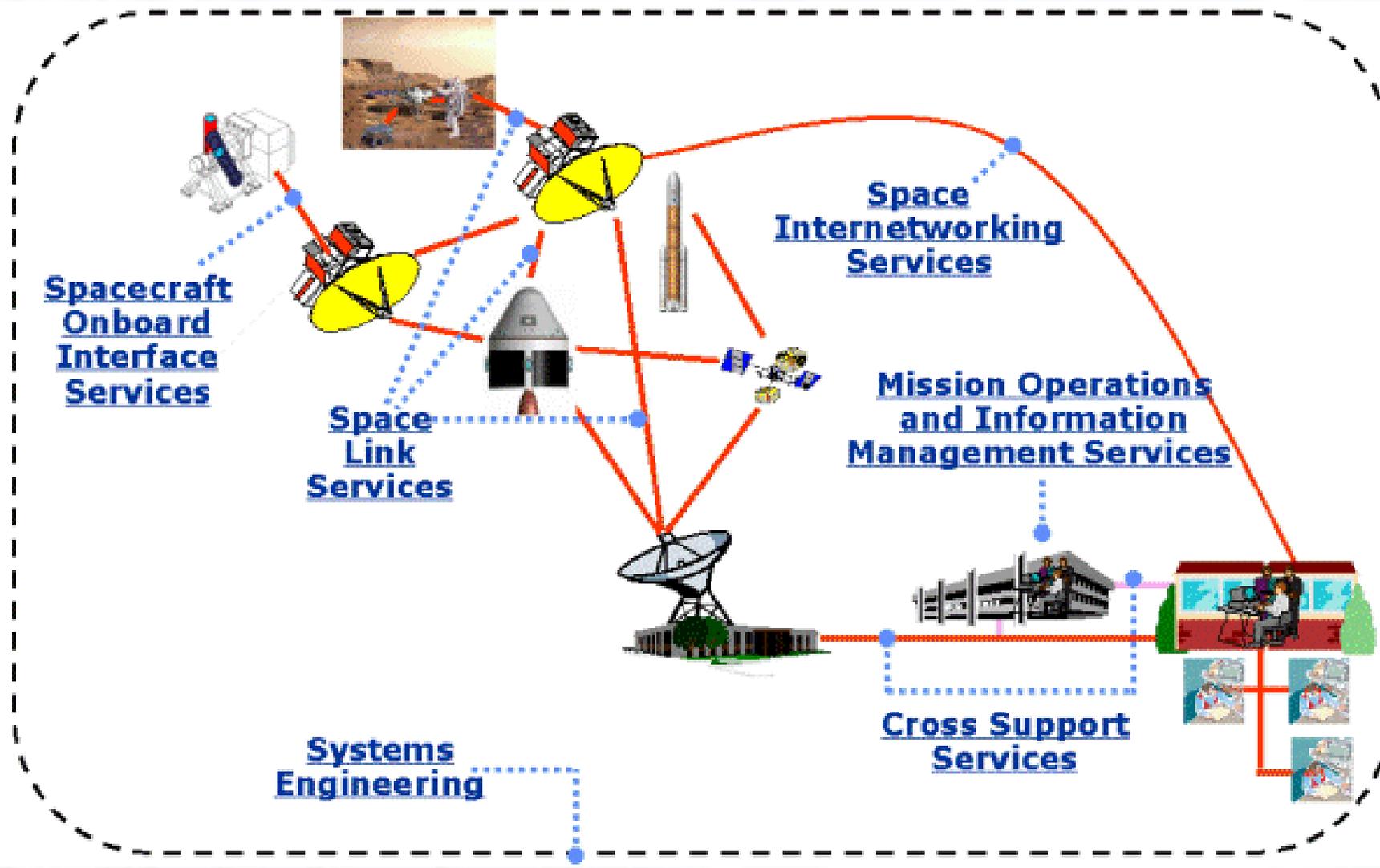
System Engineering Area (SEA)

- Objectives
  - Supports overall CCSDS architecture
  - Provides collaboration between groups
- Standards
  - Reference Architecture
  - Space Assigned Numbers Authority (SANA)
  - Security, encryption, authentication, key management
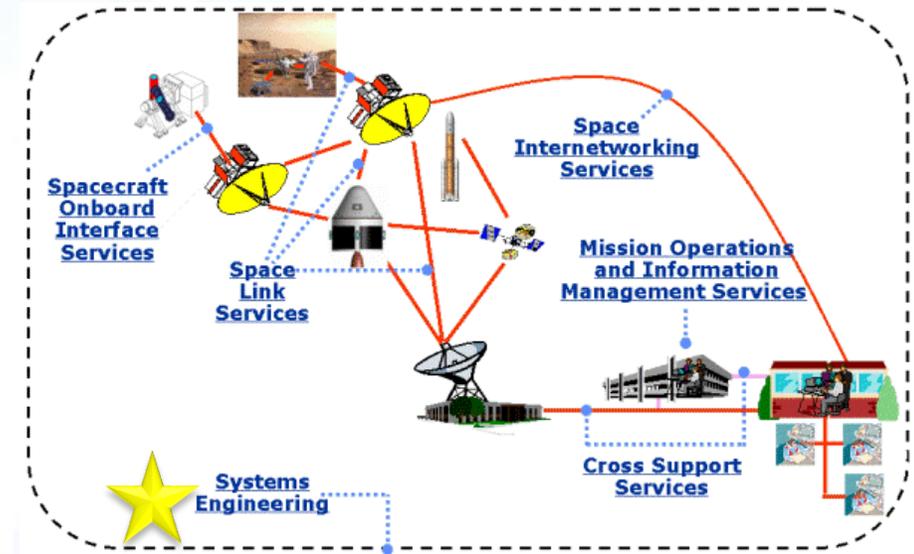
The SE area supports the work of CCSDS by providing overall architecture for space mission communications, operations, and cross-support; coordination and collaboration with the other areas about architectural choices and options; and evaluation of consistency of all area programs of work with the defined architecture.

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Space Assigned Numbers Authority (SANA) Registry for Various Identifiers

- Started in 2010 by the CCSDS SANA Working group
- Inspired by the Internet Assigned Numbers Authority (IANA)
- Single place for registering numbers (e.g., identifiers, namespaces, schemas)
- Reduces modifications to recommended standards by externally referencing assignments

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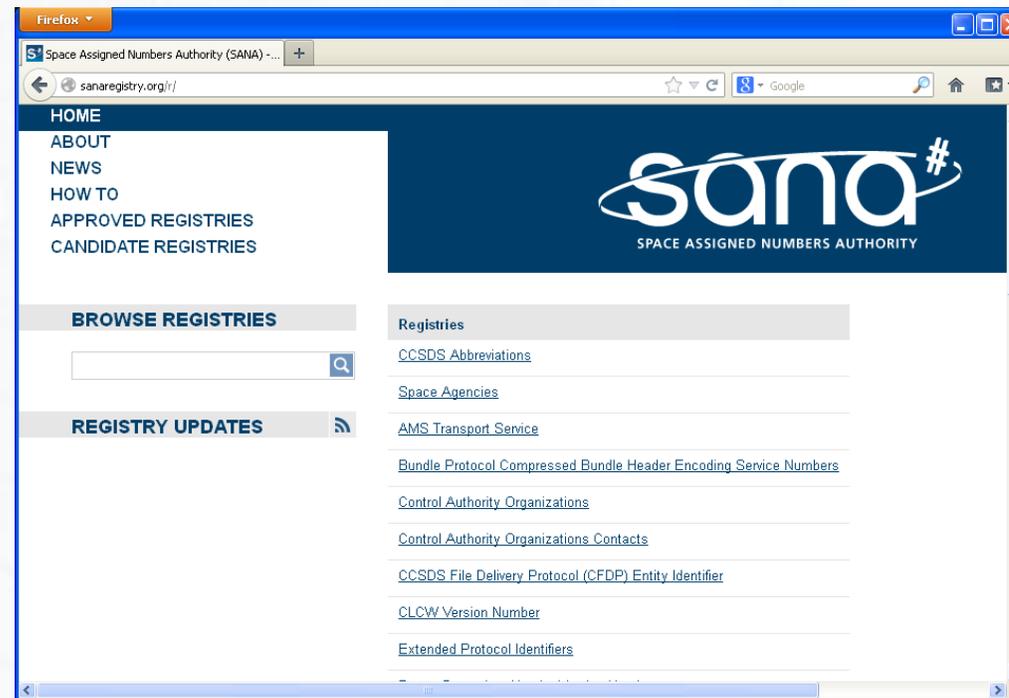
Security Within the Sub-Layer

Data Link Protocol

- Multiple Options for Encryption
- Bulk
- Frame
- Packet
- CCSDS 355.0-B-2 – (Encryption)*
- CCSDS 352.0-B-1 – (Crypto Alg.)

- * Was Red…

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CCSDS Security Core Suite

- Physical Layer Encryption
  - Bulk encryption not defined by CCSDS
- Link Layer Encryption
  - Encrypt entire frames or just data field of frame
  - Encoding left unencrypted
  - Very efficient for point-to-point encryption
- Network Layer Encryption
  - Encrypt Protocol Packets while leaving routing information unencrypted (e.g. IPSec)
- Application Layer Encryption
  - Encrypt application data (e.g., SSL)
  - Underlying protocols left unencrypted
  - Good for end-to-end security
  - No changes required for underlying protocols

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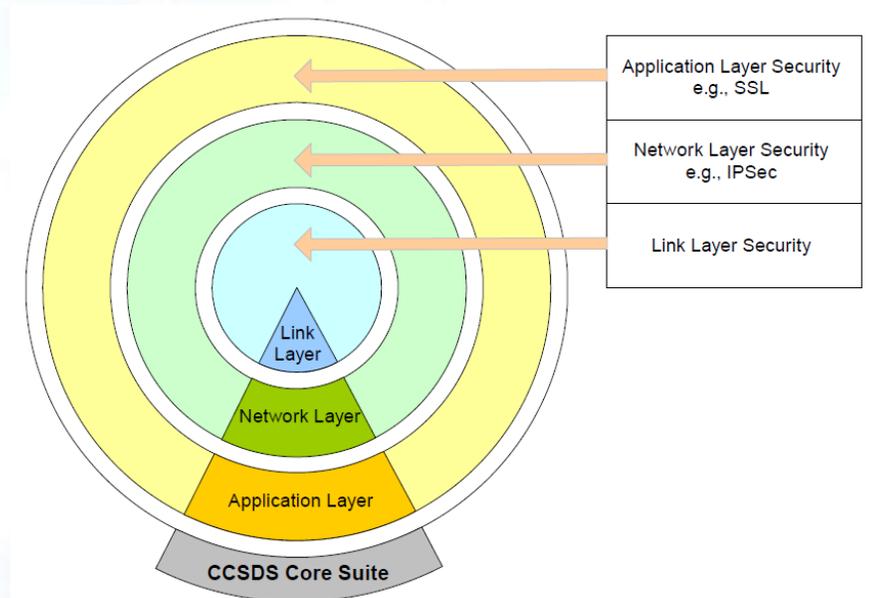
CCSDS Encryption Algorithm
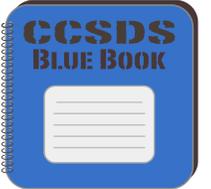
- CCSDS Recommends AES – as per CCSDS 352.0-B-1
- AES Keys of 128, 192 or **256 bits**
- Combined with Data Integrity and Origin Authentication
- High-speed algorithms available for hardware/software that allow for efficient parallel/pipelined implementation
  - o Hash-based
  - o Cipher-based
  - o Digital Signature-based
- Alternative Bulk Encryption may be applied and combined with outer-FEC codes such as LDPC/Turbo

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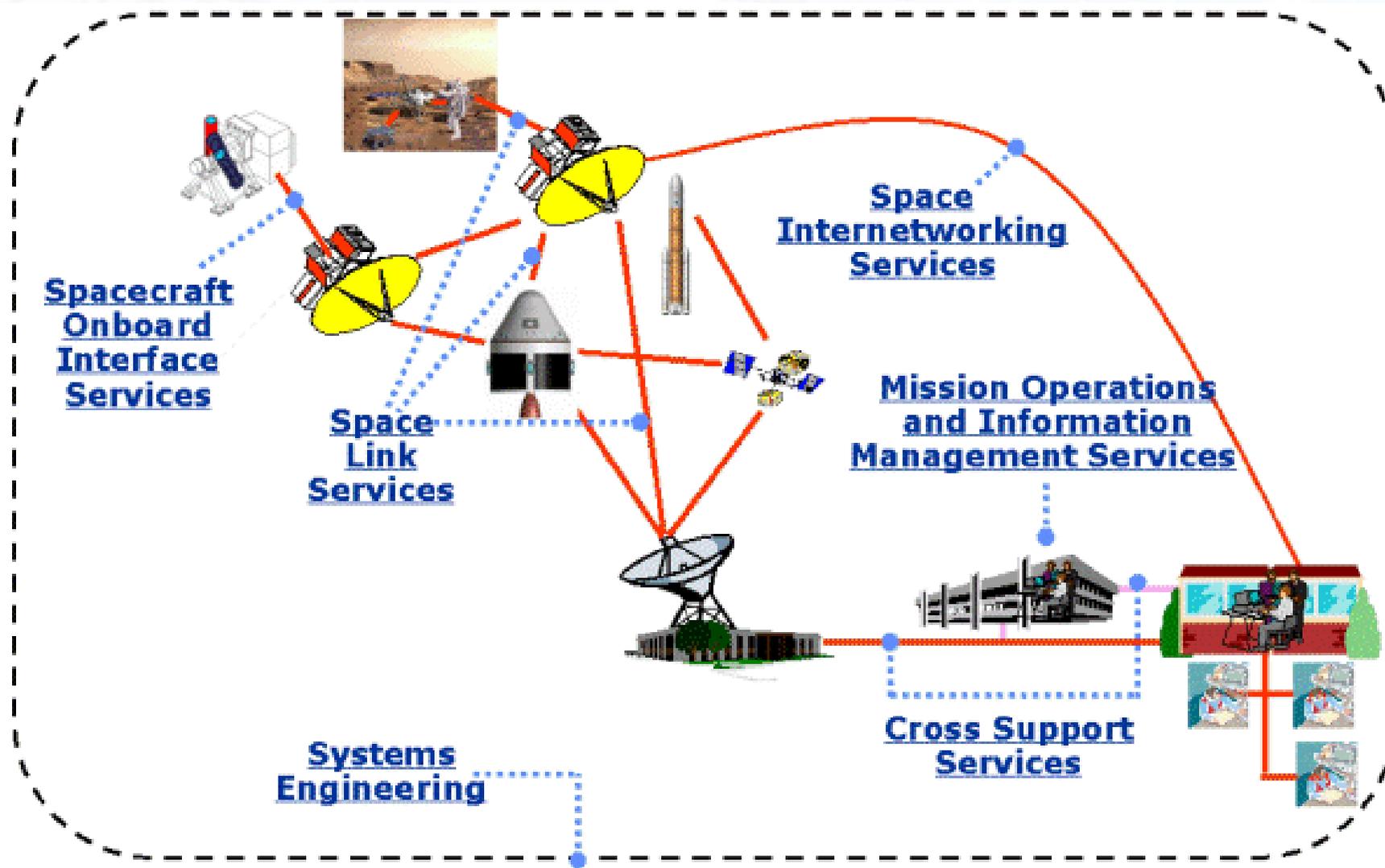
Spacecraft Onboard Interfaces Services (SOIS) Area

- Objectives
  - Define generic services that will simplify the way flight software interacts with flight hardware
- Standards
  - Spacecraft Onboard Interface Services
  - Wireless network communication
  - Subnetwork services
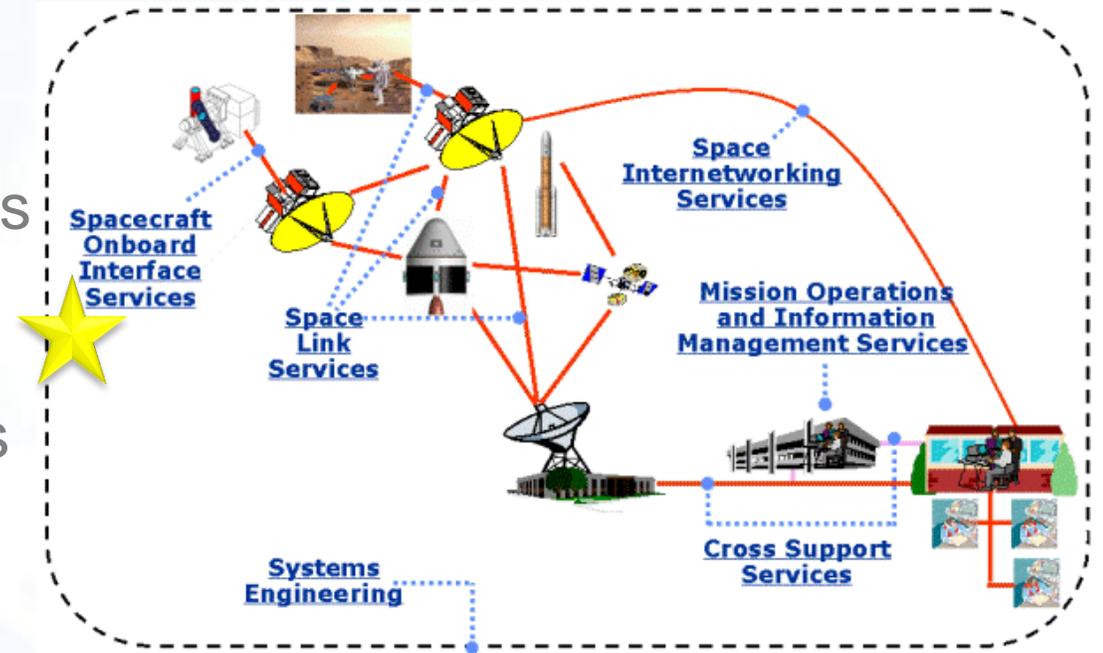
The primary objective of the CCSDS SOIS area is to improve the spacecraft flight segment data systems design and development process by defining generic services that will simplify the way flight software interacts with flight hardware and permit interoperability and reusability for the benefit of agencies as well as industrial contractors.

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SOIS Reference Stack

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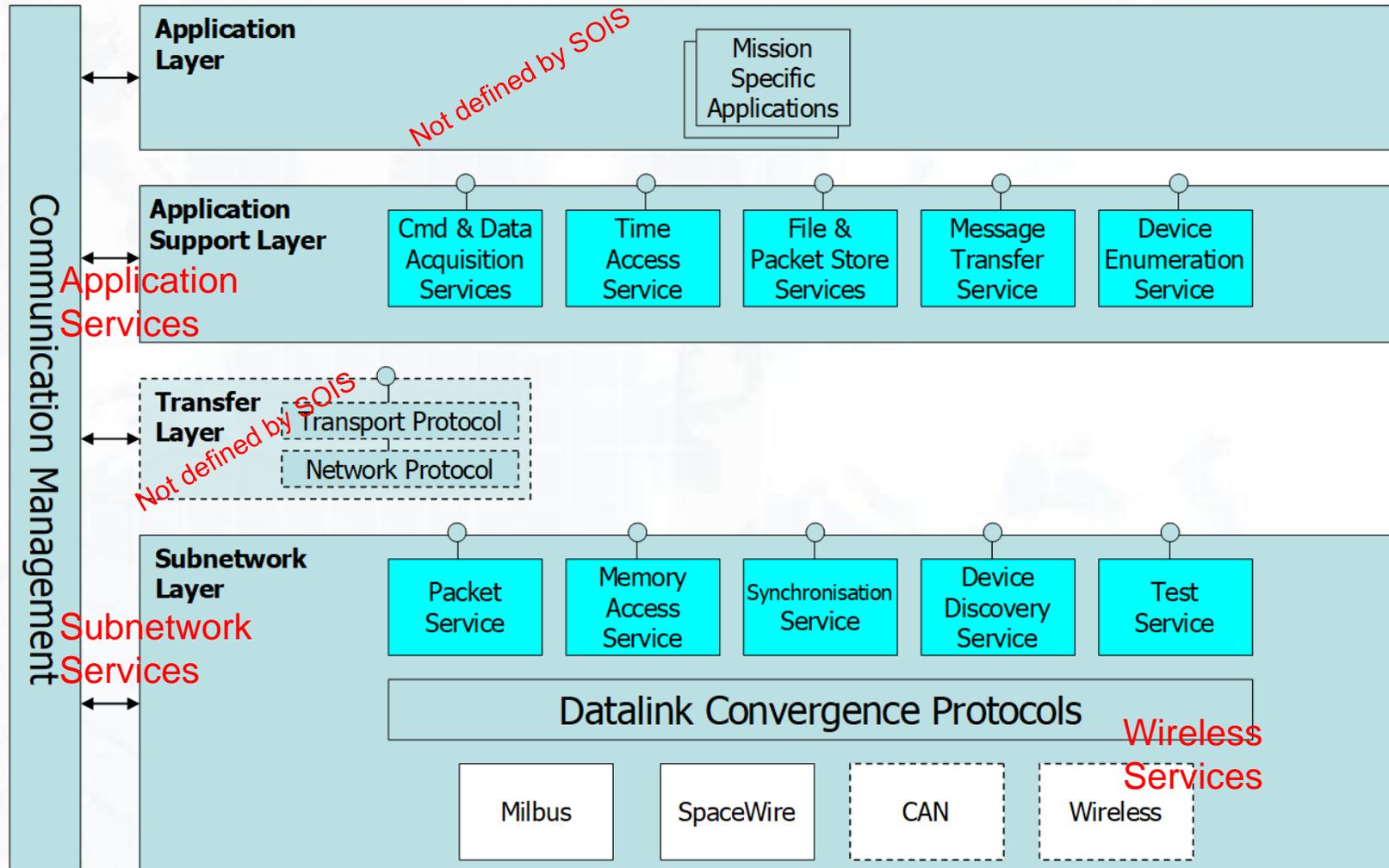
Applications Support Services

- SOIS working group has focused on defining standards to describe hardware and software service interfaces rather than define a specific standard service interface

  - Based on the realization than component vendors and system integrators have existing software and avionics architectures that are mature and operational

- With that focus in mind SOIS has published, or is developing 3 books and registries based on the Electronic Data Sheet (EDS) concept

  - Electronic Data Sheets and Common Dictionary of Terms - Overview and Rationale (Green 870.1)

  - XML Specification for Electronic Data Sheets for Onboard Devices and Software Components (Magenta 876.0)

  - Specification for Dictionary of Terms for Electronic Data Sheets for Onboard Components (Blue 876.1)

  - SEDS schema and dictionary of terms are kept in Space Assigned Number Authority (SANA) registry (http://sanaregistry.org/r/sois/sois.html)

EDS provides a standard to exchange system, device and software machine readable interface definitions between organizations and agencies

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Electronic Data Sheets for Development and Operations
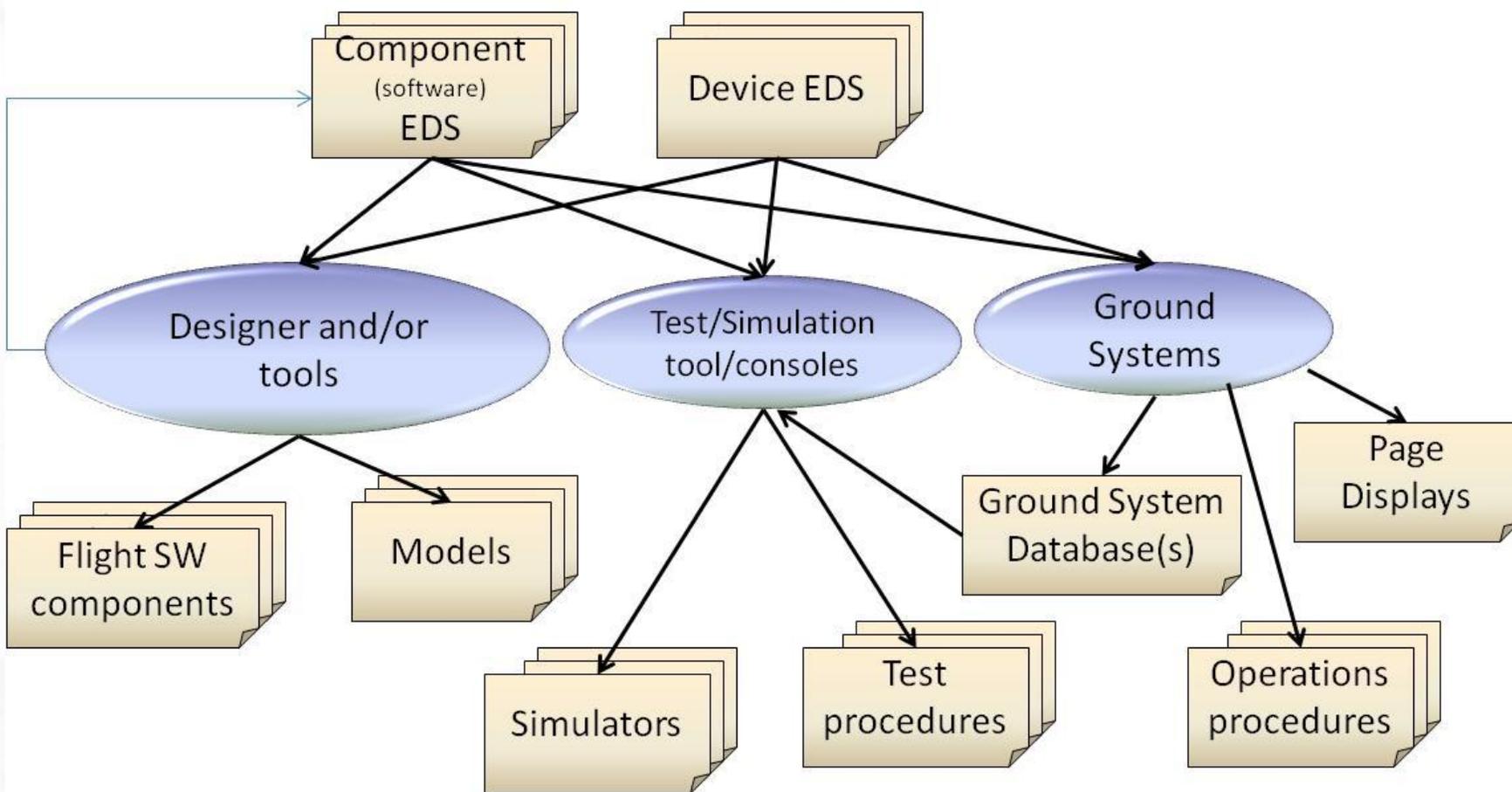
NASA and ESA have developed prototype tooling for machine generation of each of the data products shown

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Device and Software Component EDS
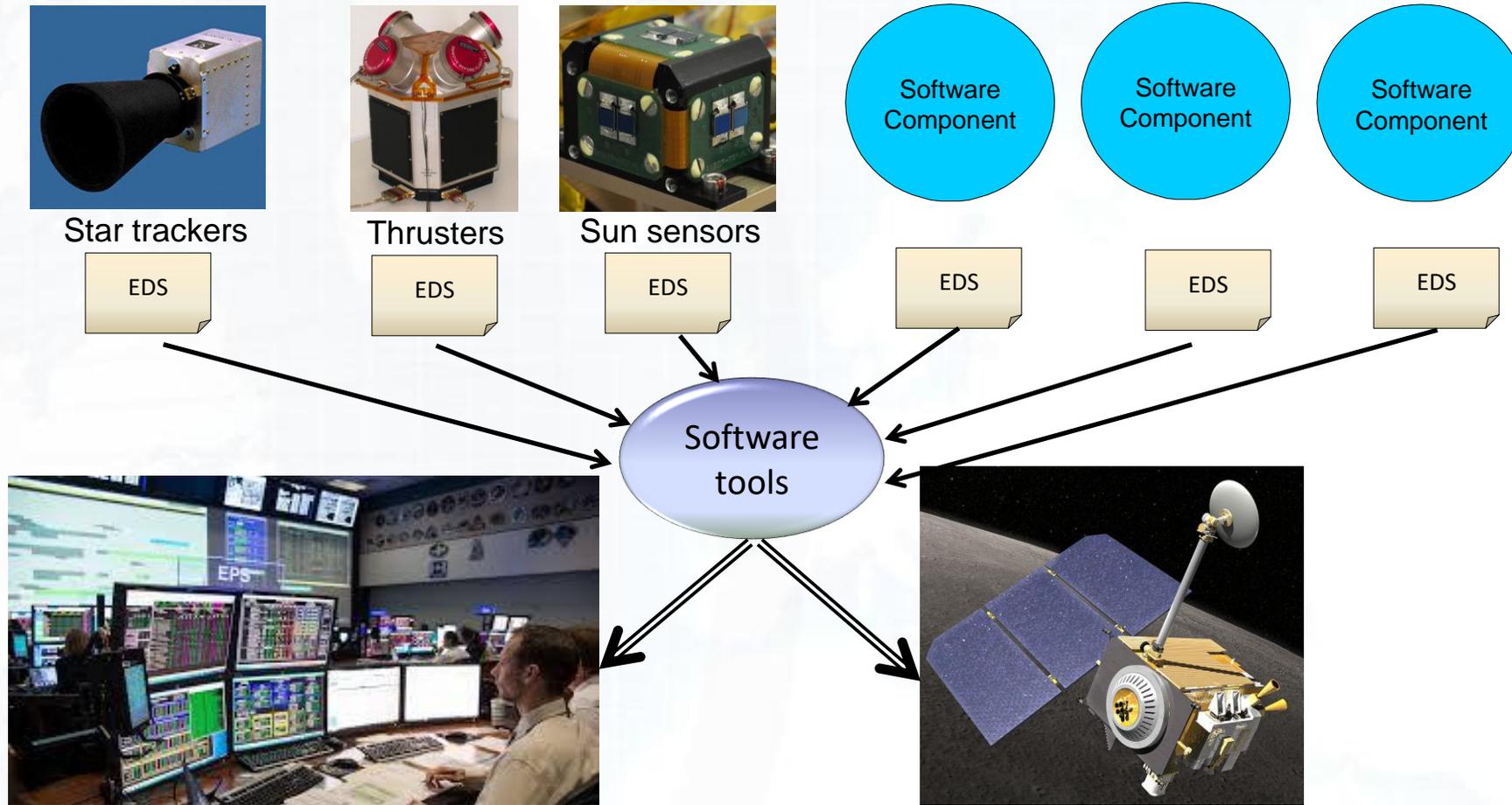
**Goal: device manufactures provide an EDS with each component
Eliminates ambiguities of paper ICD and/or specifications**

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Spacecraft EDS Extension to Ground

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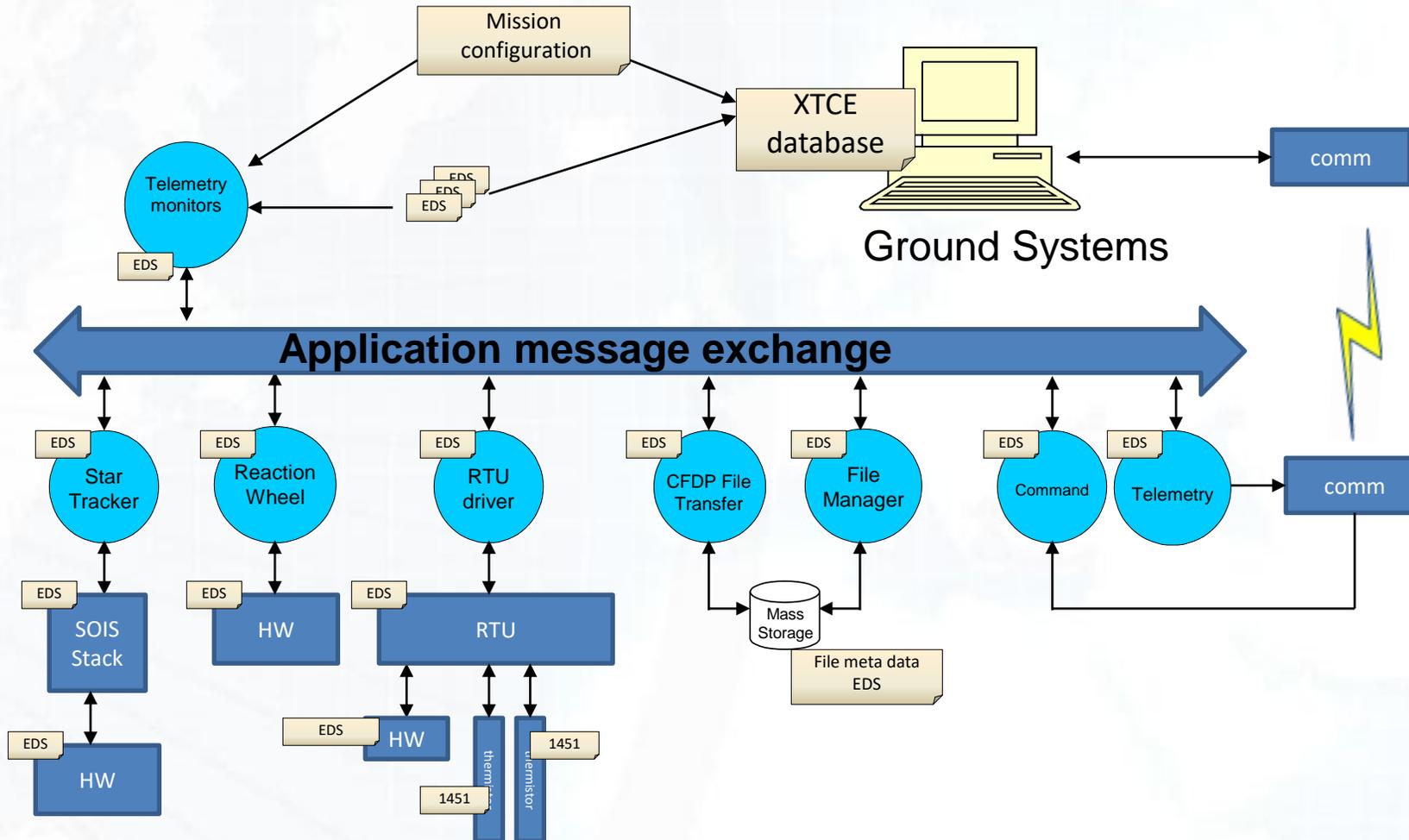
Subnetwork Services

- Develops recommendations for common application interfaces to onboard subnetworks

  – Interfaces are defined using the same EDS concepts with terms as defined by the subnetwork type (SpaceWire, MilBus, Ethernet, CAN, TTE, Wireless, …)

- Develops recommendations to define common Management Interface Bases (MIB) for control on monitoring of subnetwork interfaces

- Responsible for 5 books

  – Device Discovery Service

  – Memory Access Service

  – Packet Service

  – Synchronization Service

  – Test Service

EDS provides machine readable definitions of deployment configuration and operational interfaces for subnetworks

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- Why wireless?
  - Weight savings
  - RF ID
  - Mobility and separation of manned and unmanned systems
    - Intra-vehicle – e.g. space station
    - Inter-vehicle – e.g. satellite to satellite
    - Lander to orbiter
    - Rover to lander
    - Human or other device motion within our outside vehicle
- Why Standardize?
  - Many wireless standards
  - Choose sensible options for space interoperability to reduce cost and complexity (just like we've been talking about for all other standards!)

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Wireless Continued

- Considerations
  - Power requirements
  - Data rates
  - Data integrity
  - Security
  - Noise
    - Interference
    - Visibility
    - Atmospheric/channel effects
  - Range
  - Availability
  - Reliability
  - Channel coexistence/utilization
  - Safety
  - Existing standards

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Wireless Working Group

- The Wireless Working Group adheres to the CCSDS guiding principal of a '3-Tier Prioritized Approach to Standards':
  - adopt proven standards where practical
  - adapt existing standards to meet defined requirements
  - develop new approaches only where absolutely necessary
  - Extension to LTE gaining acceptance
  - Analysis of 5G for future deployment

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Wireless Applications and Standards

Table 2-2: Key Application Areas for Functional Space Communication Domains

Functional Domain	Application Areas	Number of nodes	Data Rate	Applicable Standards
Intra-vehicle	Inventory monitoring	100s	Very Low	ISO 18000-6C EPCglobal
	Environmental monitoring (e.g., temperature, pressure, humidity, radiation, water quality)	10s to 100s	Low to Medium	802.15.4
	Physiological monitoring (includes EVA suit biomedical monitoring)	1 to 10	Low to Medium	802.15.1 802.15.4
	Crew member location tracking	1 to 10	Medium to High	802.11 802.15.3 802.16
	Structural monitoring	10s	Medium to High	802.11 802.15.3
	Intra-spacecraft communications (voice and video)	10s	Medium to High	802.15.1 802.11 802.16
	Process monitoring and automated control and Scientific monitoring and control	10s to 100s	Low to High	802.15.3 802.15.4 802.11 802.16
	Retro-fit of existing vehicle with new capabilities	10s to 100s	Low to High	802.15.3 802.15.4 802.11 802.16
AIT activities	Spacecraft assembly, integration and test	10s to 100s	Medium	802.15.3 802.15.4 802.11
Inter-vehicle*	Inter-spacecraft communications (voice, video and data)	10	High to extremely high	802.16 Prox-1 AOS
Planetary Surface*	IVA-EVA, EVA-EVA, Habitat-to-LRV, LRV-crew communications (voice, video and data)	10	Medium to High	802.11 802.16
	Robotic Operations	10s	Low to High	802.15.3 802.15.4 802.11 802.16
Orbiter relay to Surface*	Surface-to-orbit communications (voice, video and data)	10	High to extremely high	802.16 Prox-1 AOS

* Application areas not addressed in this Green Book

KRATOS

Spacecraft Onboard Interface Services

Space Internetworking Services

Space Link Services

Mission Operations and Information Management Services

Cross Support Services

Systems Engineering

KRATOS
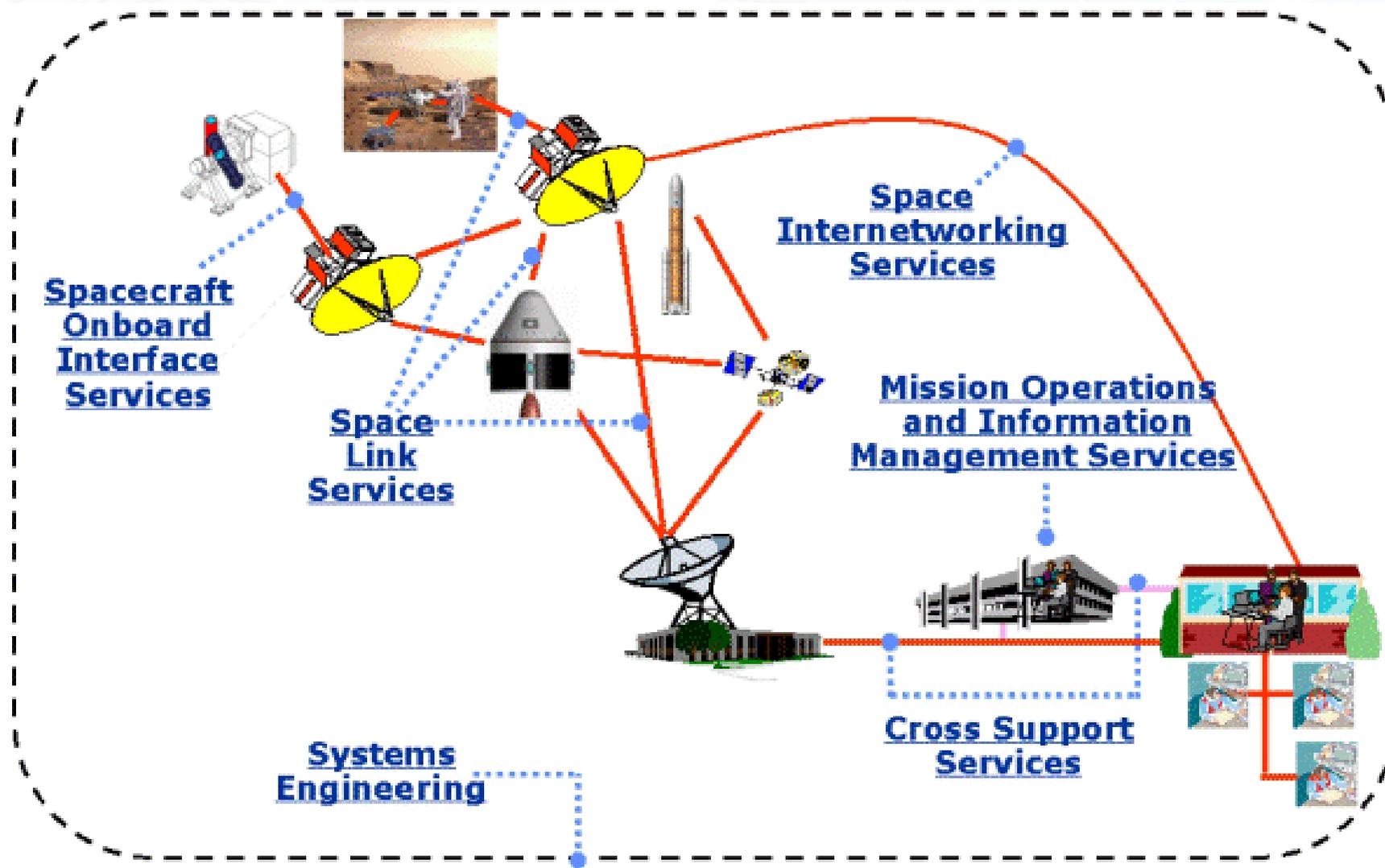
- Objectives
  - Promote interoperability between space vehicles and ground stations by standardizing the space link protocols
- Scope
  - Long haul space links (e.g., spacecraft to ground)
 - Proximity Links (e.g., orbiter to lander)
  - Data compression
  - Ranging
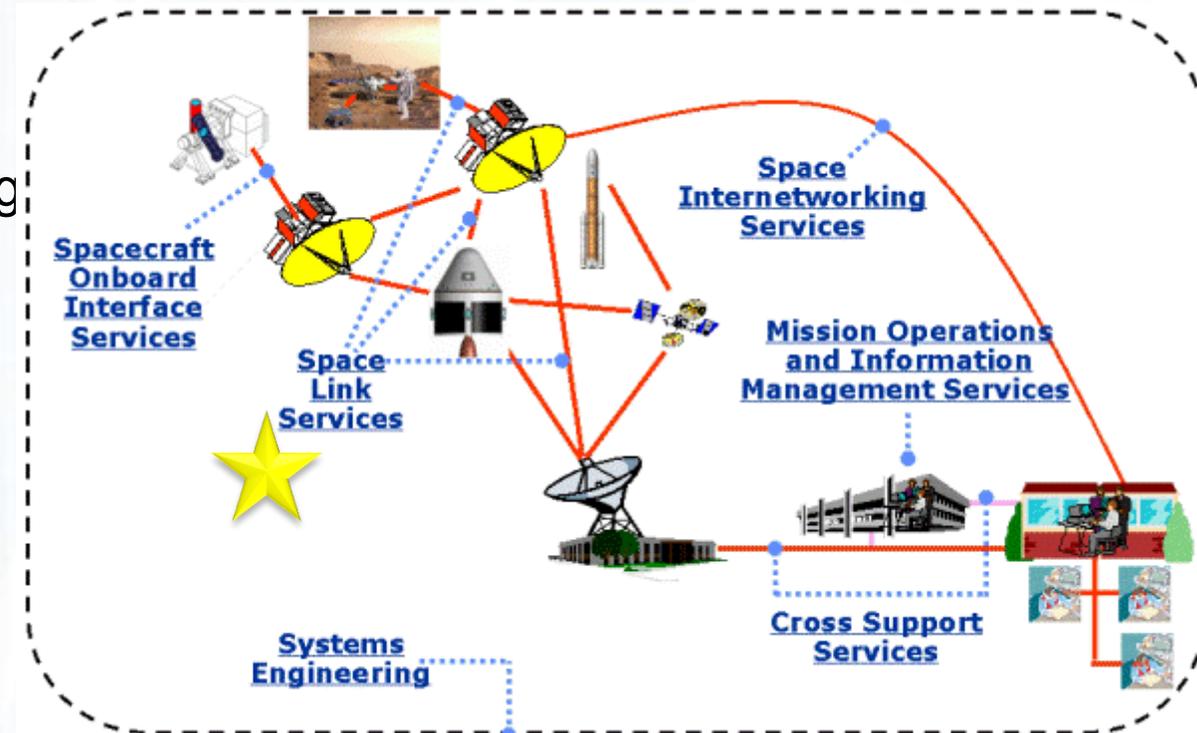
The SLS area develops efficient space link communications systems common to all participating agencies. A space link interconnects a spacecraft with its ground support system or with another spacecraft. New generations of space missions require telecommand and telemetry capabilities beyond current technologies. These new needs are for higher data rates, better link performances, and higher performing ranging systems. SLS area concentrates on radio frequency (RF) and modulation, channel coding, and data link layer -- for both long-haul (e.g., spacecraft to ground) and proximity links (e.g., orbiter to lander). Two additional SLS functions are data compression for end-to-end data transfer optimization and ranging for accurate orbit determination.

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Physical Layer

- Defines the RF Links
  - Ground to Space
  - Vehicle to Vehicle
- PLOP
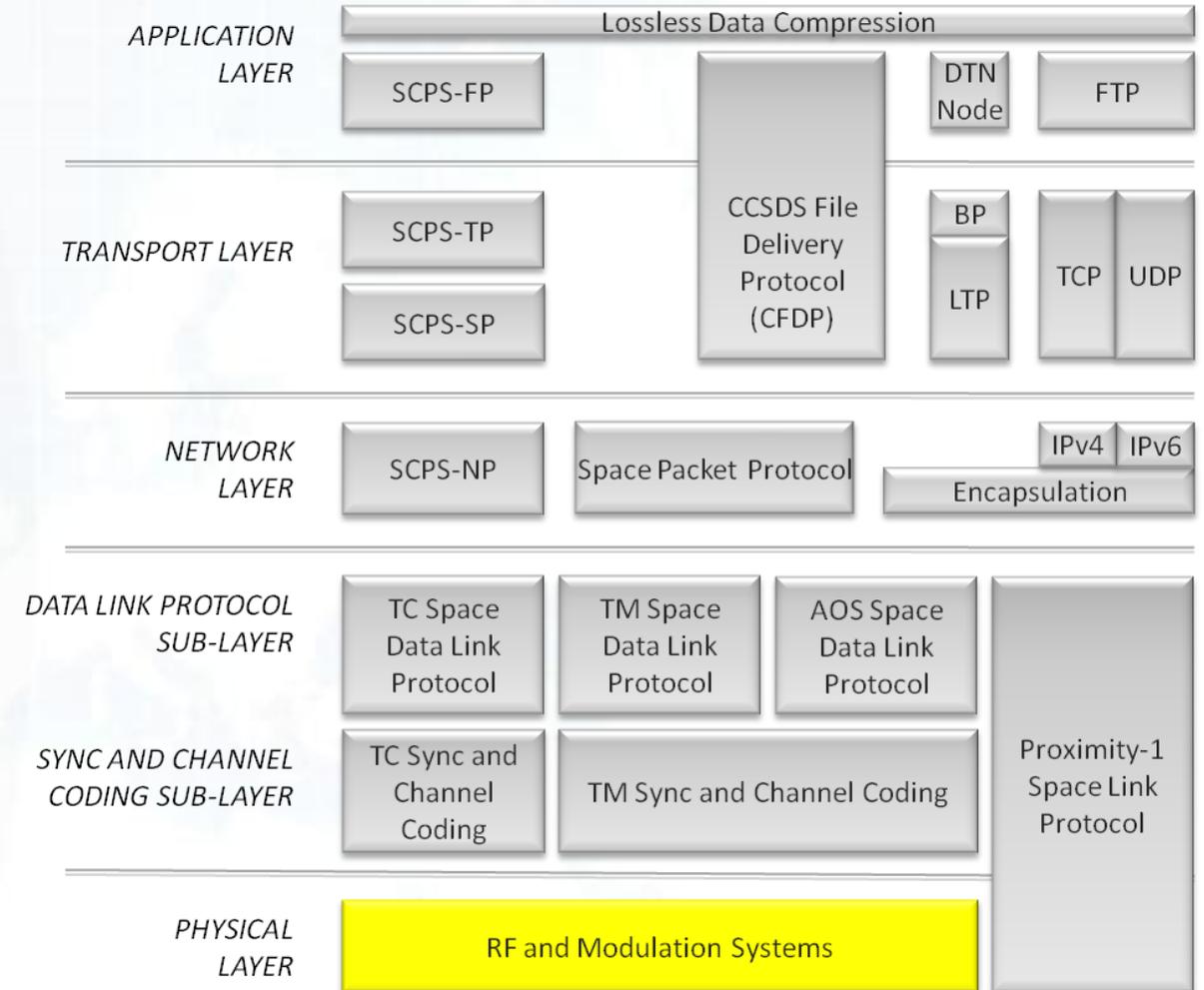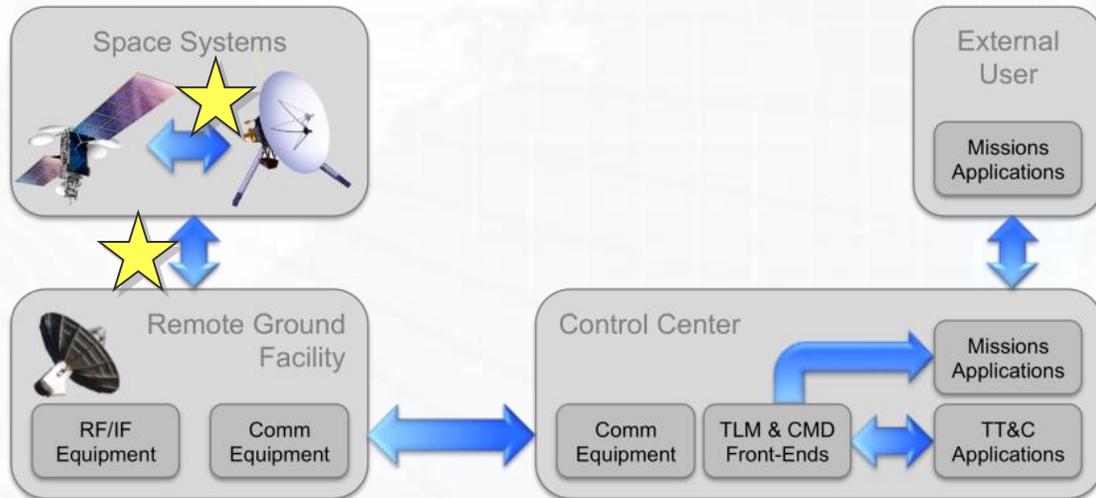
RF and Modulation Systems

- Blue Book Specification
  - [Ref 1] RF Link provides detailed information
- Included in the Recommendation
  - Modulation
  - Data Encodings
    - NRZ-L,S,M and BiPhase-L,S,M typical data formats
    - Guaranteed bit transitions keep bit synchronizer locked
      - ❖ Randomizer: simple PN XOR
  - Tone and PN Ranging
  - Convolutional coding (typical rate ½, k=7)
- How do these Schemes Compare?
  - A study was conducted that provides a good comparison of modulation schemes [Ref 2]

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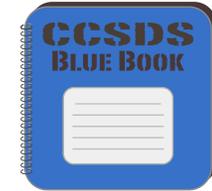
R/F Link Characteristics

- Downlink (Telemetry)
  - ○ PCM/PSK/PM Carrier Modulation Schemes
  - ○ QPSK and more for high-rate telemetry downlinks
- Uplink (Telecommand & Telemetry)
  - ○ Telecommand: PCM-PSK with coherent PCM subcarrier
  - ○ Telemetry/Data: BPSK
- Frequency Bands
  - ○ Channel frequency plans for 2, 7, 8, 32 and 34 GHz bands

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Bit Mapping for Higher Order Modulation
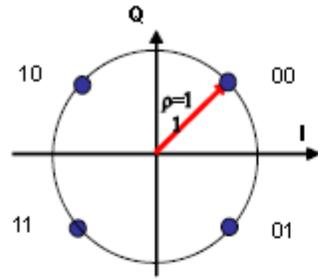
(a) QPSK
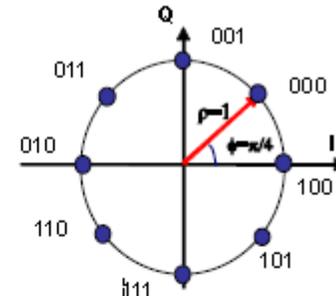
(b) 8-PSK
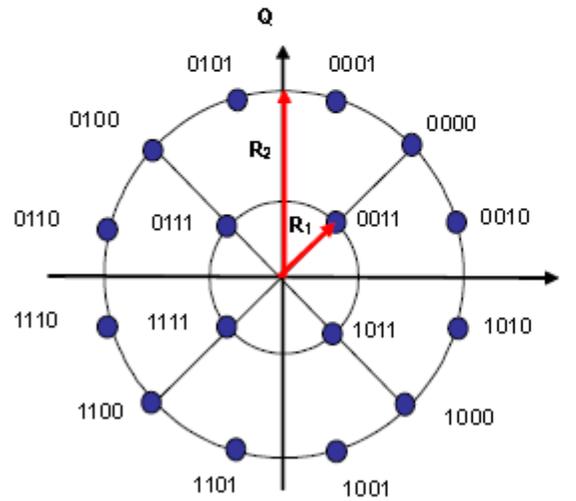
(c) 16-APSK

(d) 32-APSK

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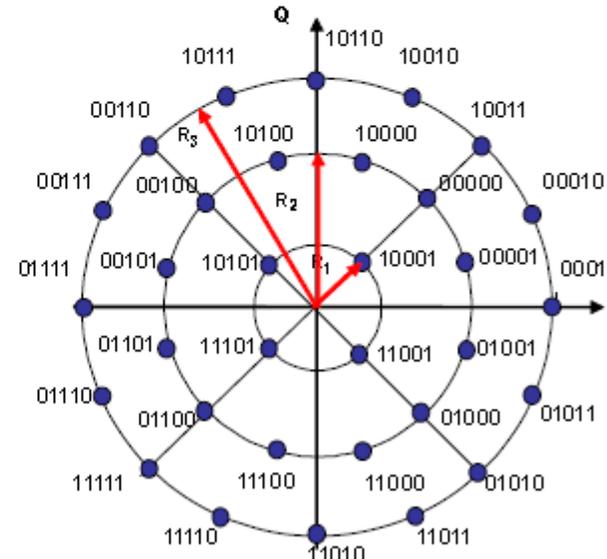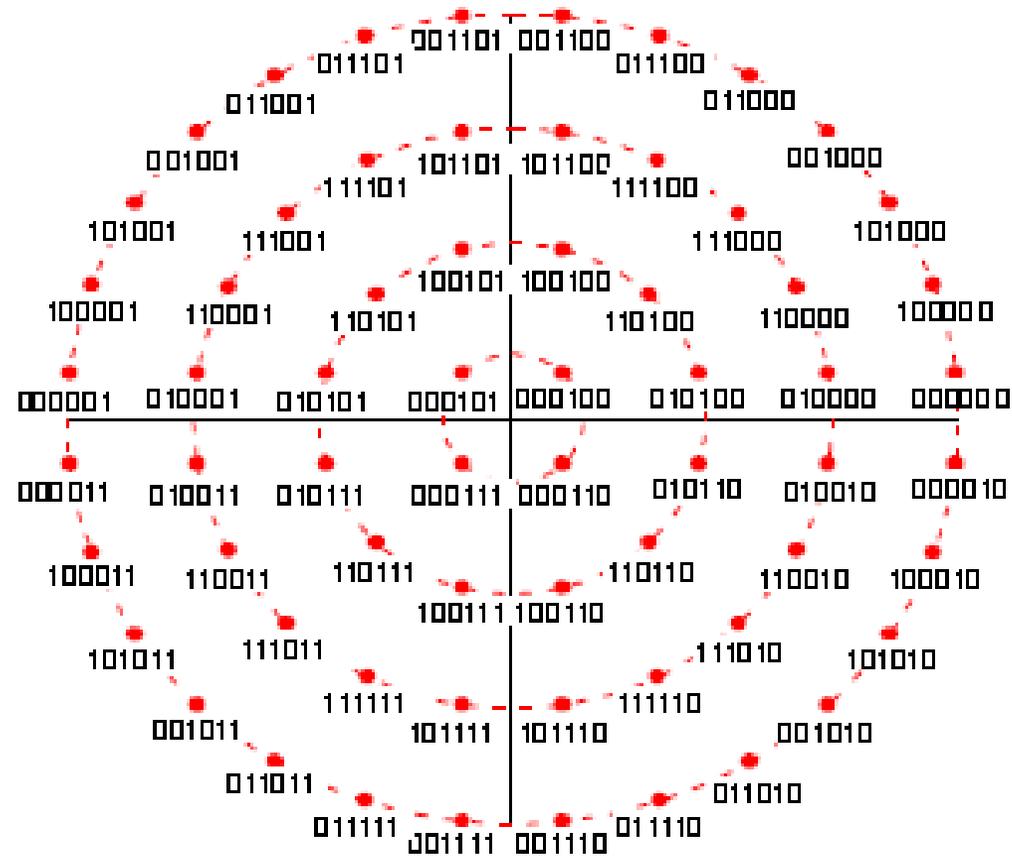
(e) 64-APSK

- The decoder is a maximum-likelihood (Viterbi) decoder with 3-bit soft symbol quantization.
- Well suited for channels with predominantly Gaussian noise that are not bandwidth limited.
- The Rate ½, constraint length (k=7) convolutional code can be modified to achieve an increase in bandwidth efficiency.
- This modification, called puncturing, is achieved by removing some of the symbols before transmission. This provides lower overhead and lower bandwidth expansion than the original code, but with slightly reduced error correcting performance.
- Puncturing allows a single code rate of either 2/3, 3/4, 5/6, or 7/8 to be selected. A rate of 5/6 means that 6 symbols are output for every 5 input bits

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- Add Guaranteed Bit Transitions
- Another Easy Encode/Decode Function!
- $h(x) = x^8 + x^7 + x^5 + x^3 + 1$
- Not Applied to ASM

DATA IN
(Codeblock, Codeword,
or Transfer Frame)

DATA OUT
(Randomized
Codeblock, Codeword,
or Transfer Frame)

X^8 X^7 X^6 X^5 X^4 X^3 X^2 X^1

Pseudo-random
sequence

Initialize to an 'all ones' state for each Codeblock, Codeword, or
Transfer Frame during ASM period

$\oplus$ = Modulo-2 adder
(Exclusive-OR)

$\rightarrow \square \rightarrow$ = Single Bit Delay

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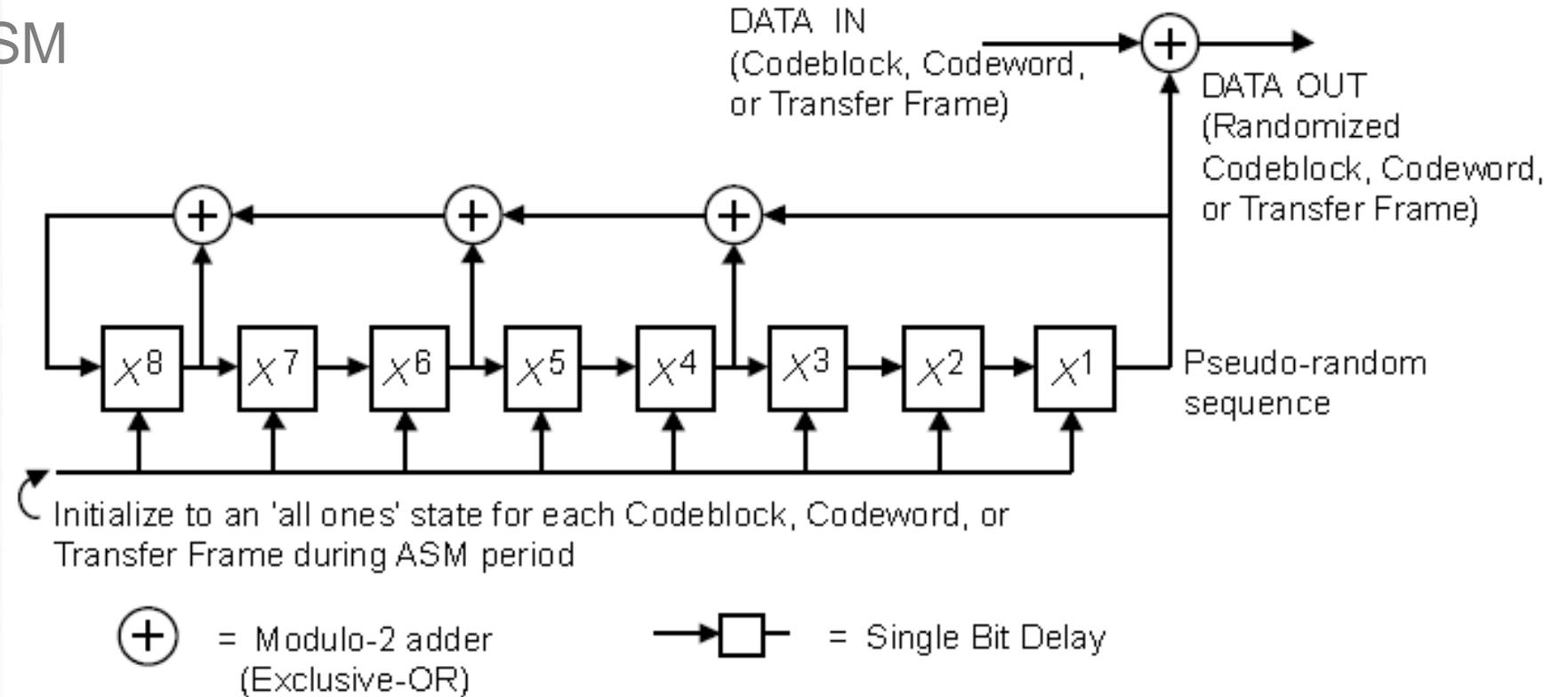
Sync and Channel Coding

- Defines Framing
    - TC, TM, and AOS
    - Synchronization
    - Error-control coding (optional)
    - Pseudo-Randomizing (optional)

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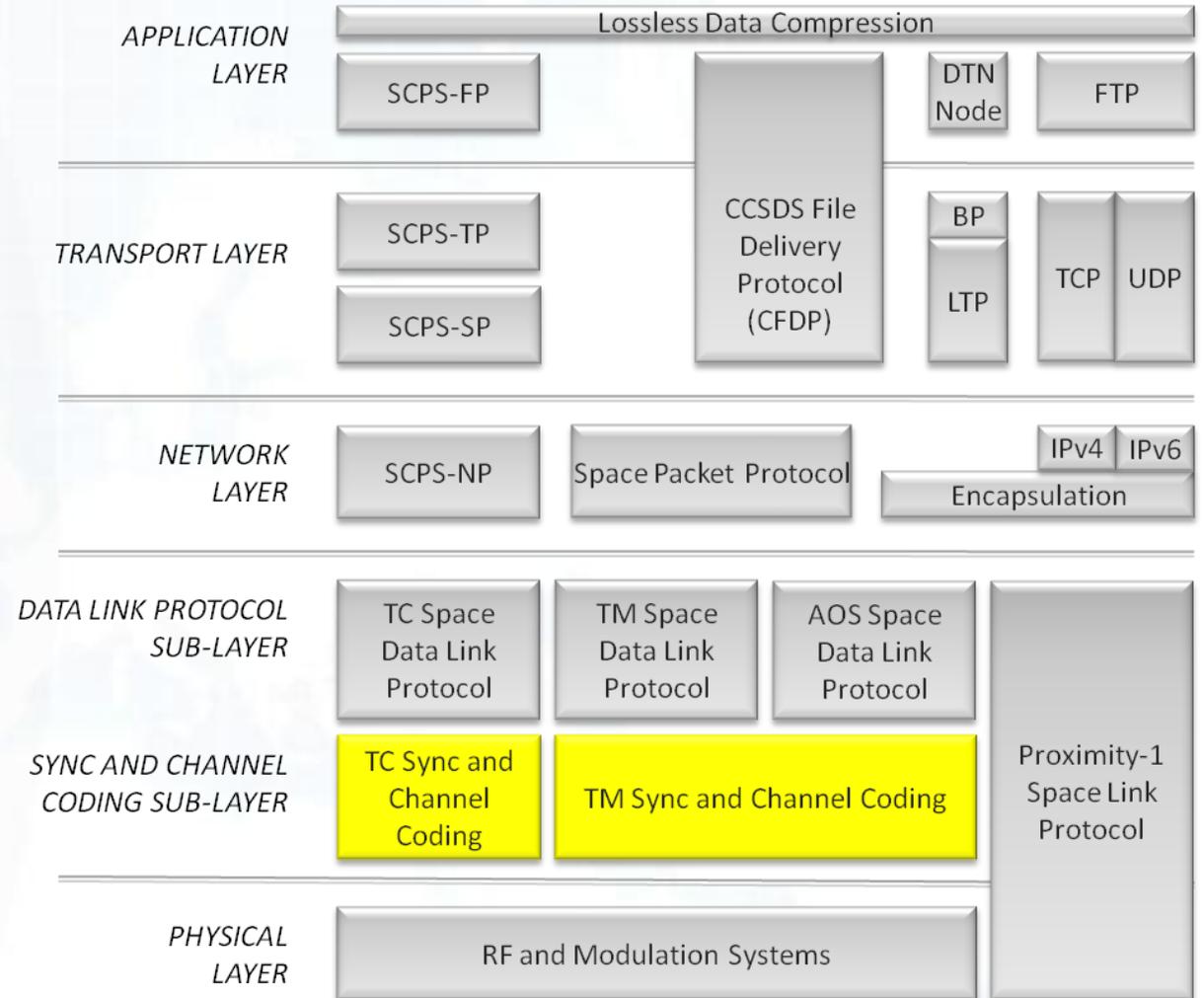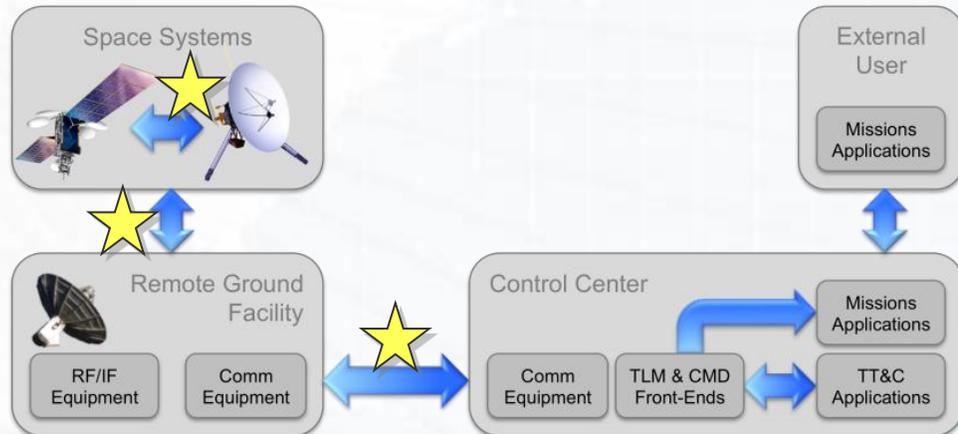
Overview of Link Types

- Telecommand (TC)
  - Commands sent from ground to space vehicle (uplink only)
  - Typically short command bursts at beginning of contact
  - Narrowband (1000 – 2000 bps typical)
  - Guaranteed delivery is imperative
- Telemetry (TM)
  - Payload data sent from space to ground (downlink only)
    - Health & Status
    - Sensor data
  - Carried as continuous fixed-sized frames
  - Wideband capable
- Advanced Orbiting Systems (AOS)
  - Full duplex frames delivery (uplink and downlink)
  - Wide variety of data types
  - Wideband capable in both directions
    - Good for manned space missions or bent-pipe applications
- Proximity-1
  - Simple protocol used for close proximity links (e.g., lander/orbiter, docking maneuvers)

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Telecommand Sync and Channel Coding

- Communication Link Transmission Unit (CLTU)
    - EB90 sync pattern (marks beginning of CLTU)
    - N codeblocks of 40, 48, 56, or 64 bits
    - Tail sequence of 55 55 … 55 or C5 C5 … 79
    - Preamble/Postable part of PLOP
    - Optional randomization
- Error Handling
    - Each codeblock is BCH encoded (1 parity bit per codeblock)
    - Bose, Chaudhuri & Hocquenghem (BCH)
        - Forward Error Correction
        - Simple decode function with low processing power

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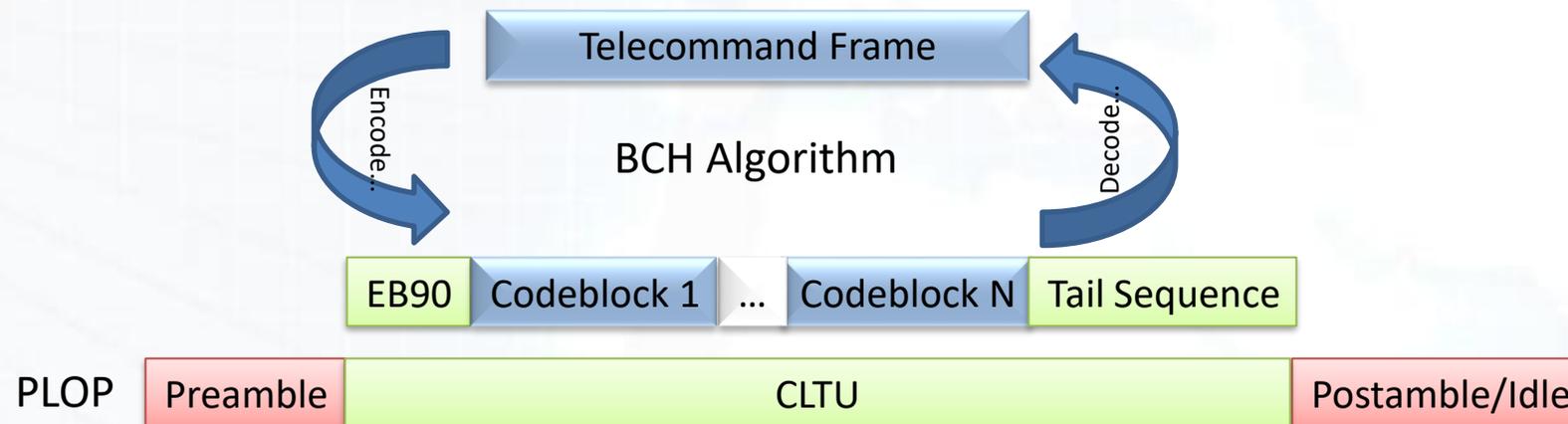
Telecommand Sync and Channel Coding

- CCSDS 131.0-P-1.1 new PINK Book – contains excellent code descriptions
- Defines the Telemetry Sync Word
  - Typically 1ACFFC1D or other PN pattern
  - Byte align serial bit stream into fixed-length blocks
- Transfer-Frame Error Handling Options
  - CRC
    - Provides basic error detection
    - Requires low processing power on-board and on-ground
  - Reed-Solomon
    - Powerful interleaved block code (255/223) corrects 16 bytes * block-depth burst errors
    - Powerful interleaved block code (255/239) corrects 8 bytes * block-depth burst errors
    - Easy on-board encode and medium intensity processing on ground

Sync Word	Frame (fixed size)	R-S Parity

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Frame Synchronization

- Fixed frame length with Attached Sync Marker (ASM) preceding each frame

    - 1ACFFC1D – non-turbo-coded data
    - 034776C7272895B0 – 1/2 turbo coded data
    - 25D5C0CE8990F6C9461BF79C – 1/3 turbo coded data
    - 034776C7272895B0 FCB88938D8D76A4F – 1/4 turbo coded data
    - 25D5C0CE8990F6C9461BF79C DA2A3F31766F0936B9E40863 – 1/6 turbo coded data
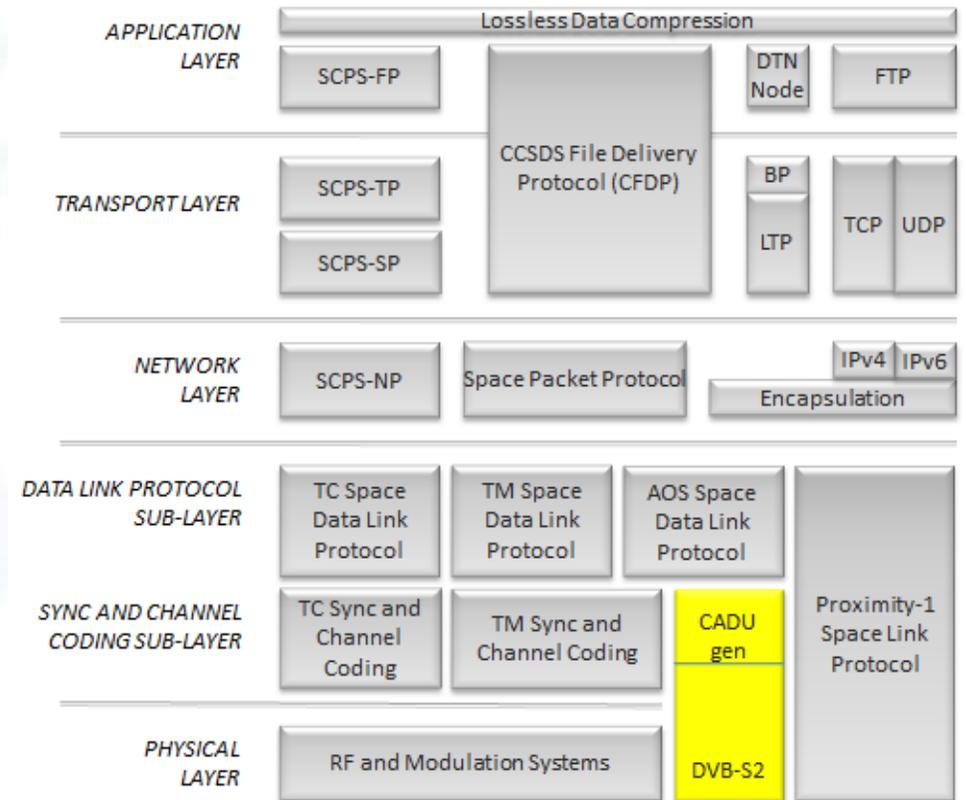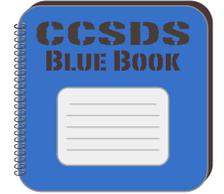   - 353EF853 – Embedded data stream

Stream of Bits

Frame-aligned data

```
Frame Synchronization
(ASM, Frame Length)
```

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Interleaving Forward Error Correction

- Interleave example using Reed-Solomon (255,223)
  - A Reed-Solomon code with an interleave depth of 5 computes parity for each block on every fifth byte of data
  - If the non-interleaved R-S code can correct 16 contiguous octets (128 bits) in error, then the interleaved code can correct 5x16, or 80 contiguous octets (640 bits) in error

Data

Parity

1   2   3   2 2 2   2 2 3   P P P P P

Contains parity for every 5th octet in the data

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- Turbo Codes
  - High-Power Forward Error Correction for Noisy Links
  - Originally Designed for Deep Space Applications
  - Based on Long Random and Arbitrarily Space Codes
  - Very Processing Intensive (on ground)
  - Large Group Delay
- Low Density Parity Check (LDPC)
  - Close to Theoretical Shannon Limit
  - Most Powerful Correction (up to 2.4 dB lower Eb/No compared to Reed-Solomon) Uses Soft-symbols and Blocks
  - Very Processing Intensive (on ground)
  - Good Reference Brief Found in Ref #3

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- New Generation of Digital Video Broadcast coding

- Developed 2003 and ratified 2005

- A powerful coding scheme based on a modern LDPC code. For low encoding complexity, the LDPC codes chosen have a special structure, also known as Irregular Repeat-Accumulate codes.

- BCH Outer code for AWGN – simple decode

- Supports higher order modulations (e.g. 32APSK), IP transport, MPEG4

- VCM (Variable Coding and Modulation) and ACM (Adaptive Coding and Modulation) modes, which allow optimizing bandwidth utilization by dynamically changing transmission parameters.

- CCSDS Blue Book 131.3-B-1

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High Performance FEC (cont.)

- DVB-S2
  - 2nd generation of Digital Video Broadcasting FEC
  - Suited for high data rate transmission
  - Variable or adaptive coding and modulation
  - Bandwidth efficient
  - Supports 4, 8, 16, and 32 PSK/APSK
  - ¼ to 9/10 rate LDPC codes
  - Variable Coding and Modulation (VCM) mode with Telecommand feedback (Can change code rate, e.g. decrease rate when errors reported)
  - Supports use of commercial ASICs and FPGA/VHDL commercially available
  - Patent constraints

- CCSDS and DVB-S2
  - Includes Pseudo-Randomizer
  - Use of attached sync marker ASM, etc. to embed transfer frames into channel access data units CADU with frame validation
  - No alignment of bits needed
  - Can encrypt CADU data
  - May use CRC for final integrity check of transfer frame

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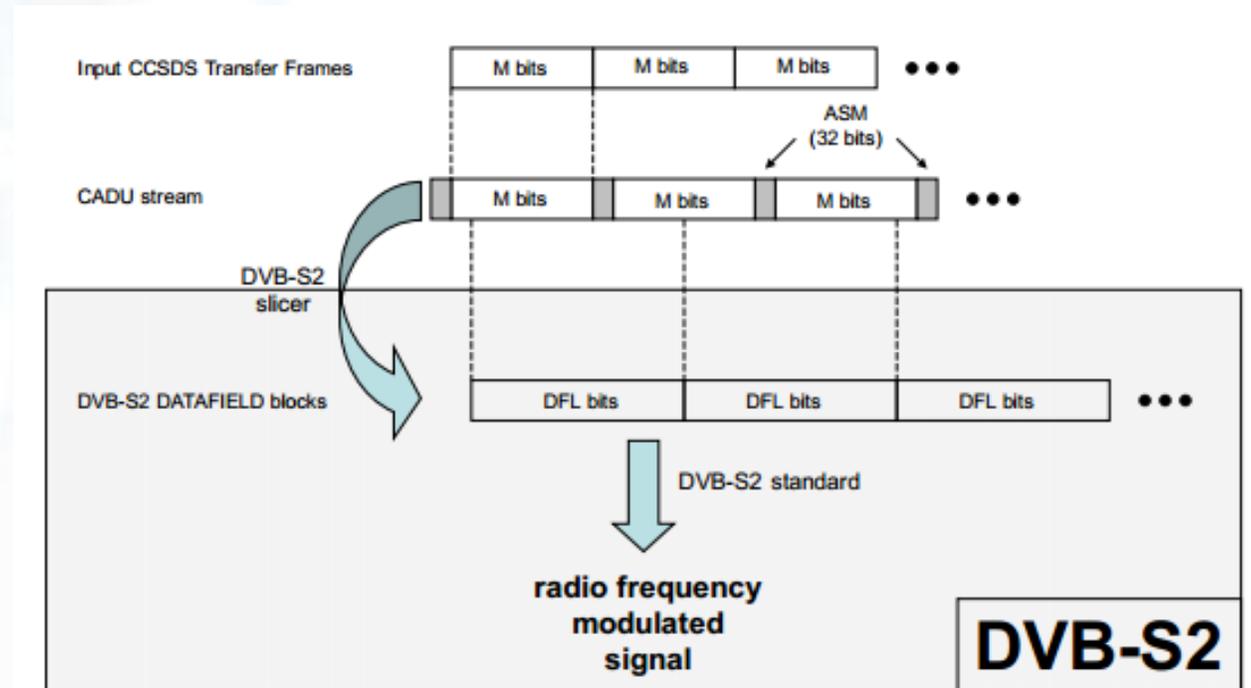
Variable and Adaptive Coded Modulations

- Variability in downlink data rates and modulation order
  - Low rates and lower-order modulations for challenged link
  - Higher rates and higher-order modulations for strong links

- Adaptive coded modulation
  - Measurement of computation of link quality
  - Feedback mechanism to vehicle to change rate and/or modulation

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Variable and Adaptive Coded Modulations

- VCM is a built-in feature of:
  - SCCC codes in CCSDS 131.2-B-1, "Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications," Blue Book. Issue 1. March 2012.
  - BCH+LDC codes in CCSDS 131.3-B-1, "CCSDS Space Link Protocols over ETSI DVB-S2 Standard," Blue Book. Issue 1. March 2013.
- VCM is not feature of
  - Convolutional, RS, concatenated, turbo, and AR4JA/C2 LDPC codes in CCSDS 131.0-B-2, "TM Synchronization and Channel Coding," Blue book. Issue 2. August 2011.
- Status of adaptive coded modulation (ACM):
  - None of the three standards above specify an ACM protocol (although the term "ACM" is used in the Blue Books)
  - This is because these standards relate to *downlink* only. As such, they do not specify a protocol for estimating signal quality or feeding channel-state information back to the spacecraft for the purpose of selecting a new transmission mode.
  - The SCCC and DVB-S2 standards are compatible with ACM: the transmission modes may be modified and the slicer must be able to apply the change without losing Transfer Frames
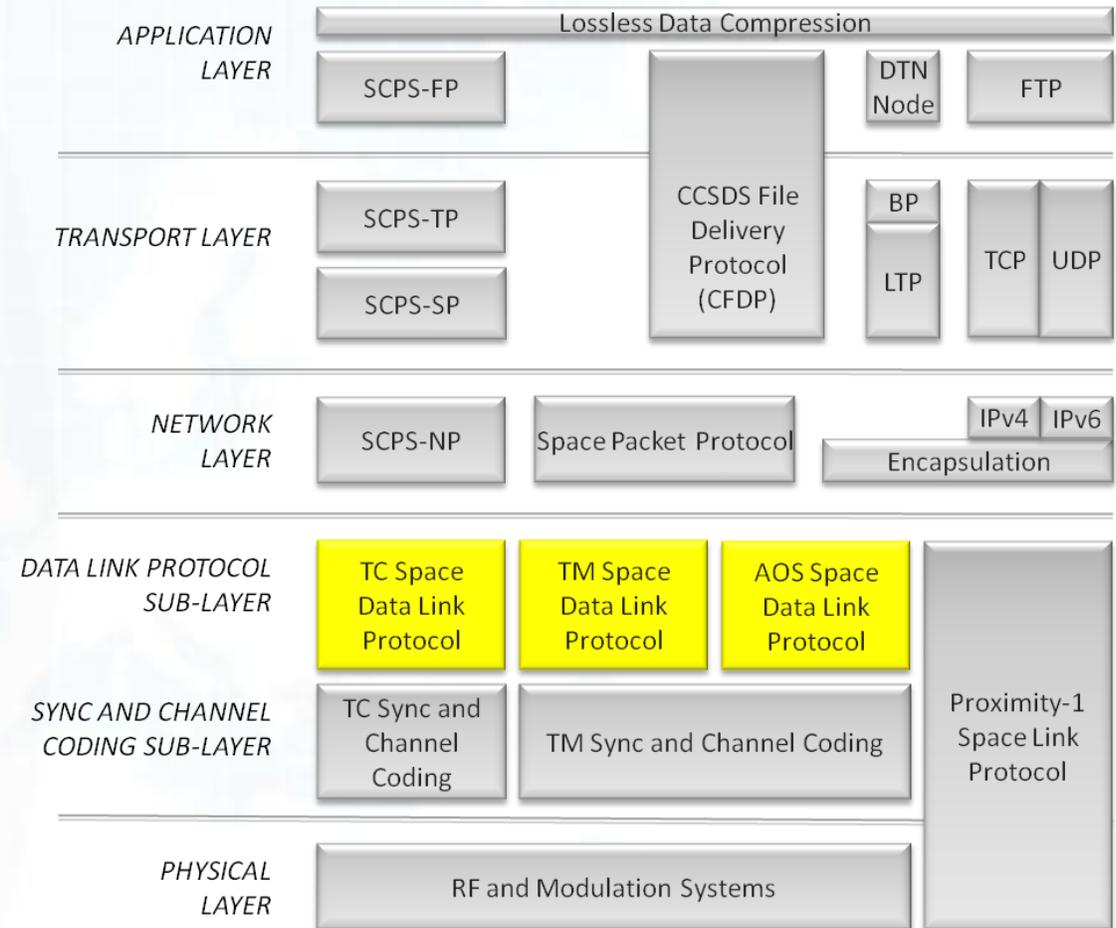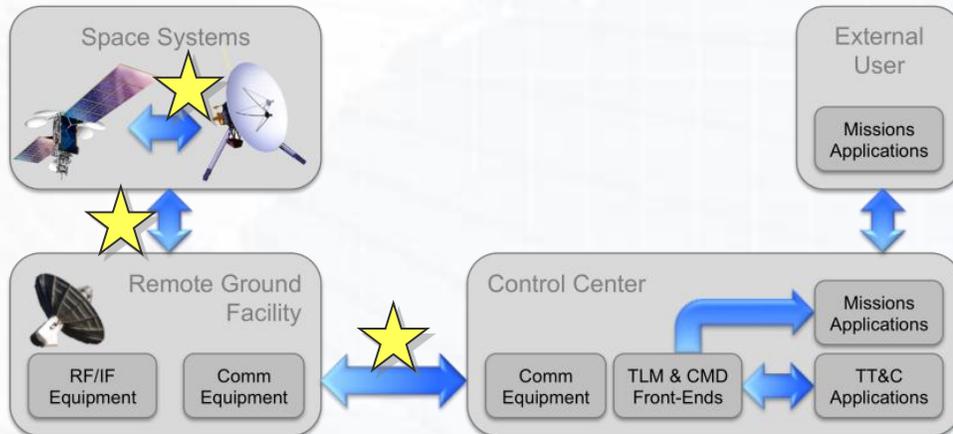
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Telemetry Code Performance

Code Type	Required Eb/No (dB) for 10E-05 BER
PSK – No coding	9.6
Reed Solomon (255/223)	6
Conv. (R1/2,K=7)	4.1
RS + Conv	3.8
RS + Conv Interleaved	2.2
LDPC (8160/7136) / DVB-S2	~0

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Data Link Protocol Sub-Layer

Data Link Protocol

- Defines Frame Contents
  - Standard Headers
  - Virtual Channels
- Defines Telecommanding
  - Structure / Behaviors
  - COP-1

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Telemetry Space Data Link Protocol

- Virtual Channels
  - Provide for multiplexed data on a single physical channel
  - Telemetry is sort-able in 8 or 64 (if AOS) VCDUs, typically related to major payload systems
  - Can have specific Error Detection and Correction algorithms beyond the frame-level
  - Major contents:
    - Filtered data based on Spacecraft ID, Virtual Channel ID etc
  - Provision for Prioritization
  - Commonly used to multiplex major data categories such as TT&C and Mission Data

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Physical Layer Operating Procedures (PLOPs)

- Defined in CCSDS 201.0-B-2 to specify the sequences required to uplink 'TC Data' to a space vehicle
- Carrier Modulation Modes
  - CMM-1 – Unmodulated CARRIER only
  - CMM-2 – CARRIER modulated with ACQUISITION SEQUENCE
  - CMM-3 – CARRIER modulated with TC data (e.g., CLTU)
  - CMM-4 – CARRIER modulated with IDLE SEQUENCE

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Data Link Channel Multiplexing

- Transfer Frame Version Number (TFVN) – Only one per physical Channel
- Spacecraft Identifier (SCID) – Alias: Master Channel – Typically one per physical channel, but more than one is feasible
- Virtual Channel Identifier (VCID) – Typically used to multiplex data types (e.g., TT&C, Mission data)
- Multiplexer Access Point Identifier (MAPID) – Another optional multiplexing layer used for Telecommand only

MAP Channel (TC only; Optional):
Identified by MAP ID

Virtual Channel (VC):
Identified by VCID

Master Channel (MC):
Identified by MCID=TFVN=SCID

Physical Channel:
Identified by Physical Channel Name

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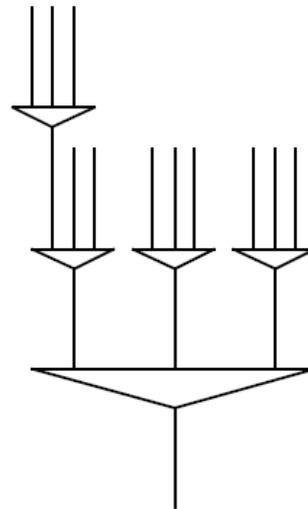
Telecommand Space Data Link Protocol

- Telecommand (TC) Frame
  - TC Frame is the data link Protocol Data Unit (PDU) that is decoded from the sync a channel coding sublayer's CLTU
- Fields:
  - Primary header
  - Data
  - Error control word (CRC)

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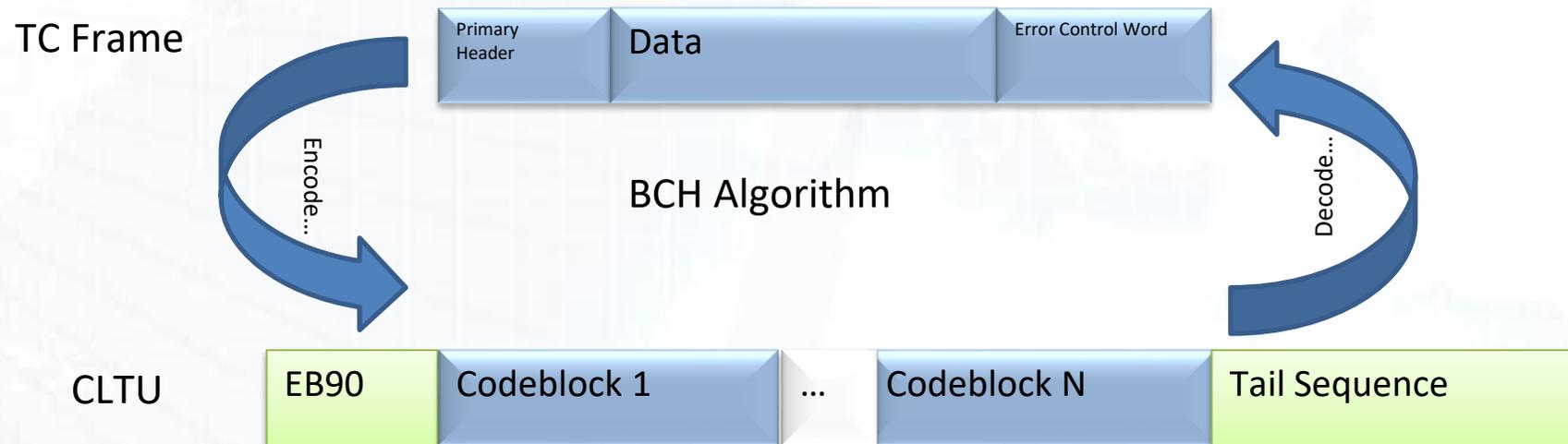
Telecommand Header Structure

- Primary Header
  - Version Information
  - Flags, Lengths, Sequence Numbers
  - Spacecraft & Channel IDs
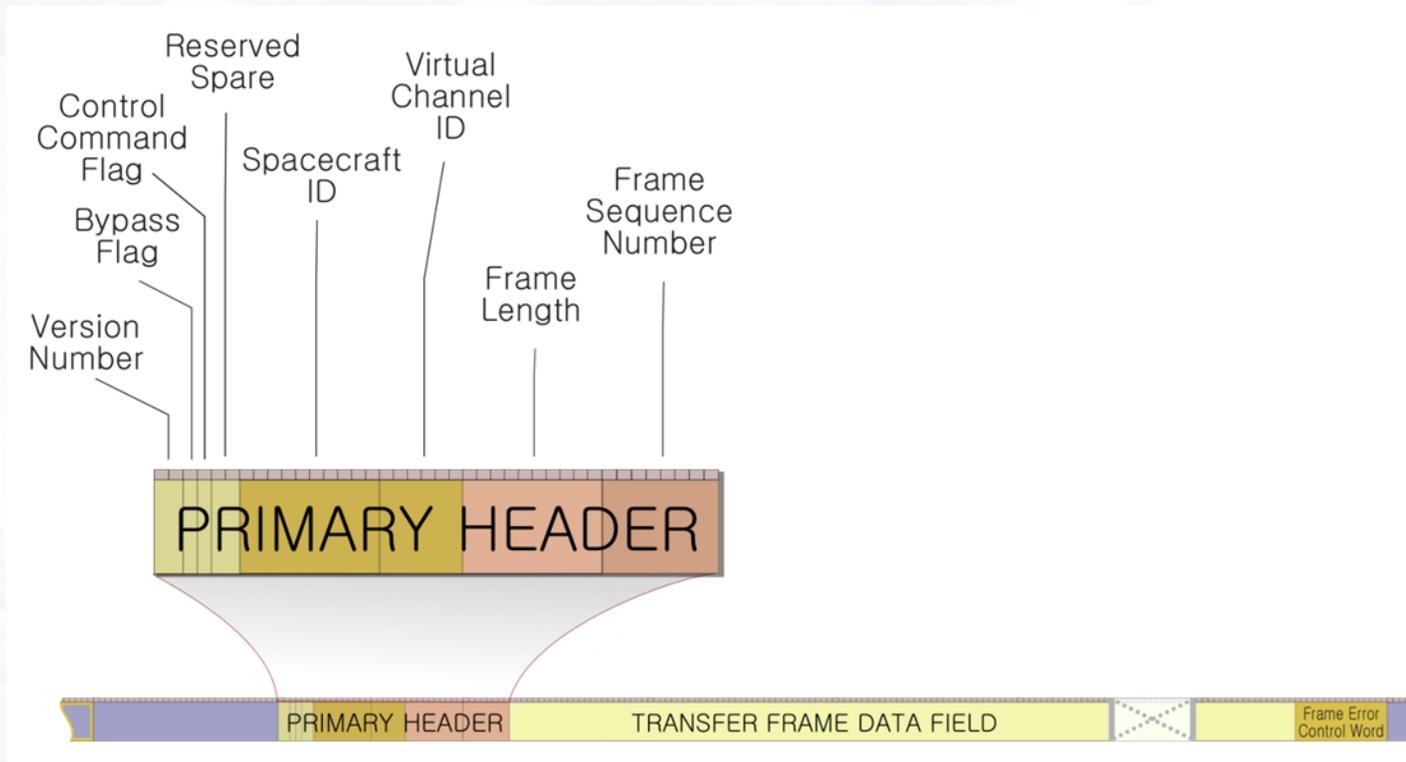
- COP-1 is a closed-loop TC protocol with a sequential ("go-back-n") retransmission technique to correct spacecraft rejected frames.
  - o The transmitting (ground) portion of the COP-1 protocol is called the Frame Operating Procedure (FOP).
  - o Frame Acceptance and Reporting Mechanism (FARM) is the spacecraft portion of COP-1
  - o The transmitting segment (FOP) is the ground portion of COP-1. FOP sequences the transmitted frames.
  - o Command Link Control Word (CLCW) is the frame acceptance status send back in the Operation Control Field (OCF) of the downlink telemetry frame.
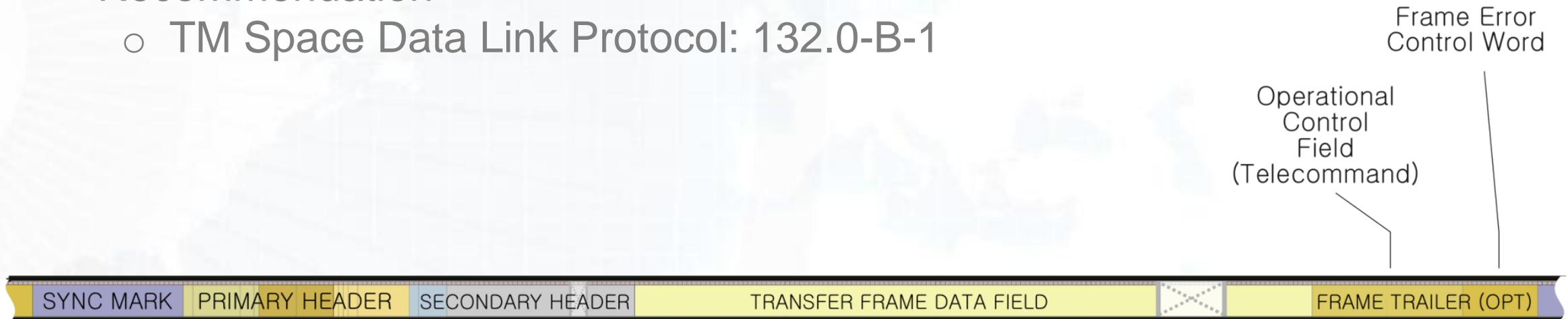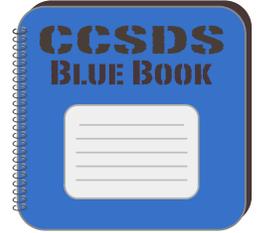
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- COP-1 Commanding Provides for Retransmitting Type A Frames
  - Uses a sliding window to support retransmit when necessary

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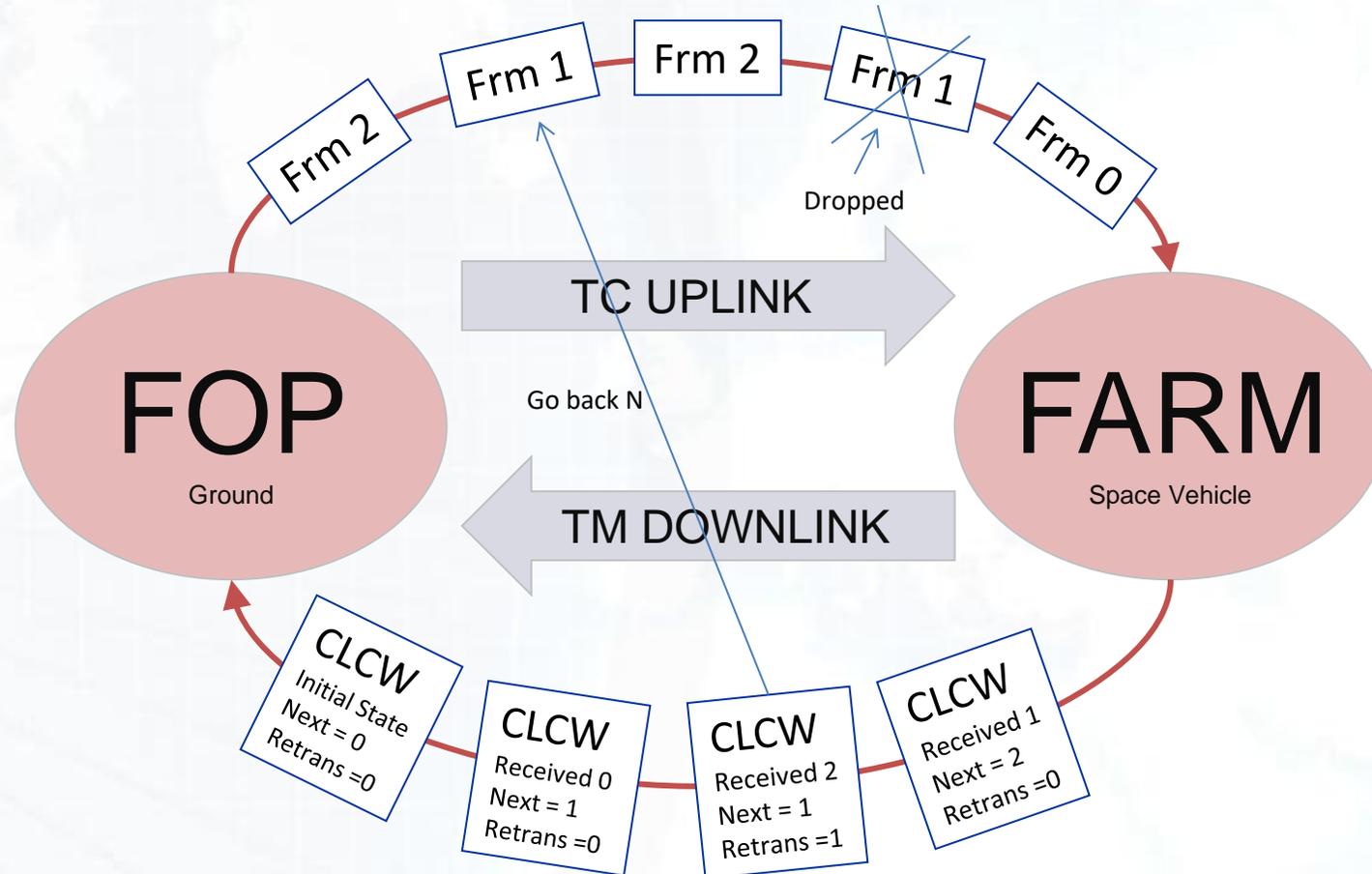
Telemetry (TM) Frame Structure

- Telemetry Structure Provides for Flexibility
  - Primary Header: Flags, Lengths, Counters, Points
  - Secondary Header: (Optional) User-Defined Data Fields
  - Transfer Frame Data Field: Where the Data Goes
  - Frame Trailer: (Optional) Telecommand & Error Correction
- Recommendation
  - TM Space Data Link Protocol: 132.0-B-1

Frame Error Control Word

Operational Control Field (Telecommand)

| SYNC MARK | PRIMARY HEADER | SECONDARY HEADER | TRANSFER FRAME DATA FIELD | | FRAME TRAILER (OPT) |

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TM Frame Header Structure

- Primary Header
  - Identifies spacecraft, virtual channel and contents of the data field
- Secondary Header
 - User defined, per-frame content

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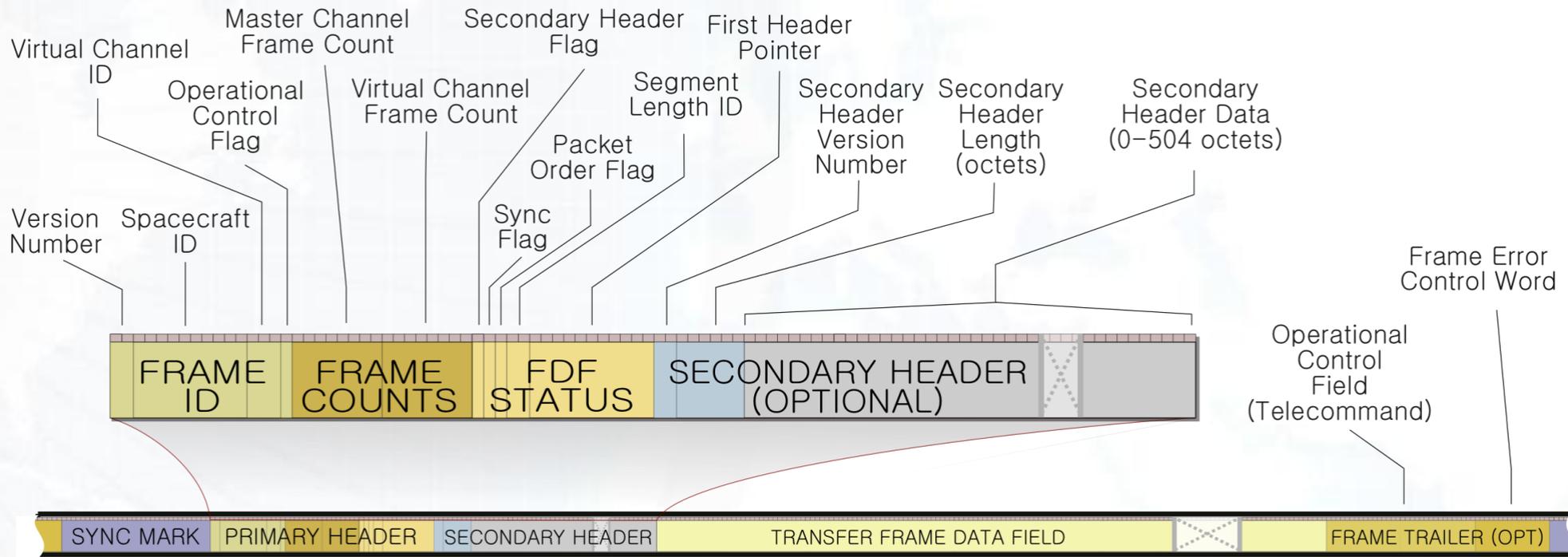
KR⬥TOS

- AOS Space Link Data Protocol Accounts For:
  - More complex payloads and need more virtual channels
  - Quality of service provisioning
  - Space Station and Relay Satellite compatibility
  - Spacecraft constellations
  - VC transport through other spacecraft
  - Private encrypted data block support
  - Audio, Video, high-rates, varying latencies, bit-stream service, multiplexing (MPDUs), recording
  - AOS Insert of small fixed-length data blocks (e.g. audio)
- Still Supports CCSDS Packets
  - Not backwards compatible, but identified by version
  - Treated as a separate service
- Not As Self Describing As Previous Version Of TM

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- Primary Header
  - Similar to TM Frame header
- No Secondary Header Per-Se
  - Now a generic 'Insert Zone'
- First Header Pointer not part of header
 - Allows for various upper-layer data types (not just space packets)

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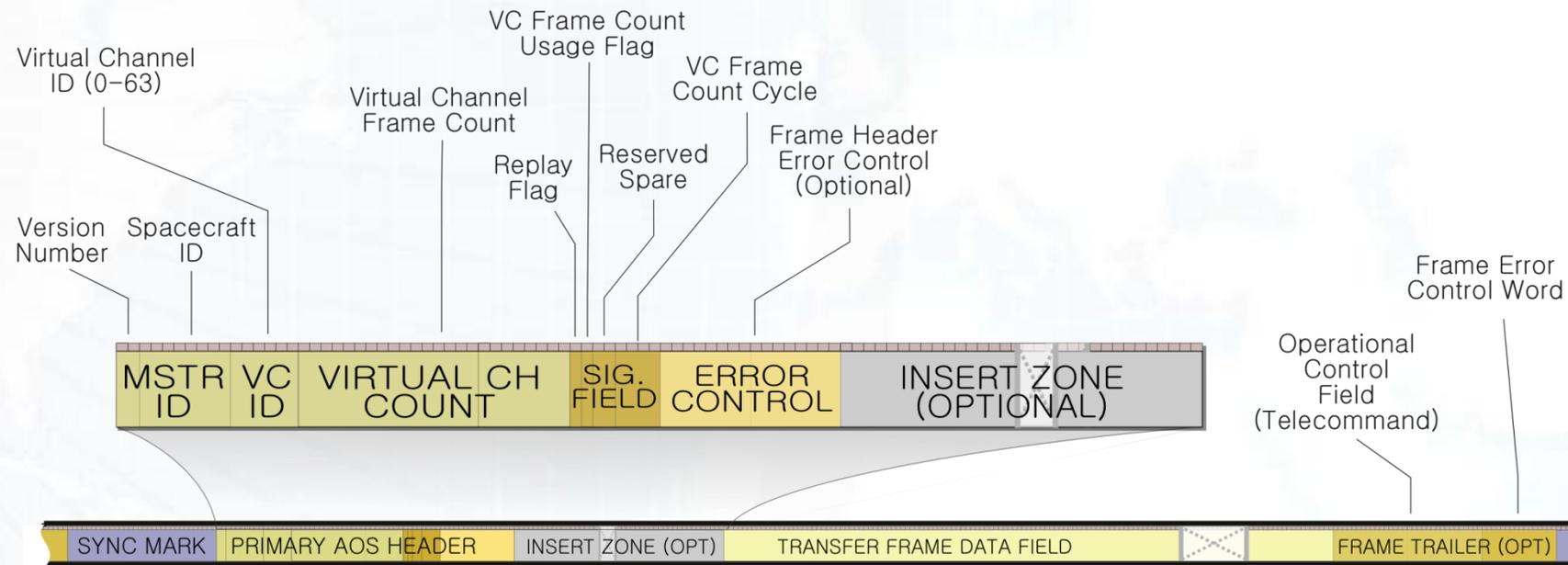
Proximity-1

- Space Link Protocol
- Close-proximity networks
- Considerations
  - Power
  - Reliability

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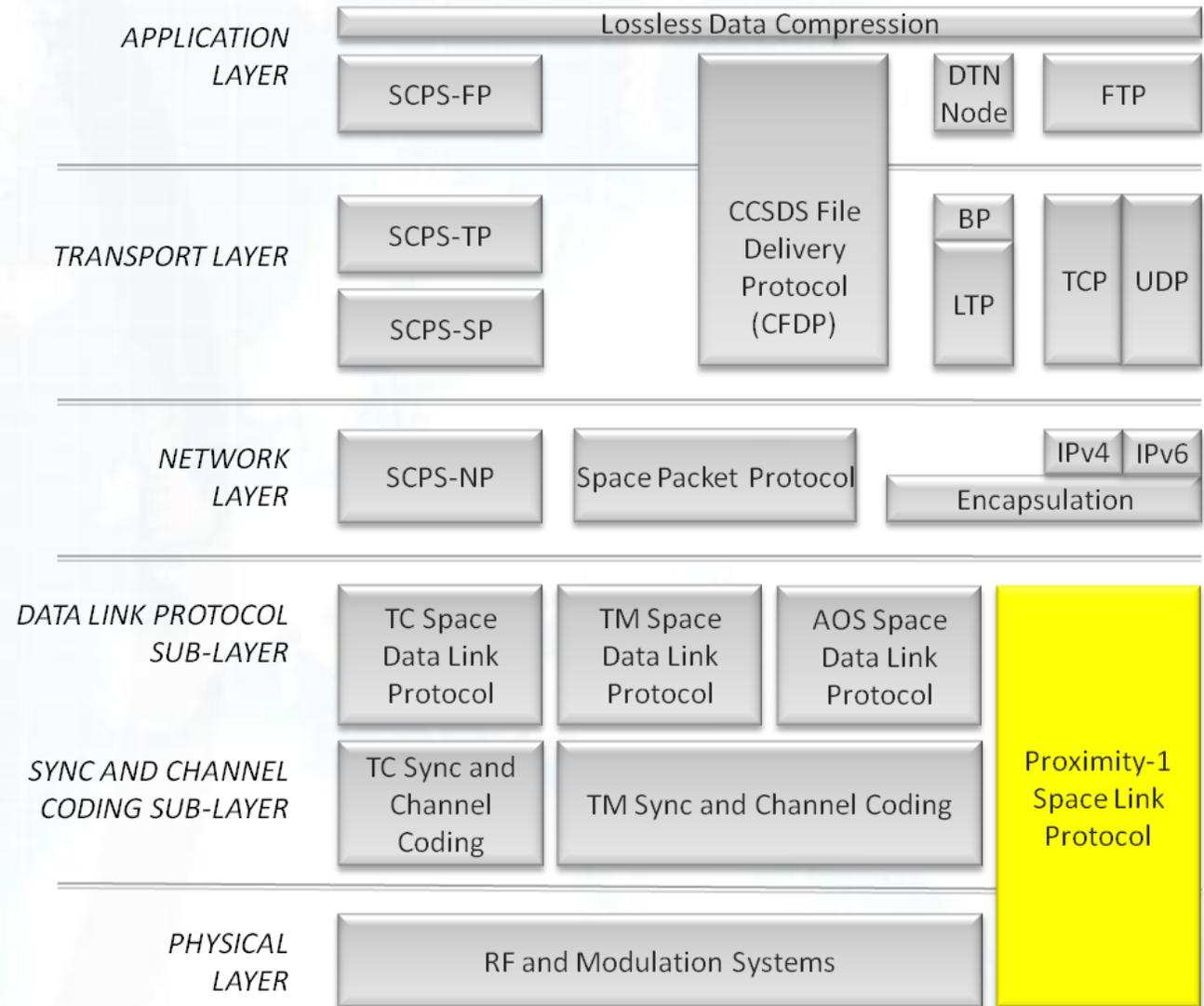
Proximity-1: Space Link Protocol

- Used for Close Proximity Networks in Space
  - Spacecraft to spacecraft
  - Spacecraft to remote sensors
  - Spacecraft to rovers
  - Rovers to other remote device networks
- Features
  - Low power – and simple CRC implemented with shift registers
  - Quality of Service provisioning
  - Spacecraft, Payload, Source, Destination and Port Identifiers
  - Optional Convolutional Code
  - Variable-length frames

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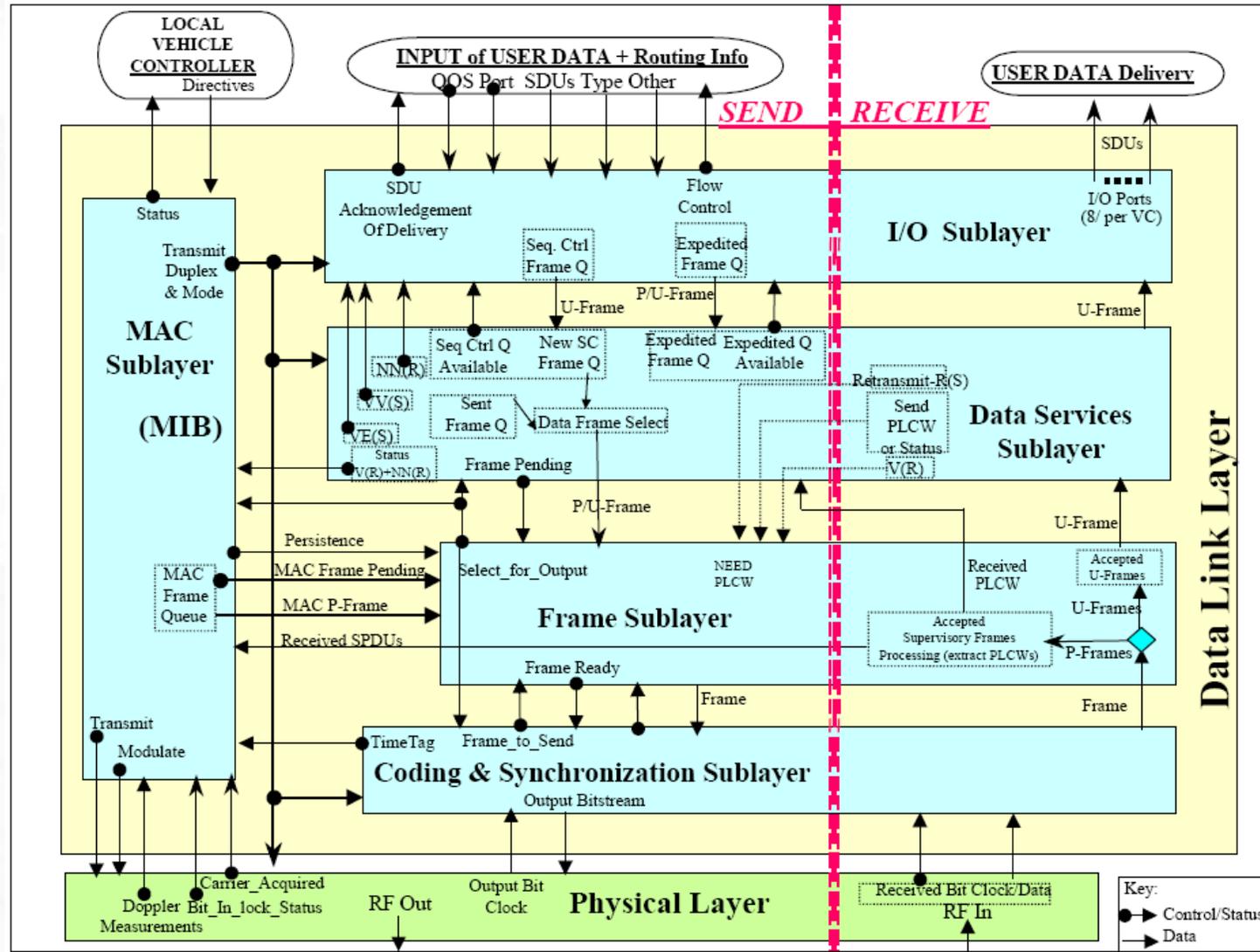
Break
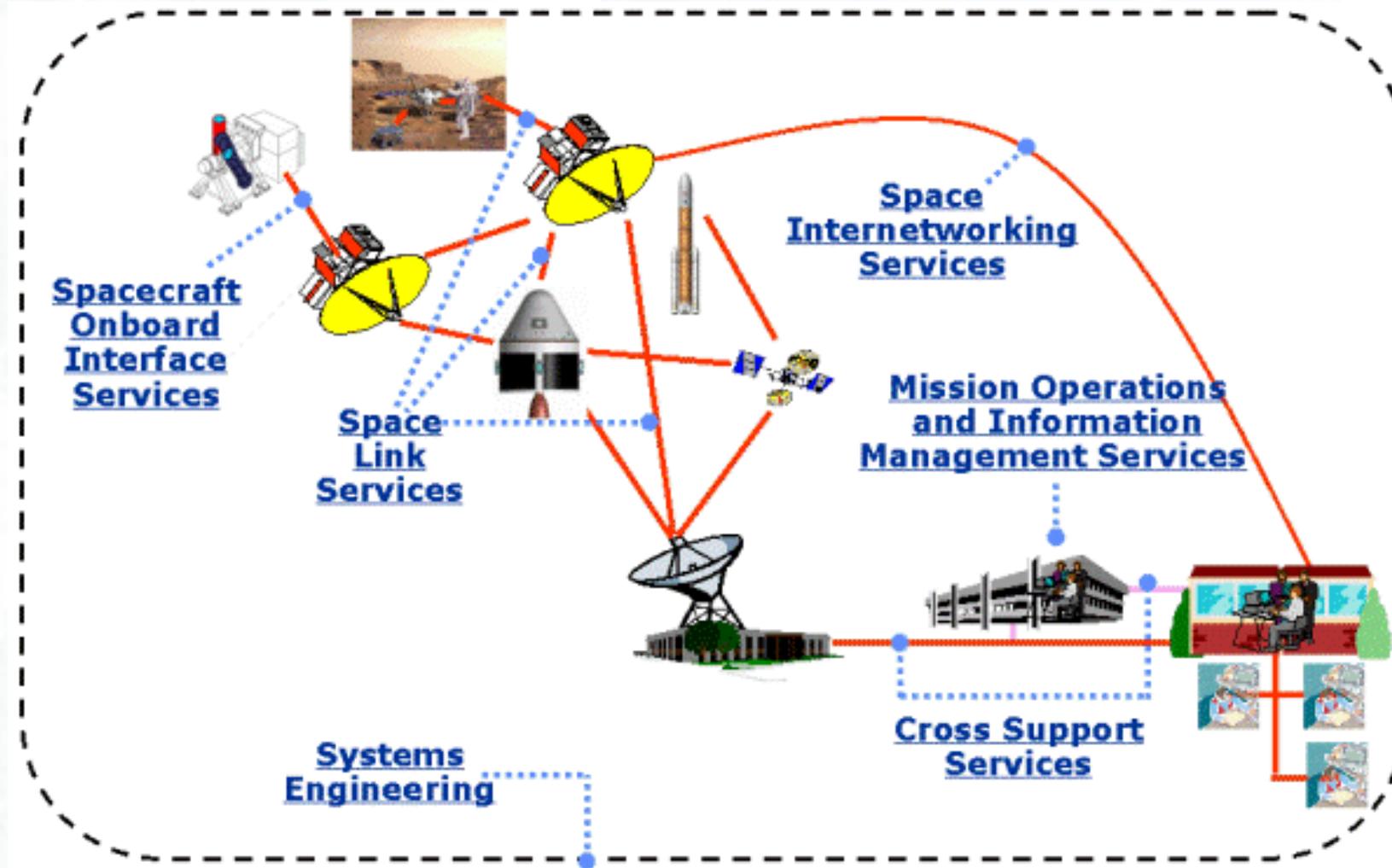
Will return at:

Laser/Optical Communications

KR⬢TOS®

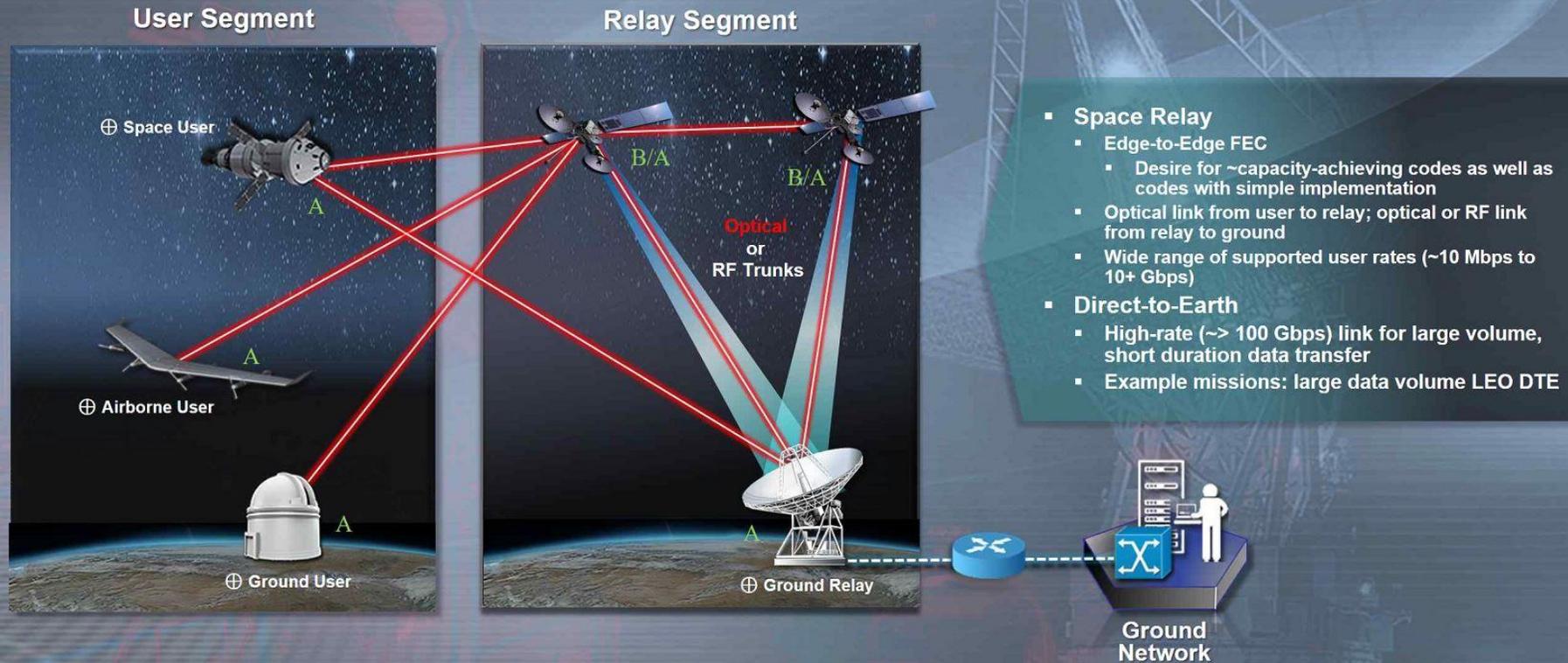## SLS Optical Communications Working Group

Scope – (1) Physical, coding, and synchronization layer recommendations for the interoperability of flight and ground optical communications terminals; (2) Recommendations for characterizing the atmosphere channel and for the concept of operations for space-to-ground links

- The Working Group has been investigating the following scenarios or "needs" for optical communications:
  - High Data Rate
  - High Photon Efficiency
  - Low Complexity
- Current Efforts
  - Blue Book: Optical Communications Physical Layer: Will cover the High Photon Efficiency and Low Complexity Recommendations
  - Blue Book: Optical Communications Coding and Synchronization: Will cover the High Photon Efficiency and Low Complexity Recommendations
  - Green Book: Atmospheric Characterization For Optical Communication Systems
  - Magenta Book: Atmospheric Characterization and Forecasting for Optical Link Operations (Just Starting)
  - NASA/CNES/JAXA/NICT Orange Book: Optical High Data Rate Communications – 1550 nm
  - ESA/DLR Orange Book: Optical High Data Rate Communications – 1064 nm
- Opportunities for Industry
  - If building systems for others, then standards will allow common hardware and software components across agencies, academia, and and commercial space optical communications systems, including both flight and ground optical terminals
  - If using the technology, then optical communications will allow increase data rates, increase security, and a much lower probability of being jammed
  - Optical communications is currently unregulated and provides "limitless" bandwidth when compared to RF systems
  - Low Probability of Intercept / Low Probability of Detection
  - Anti-Jam

KRATOS

SLS High Data Rate Optical Space Communications

User Segment

- Space User
  - A
- Airborne User
  - A
- Ground User
  - A

Relay Segment

- B/A
- B/A
- Optical or RF Trunks
- A
- Ground Relay

Ground Network

- **Space Relay**
  - Edge-to-Edge FEC
    - Desire for ~capacity-achieving codes as well as codes with simple implementation
  - Optical link from user to relay; optical or RF link from relay to ground
  - Wide range of supported user rates (~10 Mbps to 10+ Gbps)
- **Direct-to-Earth**
  - High-rate (~> 100 Gbps) link for large volume, short duration data transfer
  - Example missions: large data volume LEO DTE

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SLS High Photon Efficiency Optical Space Communications

Attributes:
- Long-distance
- Photon-starved channel
- Direct-detection

KRATOS
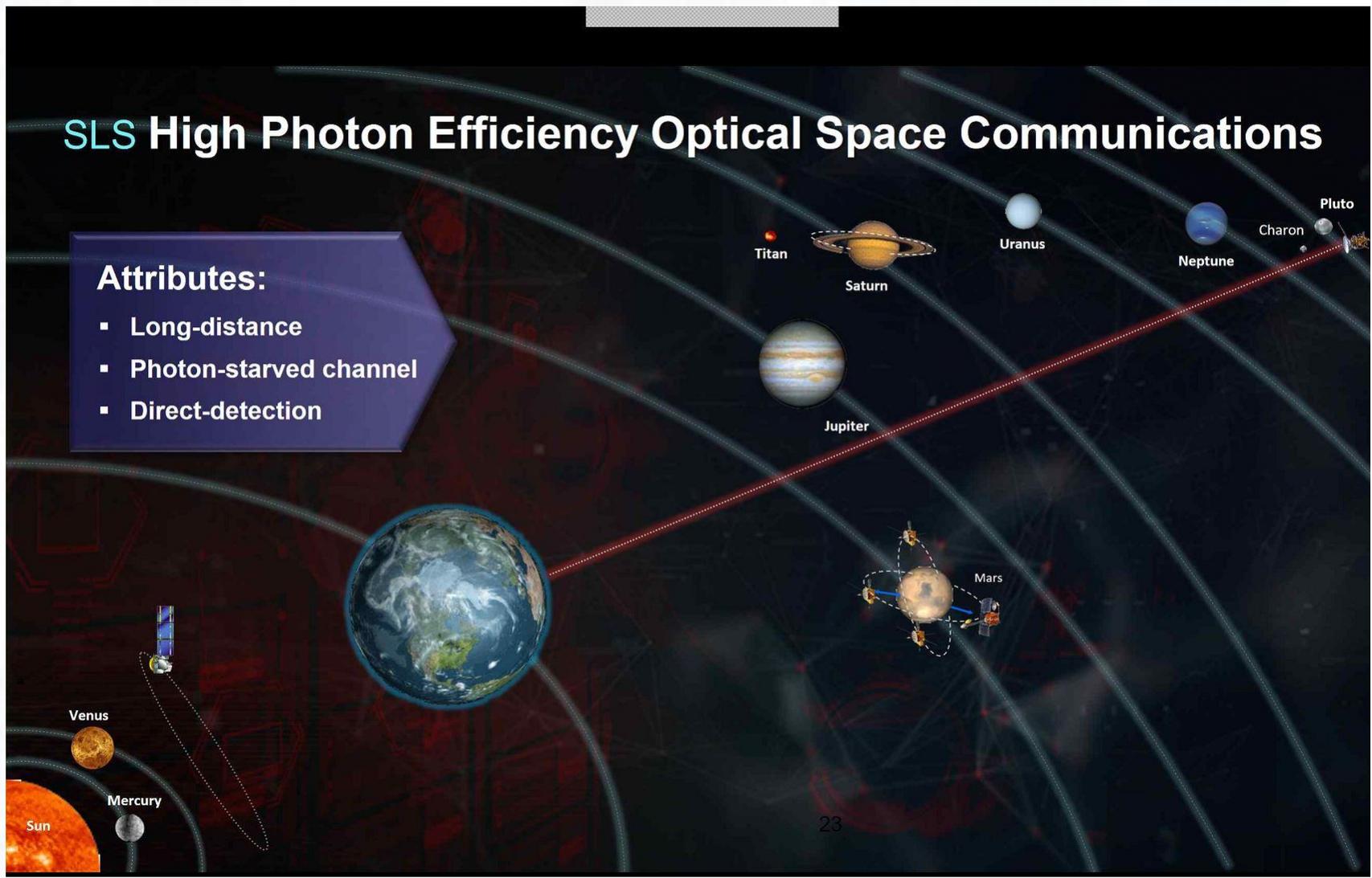
SLS Atmospheric Characterization and Prediction for Optical Space Communications

CCSDS Books will:

- Provide a narrative on atmospherics and explain why it's critical to accurately characterize

- Develop content regarding how long-term statistics of atmospherics are used to choose an optimal network of geographically diverse ground sites

- Provide content on the required instruments and parameters to support long-term site characterization and real-time decision making

Clouds are Primary Source of Attenuation

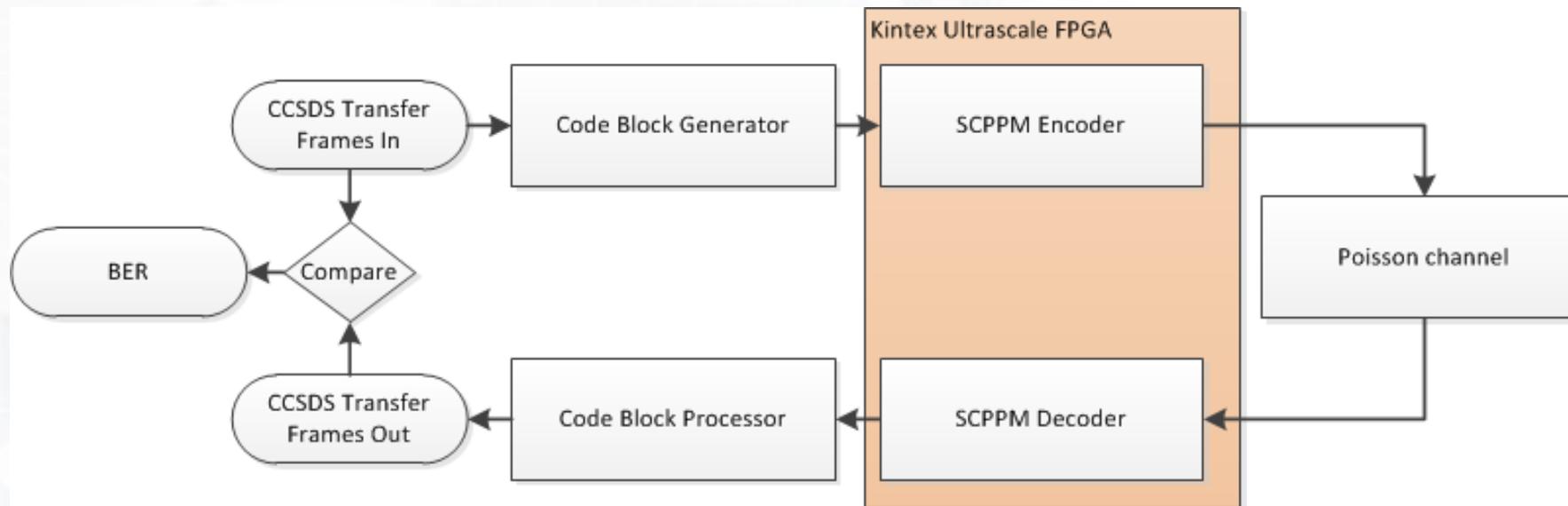GEO Sats

LEO Sats

GEO Sats

Turbulence

Dust

Clouds
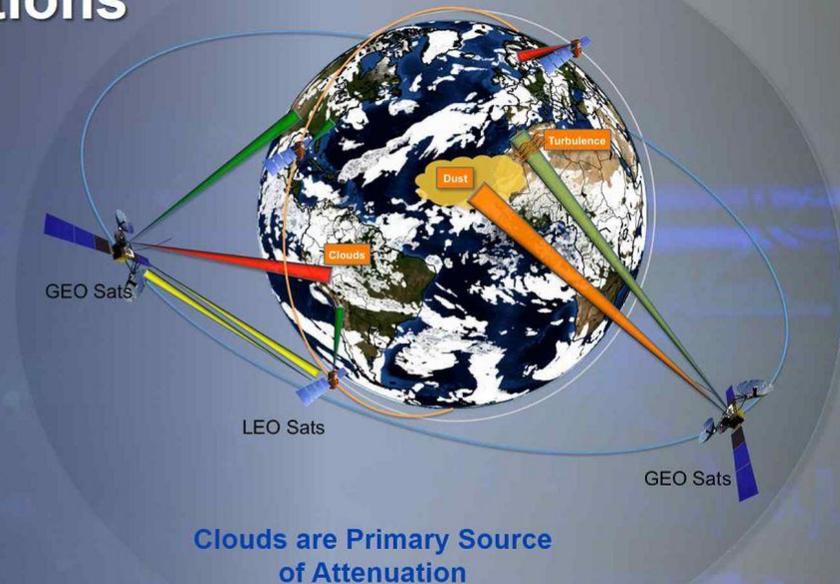
Characterization and prediction of the atmospheric channel is critical to inform Space link handovers, select ground sites, and to maximize systems availability

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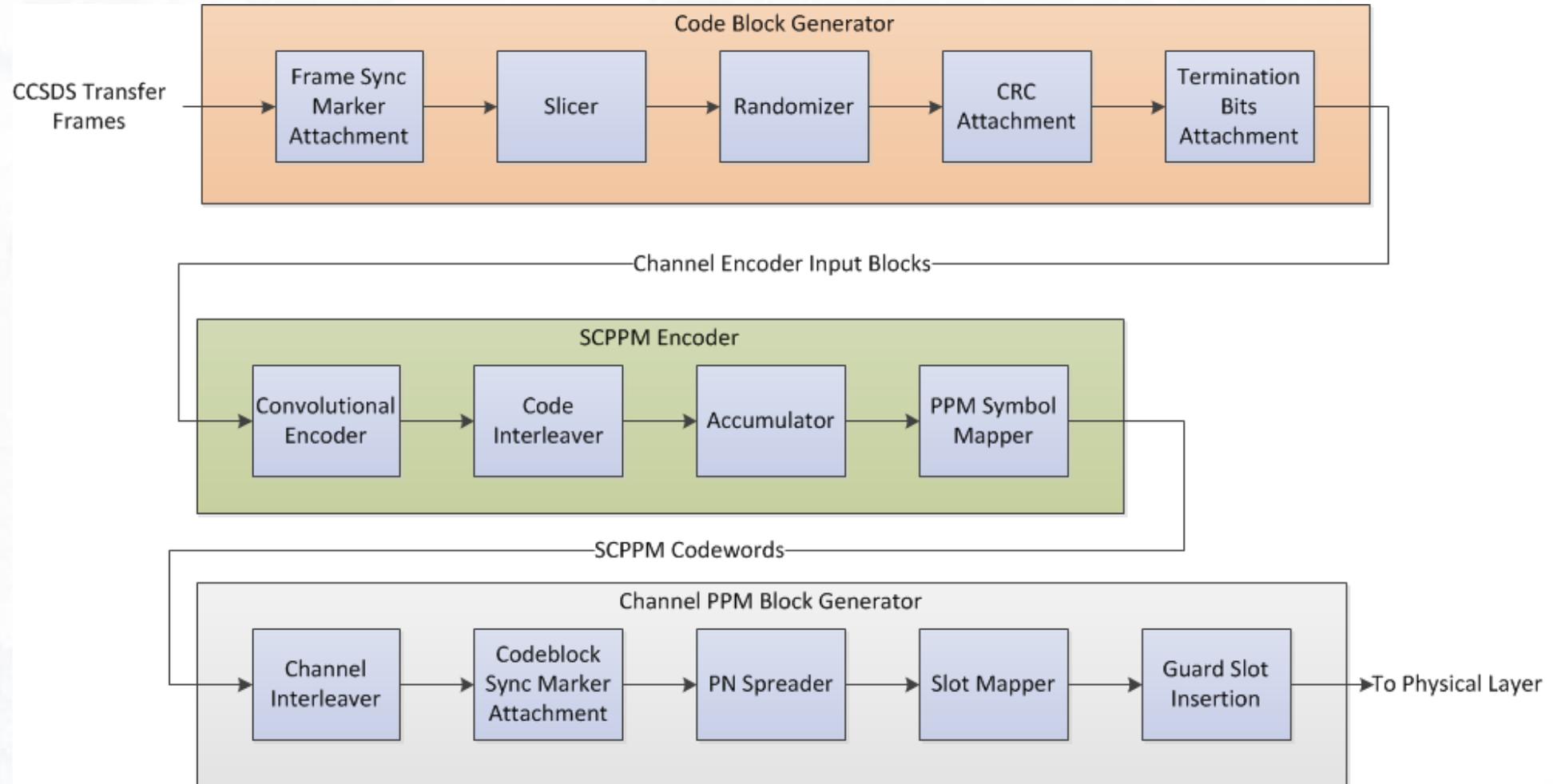
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Optical Comm Standards

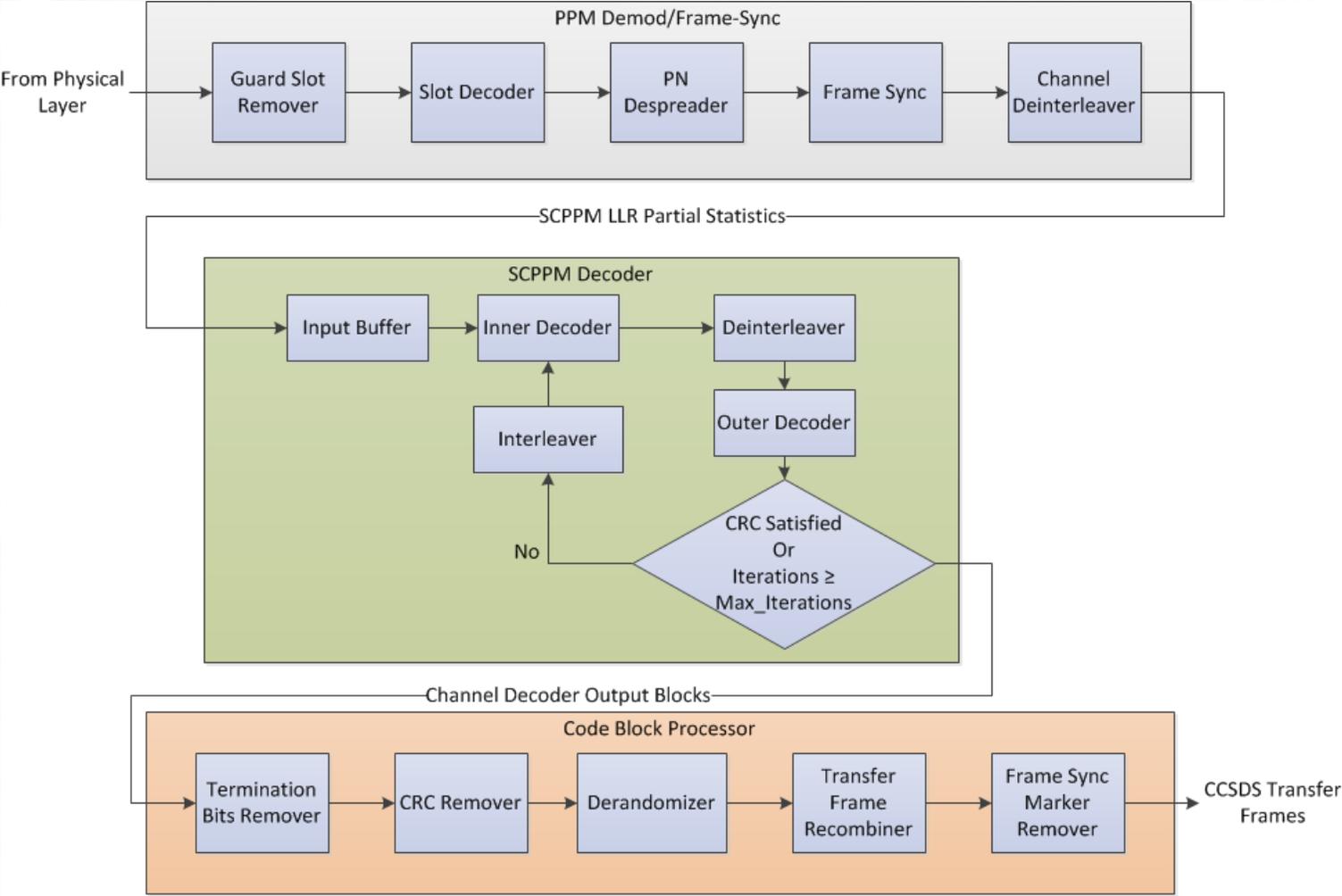| Standard/Need	Type	Data Rate	Modulation	Interleave	Randomizer	FEC
PSK (Standard RF Modem)	PSK	0.01- 4Gbps	BPSK - 32APSK	Block, Convolutional	Yes	CCSDS LDPC, DVB-S2 LDPC, Reed Solomon, Viterbi, Stack Viterbi
CCSDS Low Complexity (TBD)	LC	<10Gbps	OOK	Convolutional	TBD	LDPC, DVB-S2 with multiple code rate options
CCSDS High Photon Efficiency Draft Red Book, May 2017	HPE	0.225 – 528 Mbps	SCPPM	Convolutional	Yes	SCPPM 1/3, ½, 2/3
CCSDS High Data Rate Draft Orange Book, Apr 2017	HDR	2812.5 Msps	BPSK	Block (Reed Solomon)	Yes	LPC – Line Product Code. Muxed CADU of RS, Interleave, Scrambled
LCRD (SBU)	Parameters are Sensitive But Unclassified					
Orion (FOUO)	Parameters are For Official Use Only					

KRATOS®

- Serial Concatenated Pulse Position Modulation
- General purpose SCPPM encoder and decoder that can be configured in real-time
  - Convolutional rates 1/3, 1/2, and 2/3
  - PPM orders of 4, 8, 16, 32, 64, 128, and 256
  - SCPPM encoder and decoder algorithms hosted on Xilinx Kintex® Ultrascale (XCKU060)
- Complies with CCSDS White Book: High Photon Efficiency Optical Communications Coding & Synchronization, May 2017
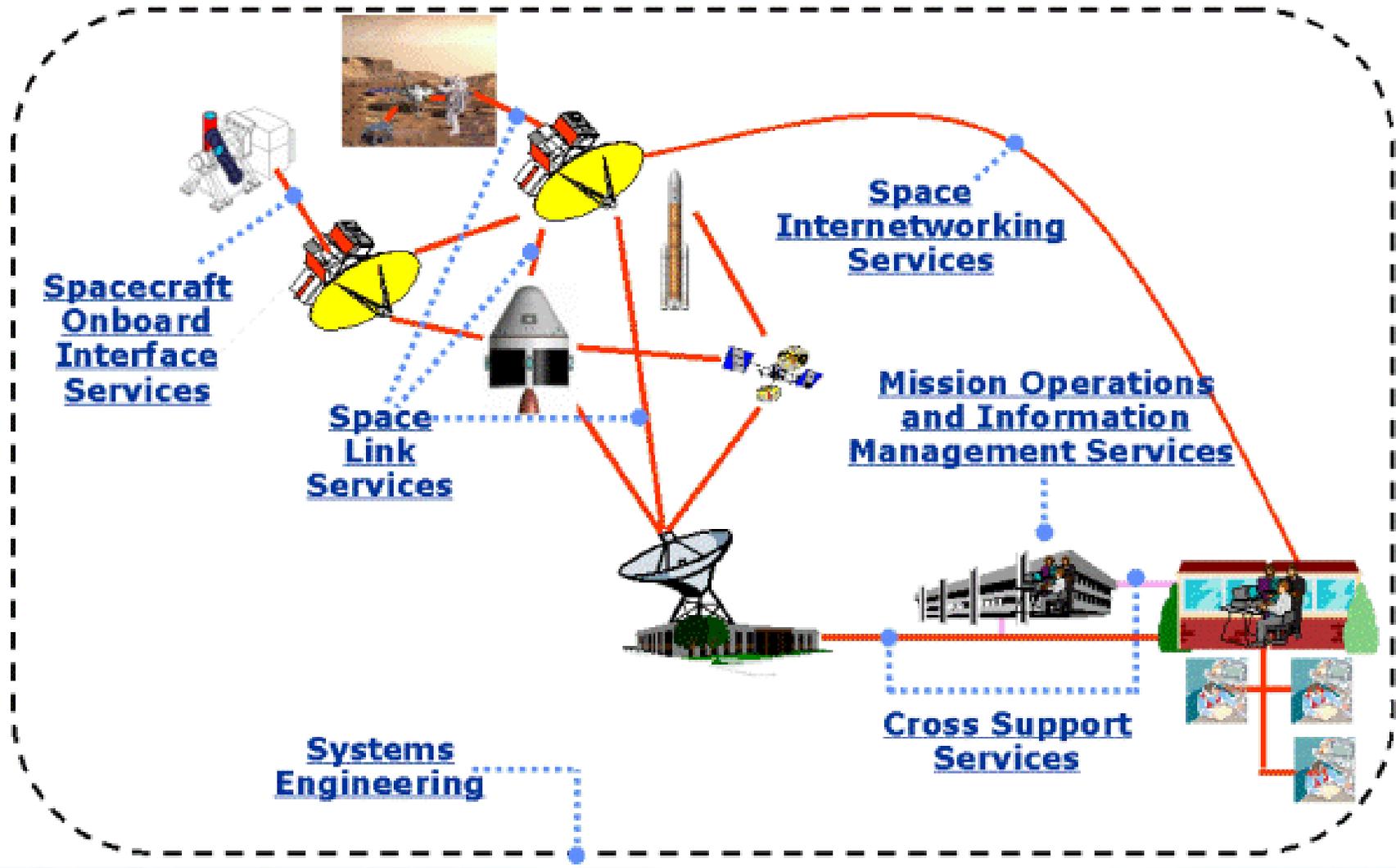
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Downlink Data Flow

KRATOS

Spacecraft Onboard Interface Services

Space Link Services

Space Internetworking Services

Mission Operations and Information Management Services

Cross Support Services

Systems Engineering
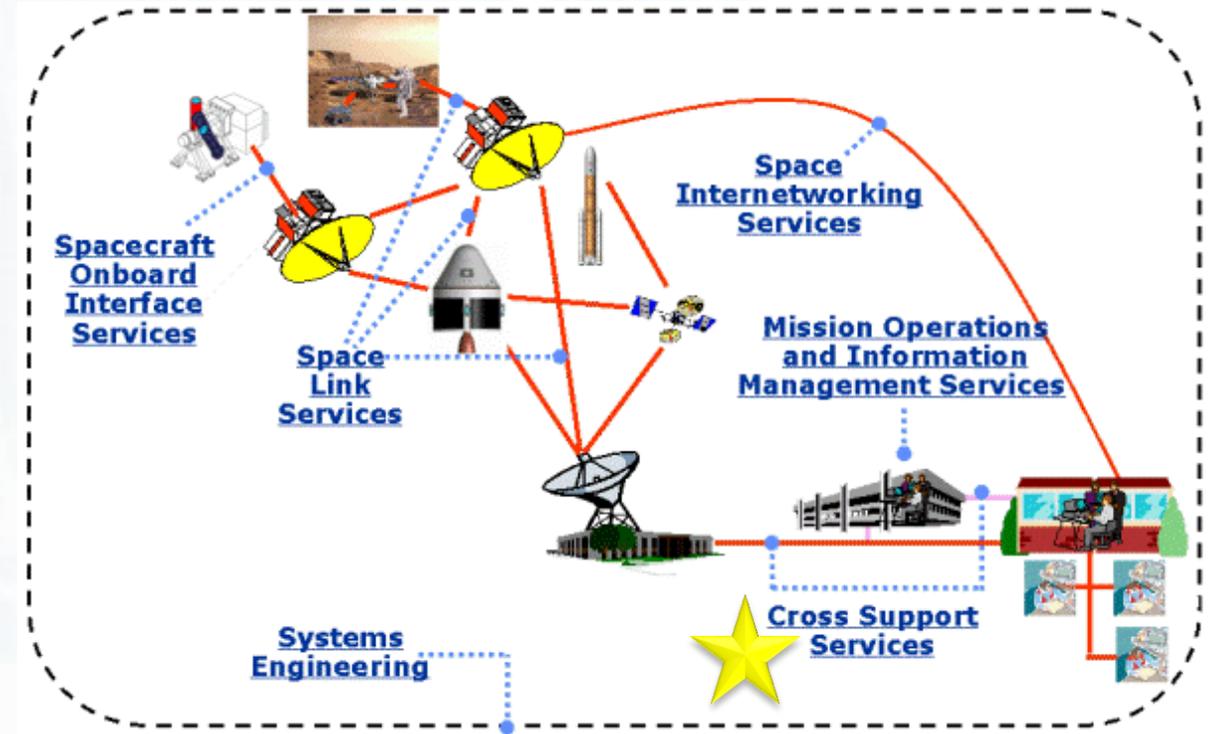
Cross Support Services (CSS) Area

- Objectives
  - Addresses interoperable cross support between ground resources and agencies
- Standards
  - Space Link Extension (SLE)
  - Service Management

The CSS area addresses how space network resources are made available by one organization to another for the purpose of "Cross Support." The objective of the CSS area is therefore to define what services are required at various cross-support interface points, and how those services are exposed, scheduled, and used by organizations that want to confederate their infrastructure in order to execute a mission.

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Overview of SLE

- Purpose
  - SLE provides a means for terrestrial transfer of CCSDS Telemetry and Telecommand data across commercial networks
- SLE is Part of the Cross Support Services
- Recommendations
  - There are 19 recommendations relating to SLE
  - Of Particular Note:
    - 910.0-G-2: Executive Summary
    - 910.4-B-2: General service description
    - 911.1-B-3: Basic telemetry transfer (RAF)
    - 911.2-B-2: Channel telemetry transfer (RCF)
    - 912.1-B-3: Telecommand transfer (FCLTU)

KRATOS
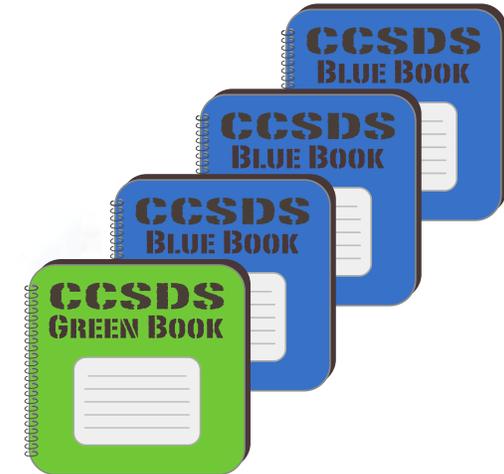
What is SLE?

- Services for Transfer of Telemetry & Telecommand Data
  - Built upon TCP/IP & ASN.1 protocols
  - Interfaces and expected behaviors for service providers & users
  - Focuses on interface between remote facility and control center
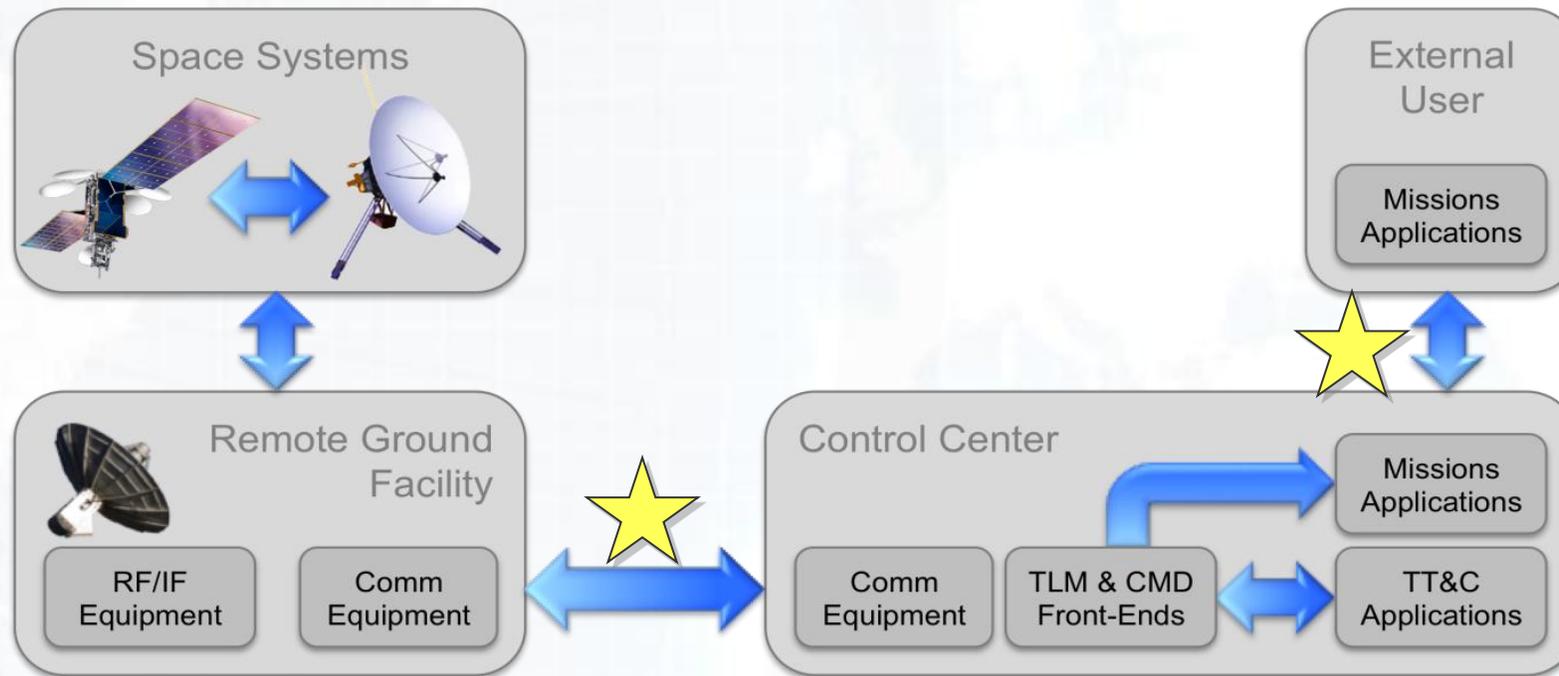
KRATOS®

- Roles
    - Service Provider
        - Provider or source of the data
    - Service User
        - User or recipient of the data
- Definitions
    - 'Forward' Data Path
        - Represents the uplink path
        - e.g. Telecommands
    - 'Return' Data Path
        - Represents the downlink path
        - e.g. telemetry

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SLE Users & Providers

Forward →

Return →

Remote Ground Facility

- RF/IF Equipment
- Comm Equipment

Provider | Telemetry (RAF) | User

Provider | Telecommand (FCLTU) | User

Control Center

- Missions Applications
- Comm Equipment
- TLM & CMD Front-Ends
- TT&C Applications

KRATOS
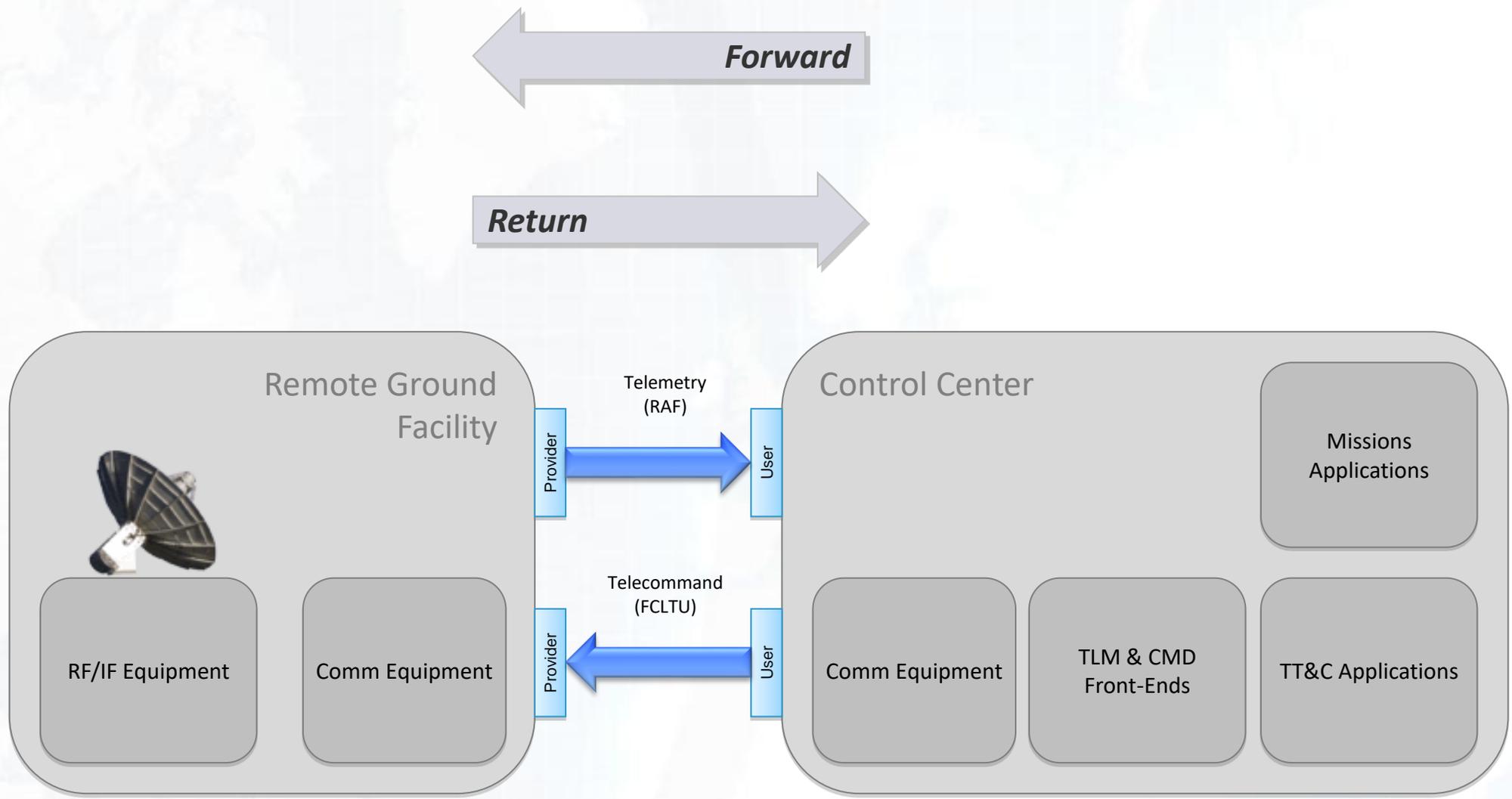
SLE Telemetry Services

- SLE Telemetry Services Provide Different Formats of Data
    - RAF: Return All Frames – all TM frames for a single link
    - RCF: Return Channel Frames – TM frames from a single channel
    - RSP: Return Space Packet – TM packets from selected APIDs
    - RFSH: Return Frame Secondary Header
    - ROCF: Return Operational Control Field
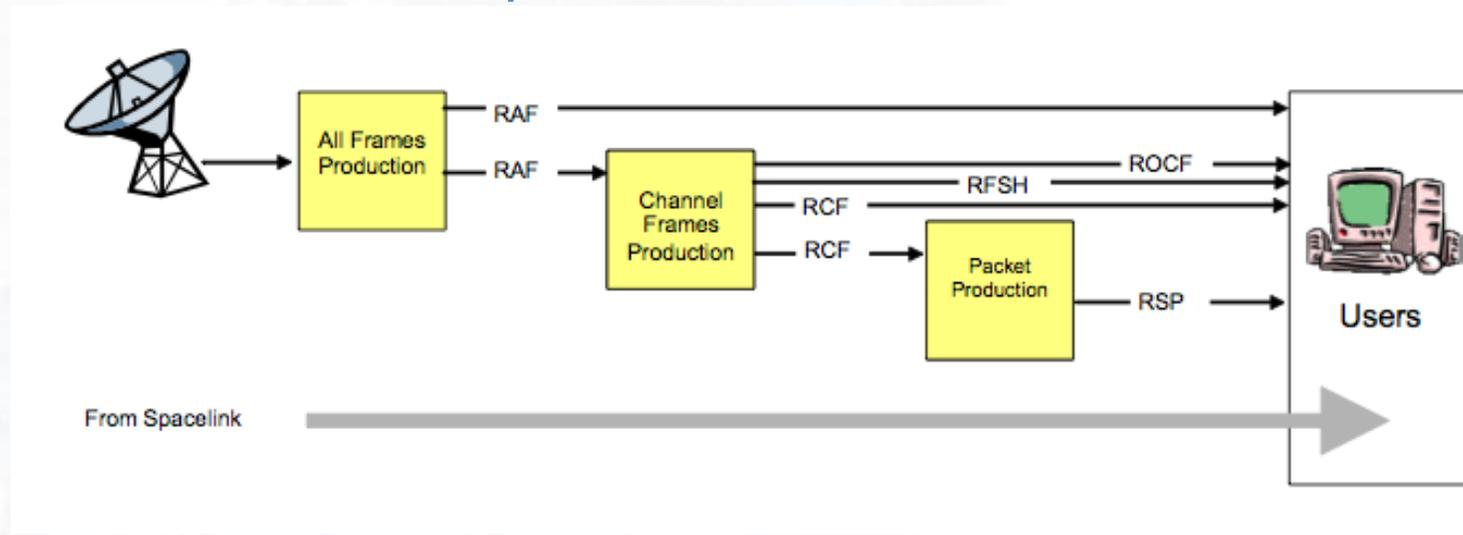
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- Typically used for Telecommand, but Provides for Data
- SLE Forward Services
  - FCLTU: Forward Communications Link Transmission Unit
  - FTCF: Forward Telecommand Frames
  - FTCVCA: Forward Telecommand Virtual Channel Access
  - FSP: Forward Space Packet – sends packets to vehicle
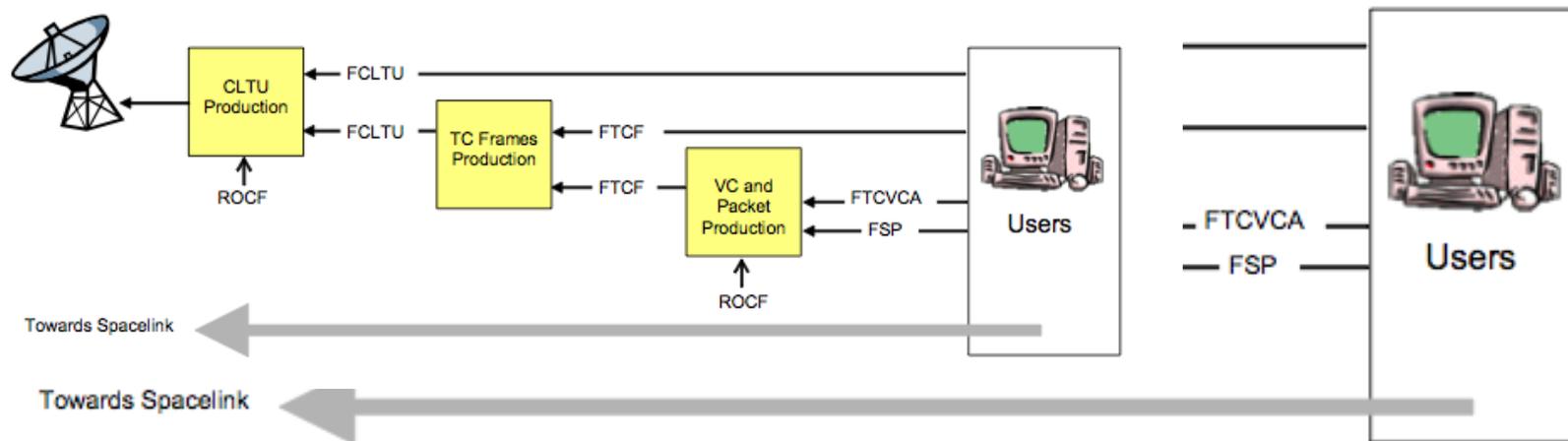
- Generic Building Blocks
  - New SLE services can be built on standard procedures
  - Standard procedures utilize standard operations
  - Operations can still be built on TCP/IP and ASN.1 or other transport layer

Space Internetworking Services

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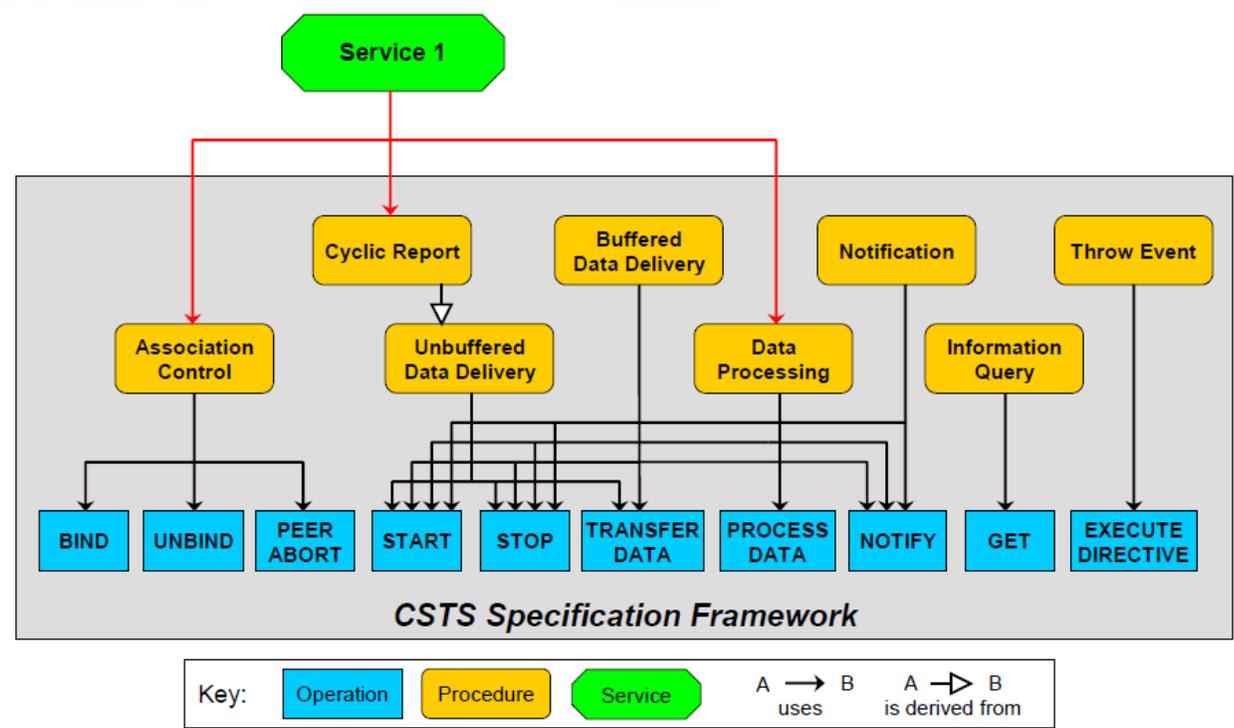
Space Internetworking Services (SIS) Area

- Objectives
  - Addresses networking between space systems and agencies, including over space links.
- Protocols
  - IP over CCSDS space links
  - Space Communications Protocol Specification (SCPS)
  - CCSDS File Delivery Protocol (CFDP)
  - Delay/Disruption Tolerant Networking (DTN)
  - Asynchronous Message Service (AMS)

The SIS area provides services and protocols to address networked interactions of many forms: between spacecraft and eart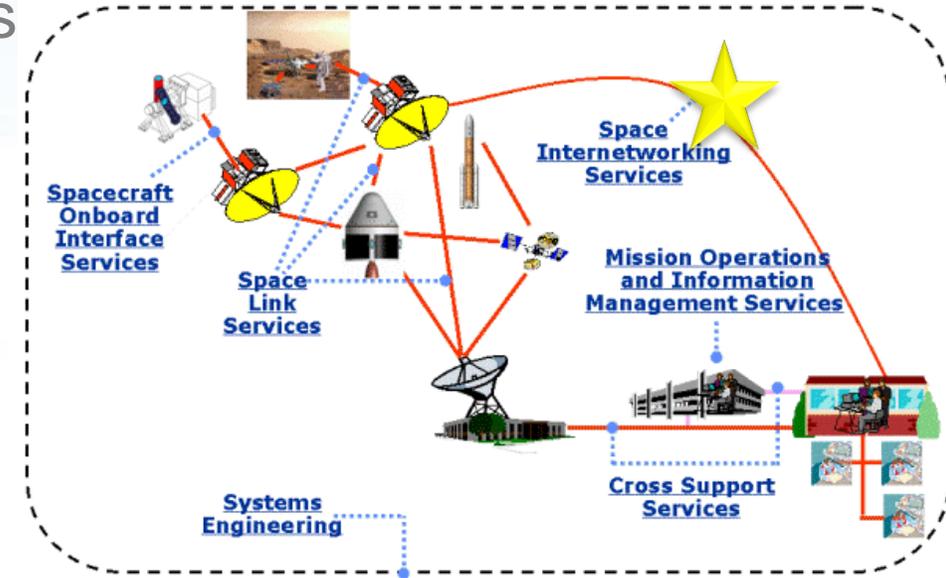h-based resources, among spacecraft, between spacecraft and landed elements, and within heterogeneous spacecraft. The SIS area deals with communication services and protocols that are independent of specific link technology (as a lower layer bound) and independent of application-specific semantics (as an upper bound). This covers essentially the network through application layers of the OSI reference model. The SIS area accommodates all ranges of delay, interactivity, and directionality, although not all protocols are appropriate for all environments.

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Network Layer

- Embeds Networking in Link
- Provides for Multiple Protocols

KRATOS
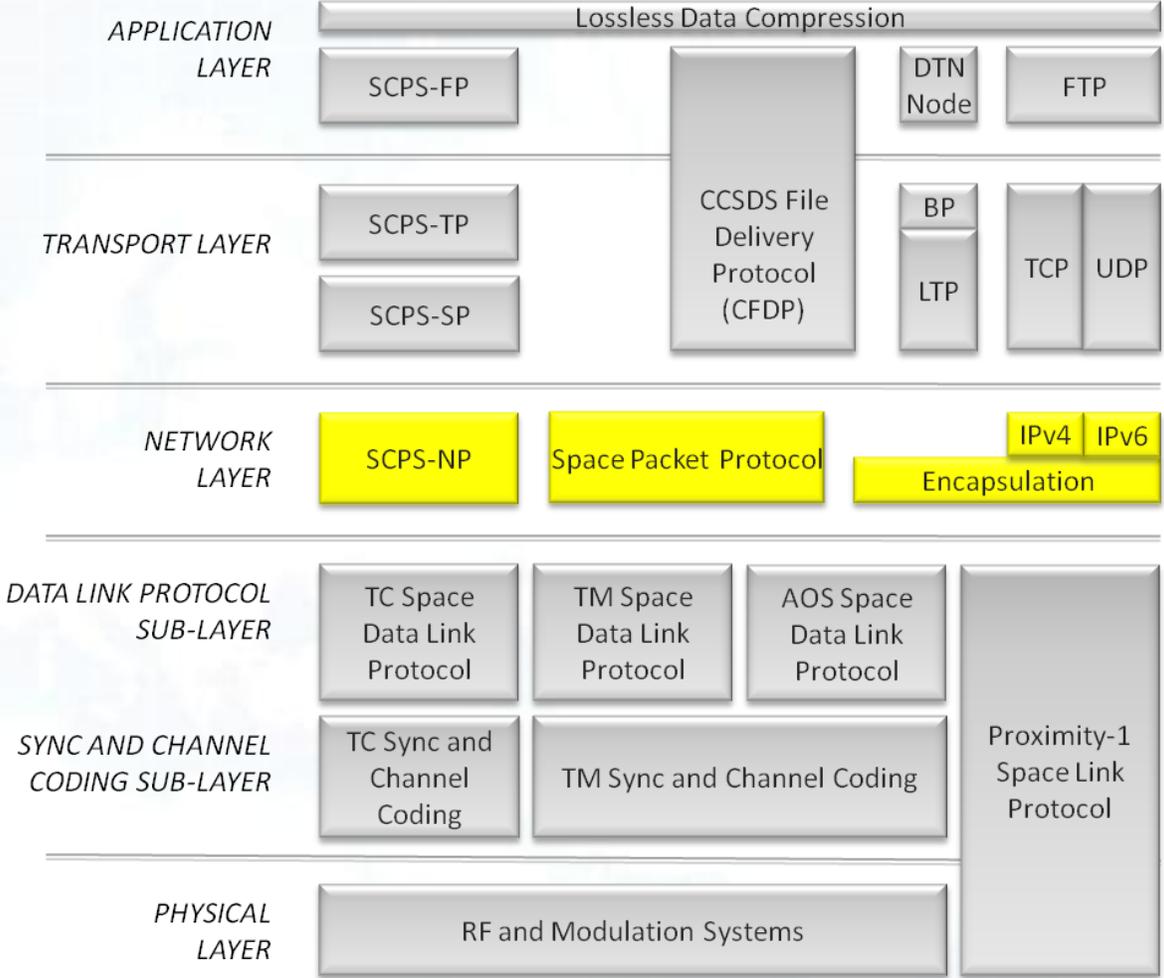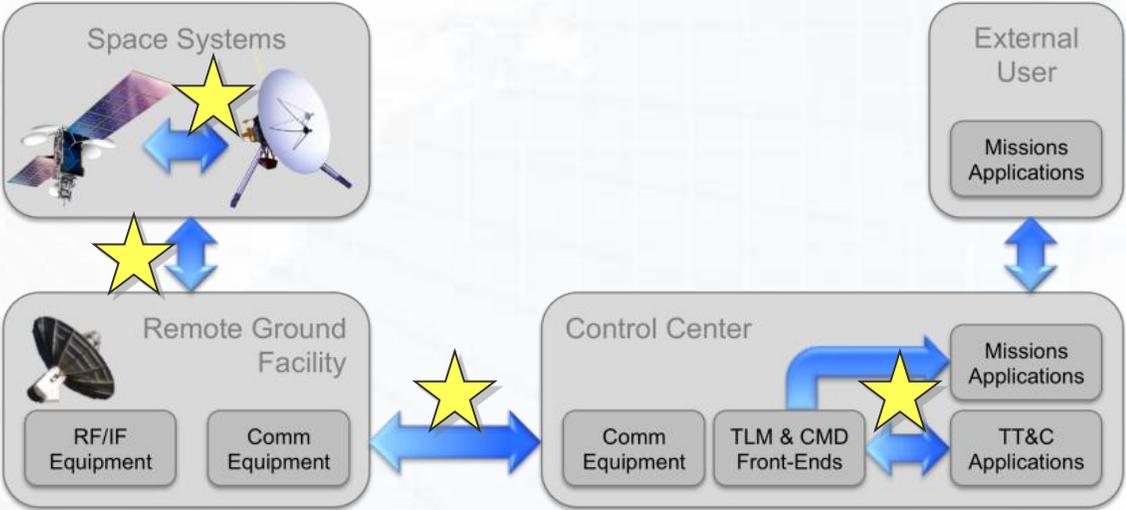
Network Service Types

- Virtual Channel Access (VCA) Service
  - Over TM, TC, AOS, and Proximiity-1
  - Non-CCSDS format
  - Simply use fixed-sized data portion of underlying frame as a mission-specific format
- Bitstream Service
  - Over AOS
  - Used for carrying a continuous, non-packetized stream of data over a virtual channel
- Packet Service
  - Over TM, TC, AOS, and Proximity-1
  - Packets of variable size
  - Packets of various types identified by first three bits
    - Ver 000 = Space Packets (same as TM)
    - Ver 001 = SCPS-NP Datagrams
    - Ver 111 = Encapsulation Packet (Another multiplexing layer for even more data types, e.g., IP Packets)

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- Packet Synchronization
  - Technique for extracting variable-sized packets from the fixed-sized data segments of the underlying layer
- Each fixed-sized transfer frame data field contains…
  - Embedded data for one virtual channel
  - Packets that are not necessarily aligned with the data field
  - The First Header Pointer in the frame header references the start of the first packet (if one exists)
  - Packet size field depends on packet type
  - 'Fill Packets' used if required to fill to the end of the frame data so the frame can be sent immediately

First Header Pointer
(from frame header)

KRATOS
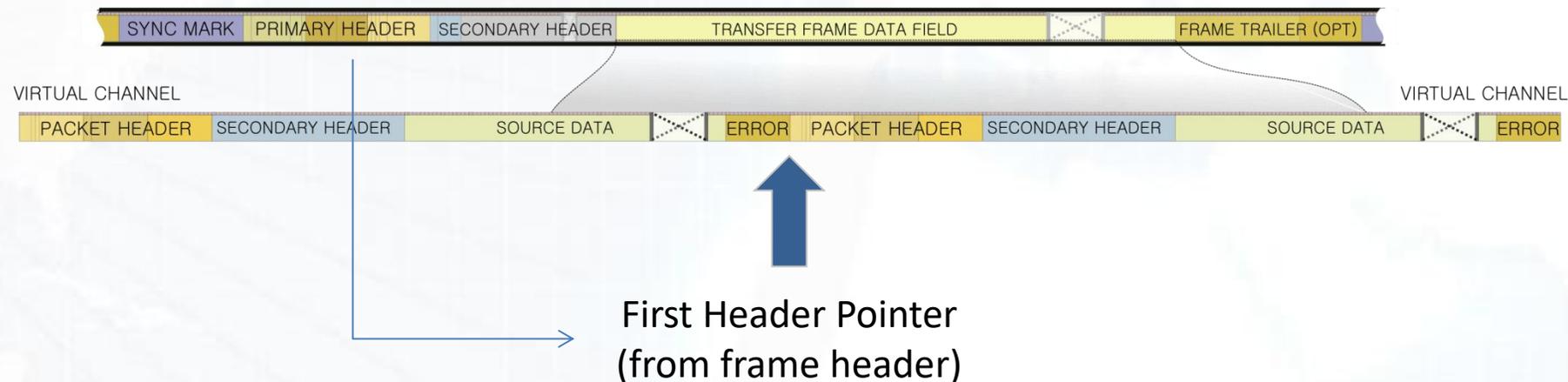
- M_PDU header contains a 'First Header Pointer'
  - Plus some spare bits for good measure
  - Used when underlying layer does not have a First Header Pointer (i.e., non-TM)

First Header Pointer
(from M_PDU header)
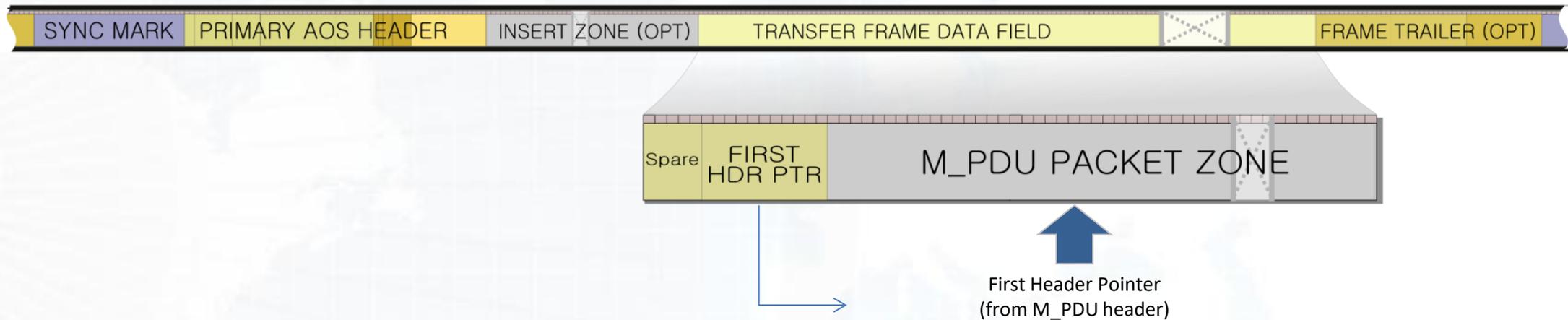
- B_PDU Header Contains The First Packet Pointer
  - Spare Bits
  - Number of valid bits – 1
  - B_PDU Bitstream Data Zone

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M_PDU Packet Types

- CCSDS Packet Types multiplexed using version field (first three bits)
  - Ver 000 = Space Packets
  - Ver 001 = SCPS-NP Datagrams
  - Ver 111 = Encapsulation Packet
- Packet version enables multiple packet types to be multiplexed on the same virtual channel (self-describing)
- Each packet type has a different size field used during Packet Processing

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IP Encapsulation with CCSDS
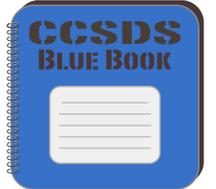
- ENCAP Header
  - Ver = 111
  - PID
    - 000 = fill
    - 001 = IPv4 packets (removed)
    - 100 = IPE (IP Encapsulation) Packet
    - 011 = CFDP PDU
    - 111 = Arbitrary aggregation of bits
  - Length of Length
    - 00 = Single byte fill
    - 01 = 1 octet
    - 10 = 2 octets
    - 11 = 4 octets
  - Length
- IPE Packet
  - IPE header multiplexes
    - IPv4 Uncompressed
    - IPv6 Uncompressed
    - Other header compression codes
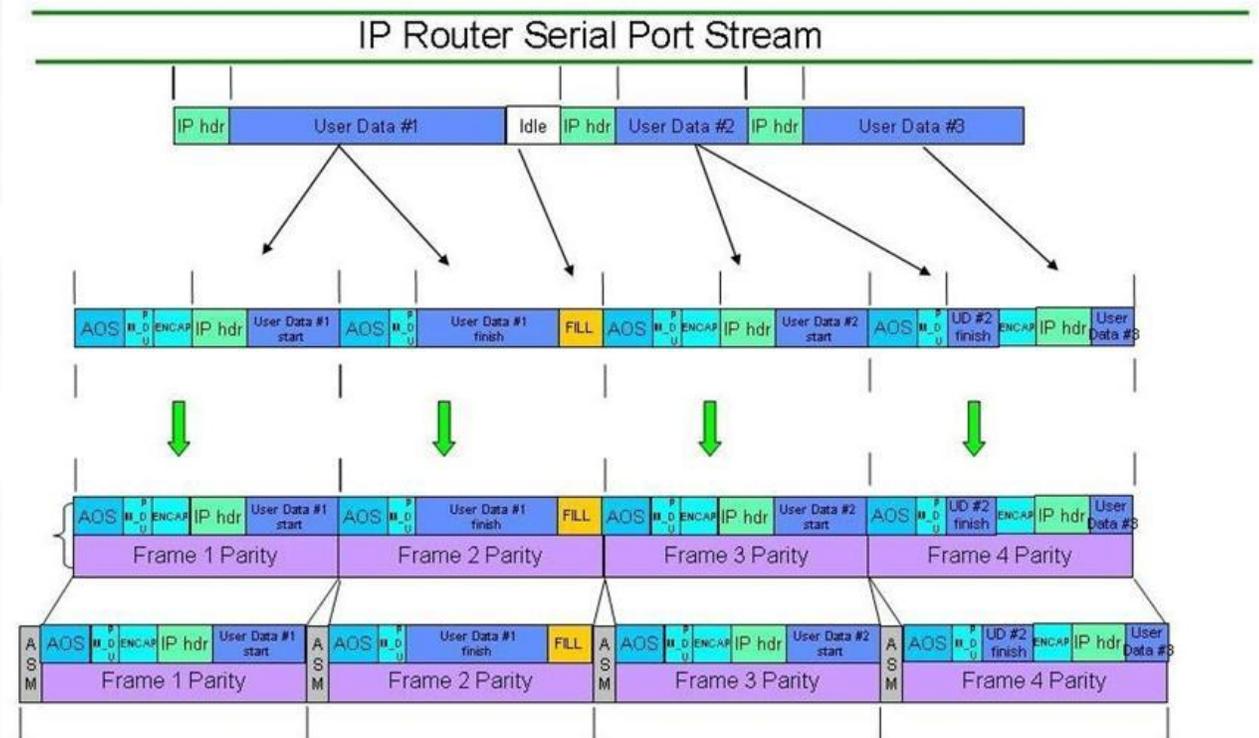
Transport Layer

- Security
- Networking (Commercial)
- DTN

APPLICATION LAYER	Lossless Data Compression		
	SCPS-FP		DTN Node / FTP
TRANSPORT LAYER	SCPS-TP / SCPS-SP	CCSDS File Delivery Protocol (CFDP)	BP / LTP / TCP UDP
NETWORK LAYER	SCPS-NP	Space Packet Protocol	IPv4 IPv6 / Encapsulation
DATA LINK PROTOCOL SUB-LAYER	TC Space Data Link Protocol	TM Space Data Link Protocol	AOS Space Data Link Protocol
SYNC AND CHANNEL CODING SUB-LAYER	TC Sync and Channel Coding	TM Sync and Channel Coding	Proximity-1 Space Link Protocol
PHYSICAL LAYER	RF and Modulation Systems		

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- UDP
  - Constant data streaming
  - No acknowledgement required
  - No error control
  - Suitable for streaming voice and video (un-compressed), where timing is more critical than noise or dropout
- TCP
  - Guaranteed delivery and packet ordering
  - Acknowledgement required to advance the data window. When the data window is full, data flow stops
  - Susceptible to slow throughput due to high latency and errors in transmission
  - Multiple clients increase bandwidth and memory usage

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Delay Tolerant Networking (DTN)
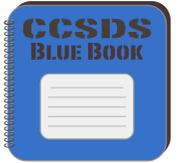
- SCPS-TP
  - Point-to-point data transport
  - Continuous data streaming
  - Selective Negative Acknowledgement (SNAK)
  - Buffering to re-transmit only specific lost packet(s)
  - Packet re-ordering
- Licklider Transmission Protocol (LTP) – CCSDS 734.1-B-1
  - Based on RFC 5326
  - Provides reliable, single-hop transport over a non-reliable data links.
    - Uses proven concepts developed for CFDP, but implemented at the transport layer
  - CCSDS LTP PDUs are currently perceived to be delivered using either Space Packets or Encapsulation Packets
- Bundle Protocol (BP) – CCSDS 734.2-B-1
  - Based on RFC 5050
  - Sits just above Transport Layer (e.g., LTP)
  - Defines end-to-end, multi-hop (store-and-forward) transfer of application-addressed messages between 'Bundle Nodes'
  - Intended to be used with LTP to create a Delay Tolerant Network (DTN)

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LTP Delivery Diagram
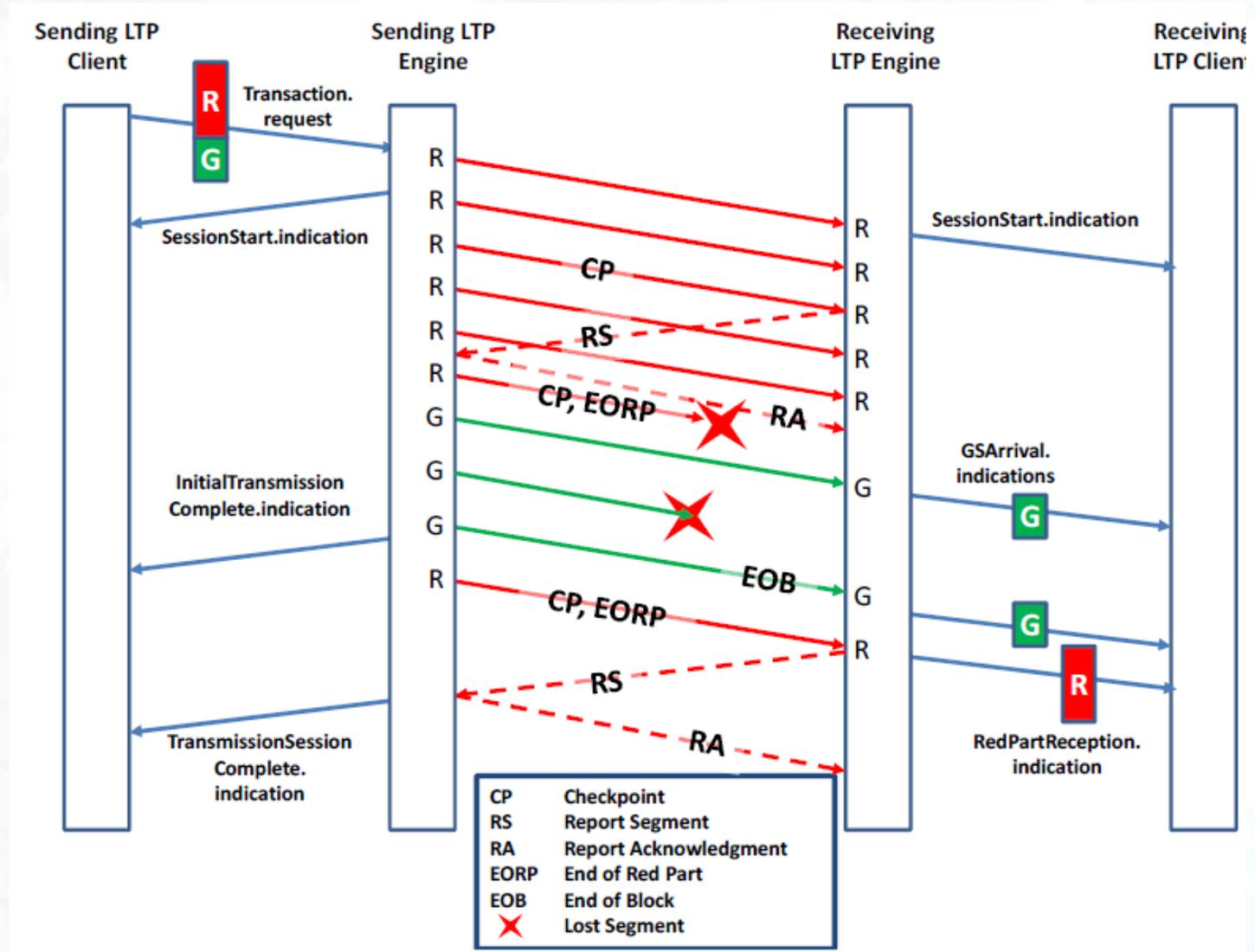
Bundle Protocol

- Bundle Protocol (BP) sits above the Transport layer (e.g., LTP) and provides…
  - End-to-end, multi-hop, store-and-forward operation.
  - Application addressing using Uniform Resource Identifiers (URIs)

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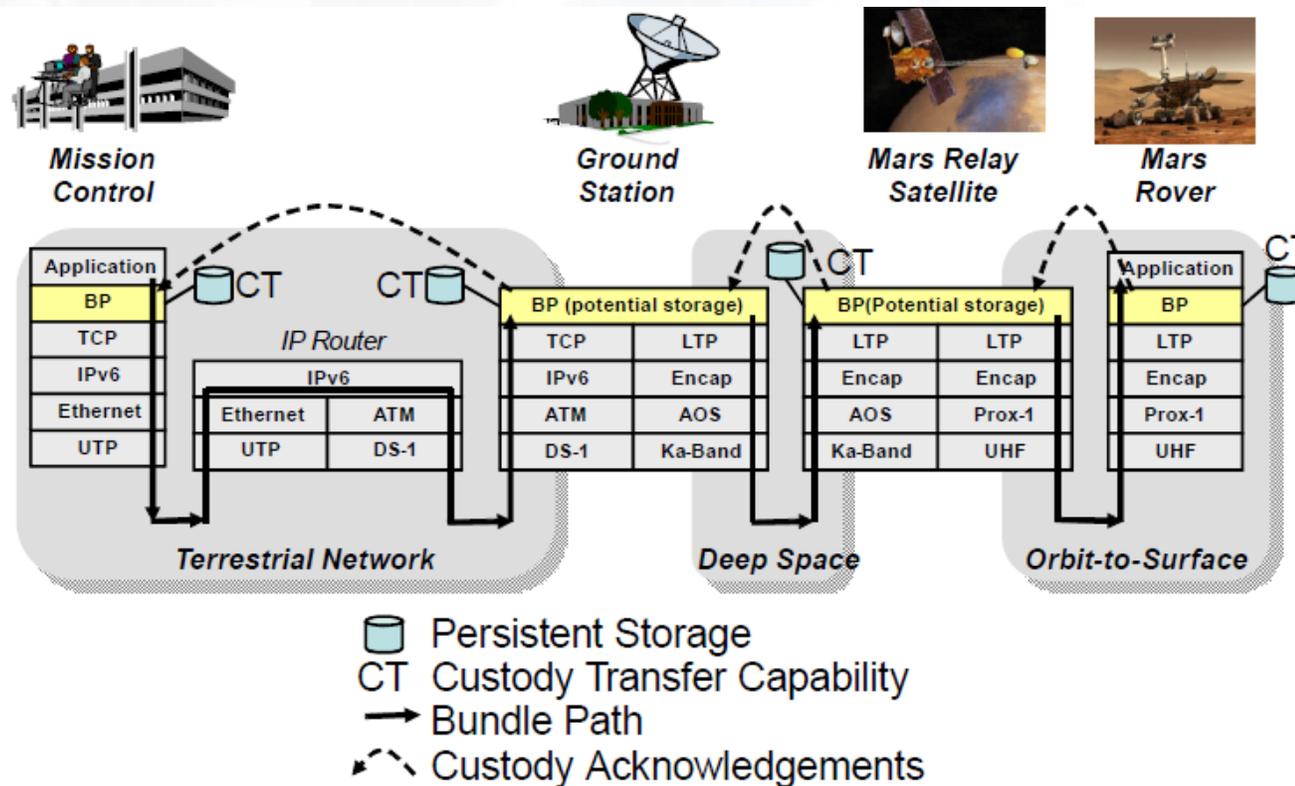
File Transport Protocols

- File delivery over the CCSDS space link

KRATOS
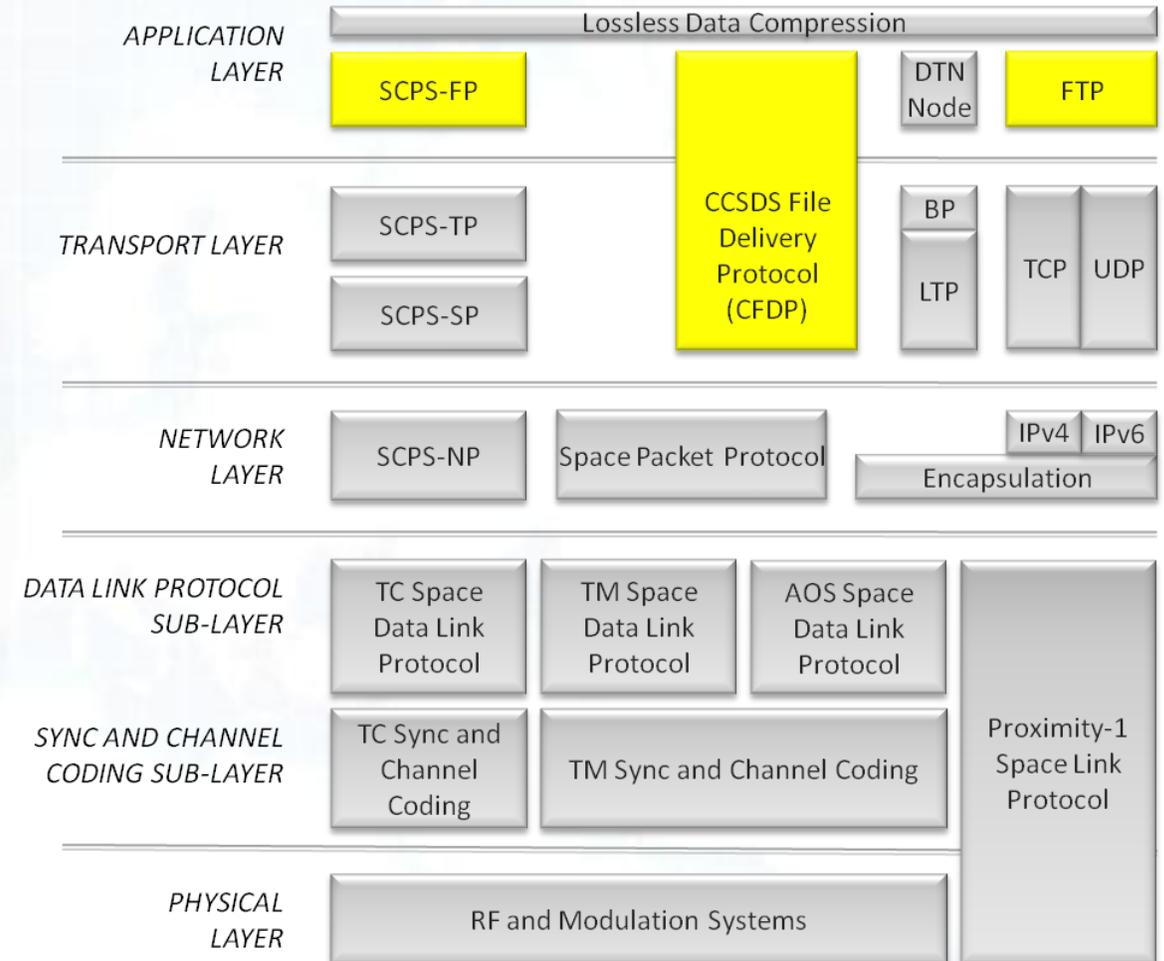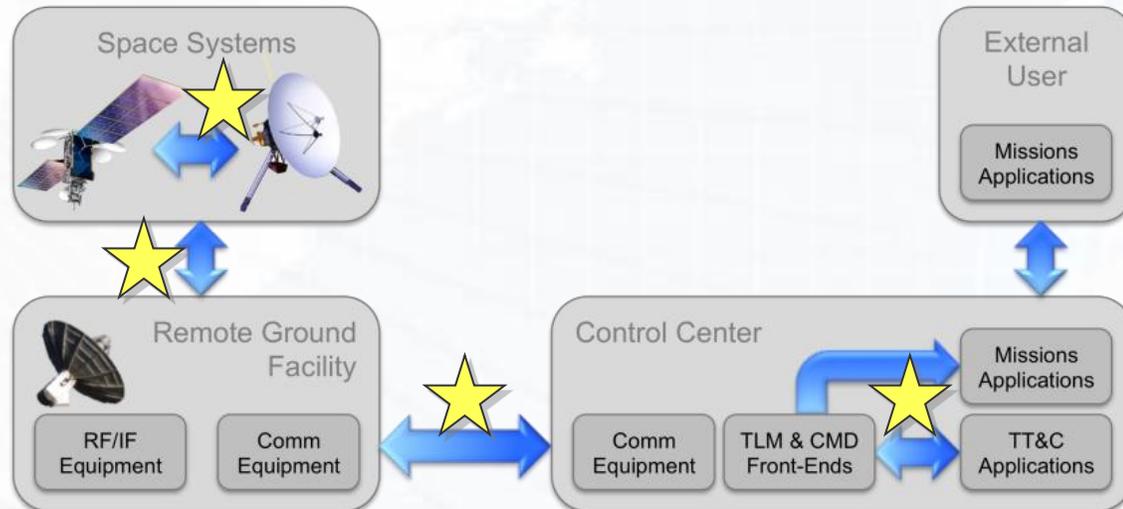
File Delivery in a High Latency Network

- FTP
  - Standard encapsulation
  - No buffering or guarantees of delivery (relies on TCP)
- SCPS-FP and CCSDS File Delivery Protocol (CFDP)
  - FTP functions – File transport to and from space vehicles
  - Transport and Application features
  - File buffering & Store and Forward
  - Guarantee of delivery
  - Retransmission capability
  - Data block ordering
  - See Ref #6

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CFDP Fundamentals

- Transport of files between "Users" and via Waypoints
- User Addresses User via IP, Radio Device Buffer, VCID or APID
- Links can be continuous or discontinuous
- Source, Destination and Waypoints are described in PDU Header
- CRC Error Detection can be included
- PDU ordering is maintained
- NAK sent, only when retransmission is required
- EOF sent and verified

CCSDS 727.0-B-4

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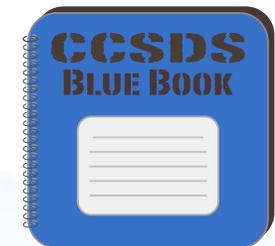
CFDP Functions

- create file
- delete file
- rename file
- append file
- replace file
- create directory
- remove directory
- list directory

CFDP Classes

- Class 1—Unreliable Transfer
- Class 2—Reliable Transfer
- Class 3—Unreliable Transfer Via One Or More Waypoints In Series
- Class 4—Reliable Transfer Via One Or More Waypoints In Series

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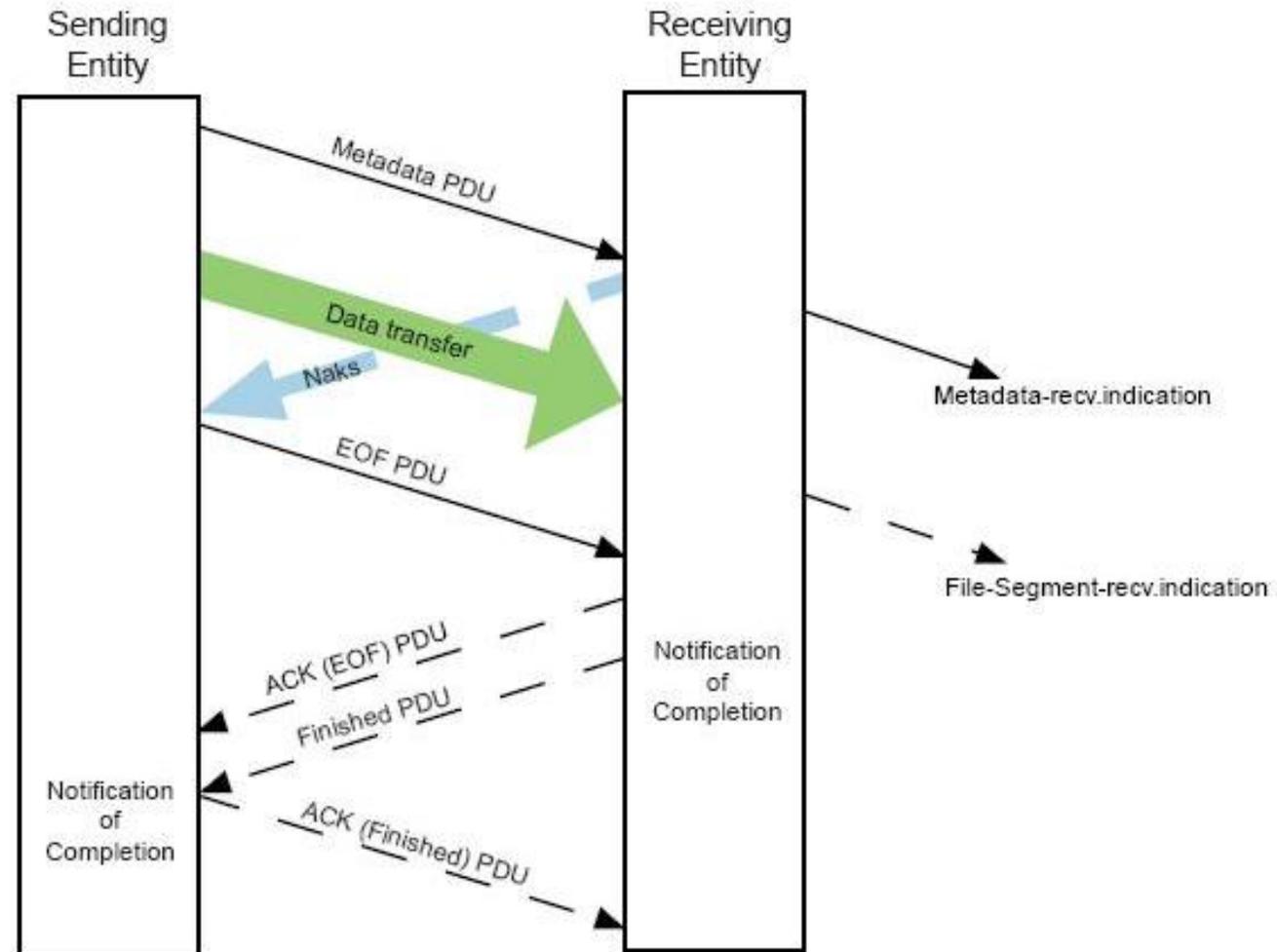
Copy Operations, Sequence of Events

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CFDP File Transport Process Via Waypoint

(a.k.a. Eye-Chart)

EVENT DIAGRAM FOR CLASS 4

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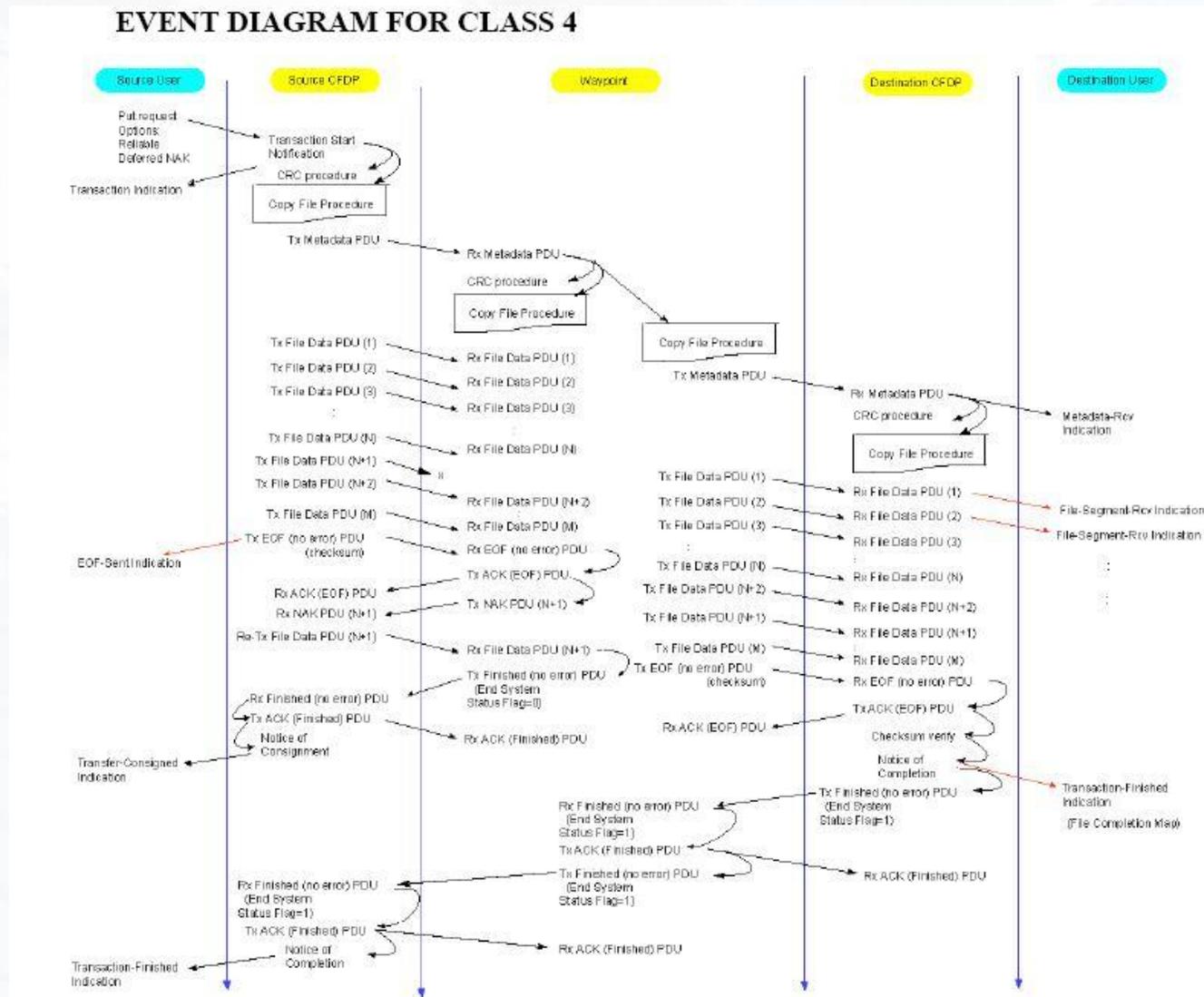
Rice Lossless Data Compression

- Note: Part of Space Link Services Area but placed here based on its position on the protocol stack

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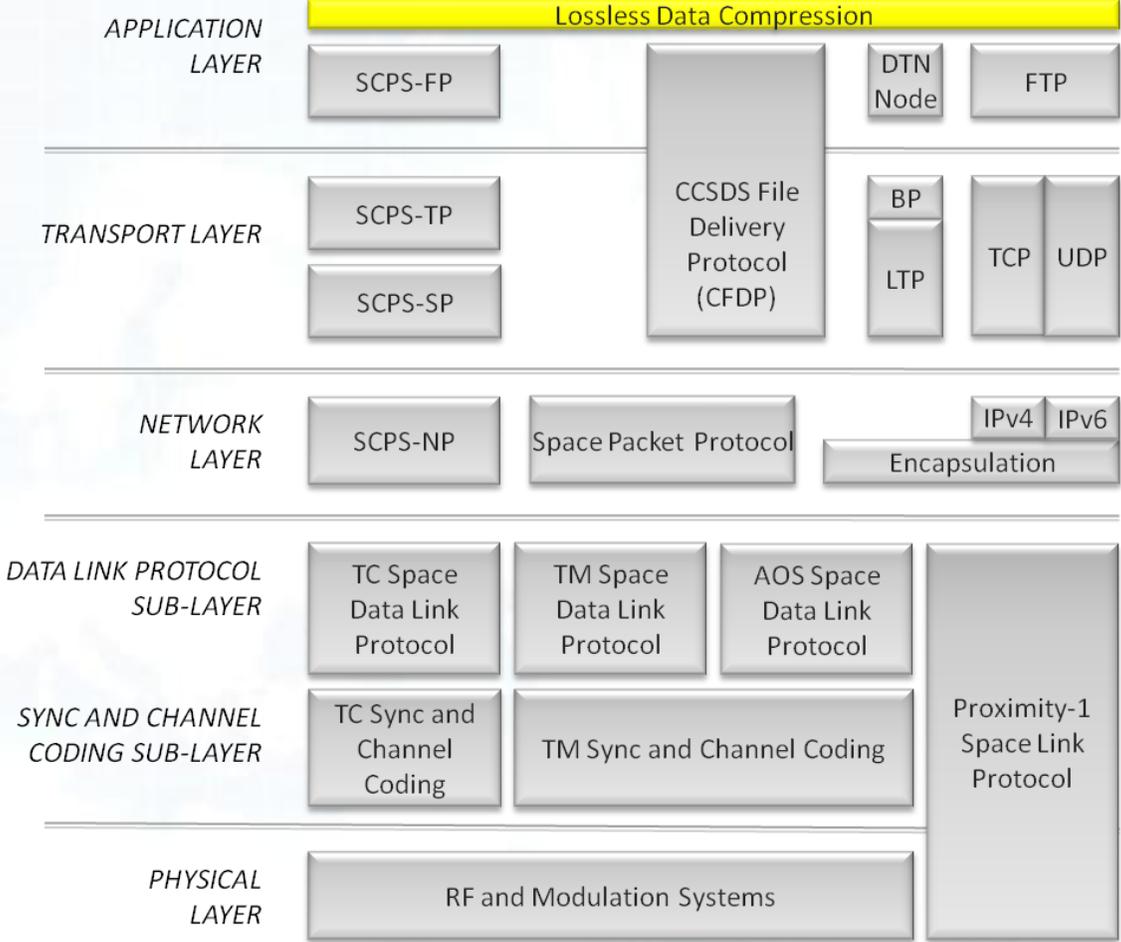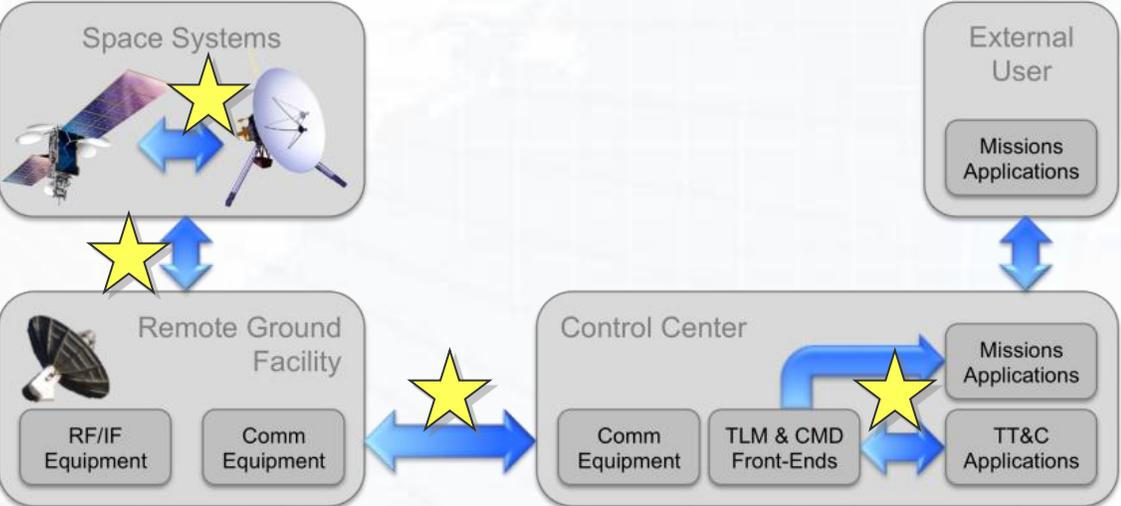
Lossless Data Compression

- Rice Compression CCSDS 120.0-G-4
- Adaptive Huffman code on de-correlated data. Good application for video sensors.
- Short code-words for high-probability data, and long code-words for low-probability data
- See Ref #7
- Discrete Wavelet Transform (DWT) CCSDS 120.1-G-3

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Spacecraft Onboard Interfaces Services And Space Link Services *Updates for USLP

KRATOS
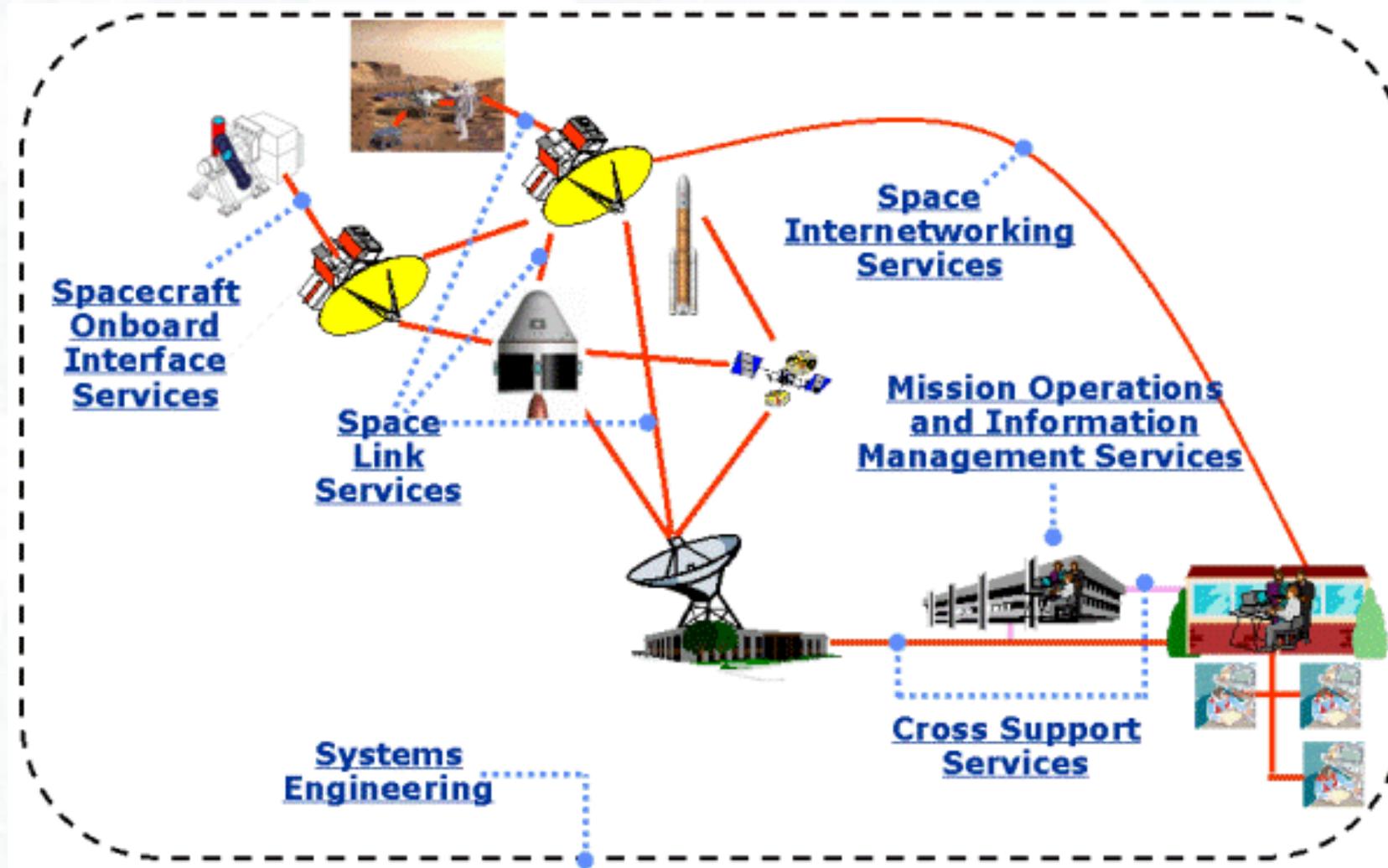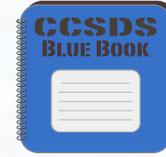
Unified Space-data Link Protocol (USLP)

Question: Why the change of name from NGSLP to USLP?
Answer: 1) In time the next generation will be the previous generation
2) This Protocol ties together the capabilities of all current
CCSDS link layer protocols.

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Evolving Space Communications Environment

- Development of very high rate Optical Communications
- Evolution of very small low cost space vehicles
- Small remote enterprises of communicating space entities (e.g. Multi-agency Mars enterprise)
- Manned missions' utilization of Internet Protocols
- Growth of Delay Tolerant Network technology for use of selective retransmission and reliable link layer protocols.
- Flight technology to support high performance Forward Error Correcting Codes and VCM/ACM
- What's next?

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Emerging Requirements on Link Layer

- Higher Data Rates put increased pressure on current implementations and operational data handling and routing
- Larger number of space vehicles requires more spacecraft identifiers
- Inclusion of uplink security (SDLS) will require new flight implementations
- Advances in technology provides the means to improve uplink performance using improved codes and FPGA devices.
  - Support reprogramming of Flight FPGAs systems
  - Increased control command size due to inclusion of security

- *NOTE: Significant advances in technology also provides the capability to incorporate regenerative ranging for improved tracking and spacecraft clock calibration.*

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How USLP addresses the future needs (1-2)

- Longer frames provides more efficient frame processing
- Greater number of Spacecraft Identifiers needed
- Independence of Coding and Framing protocol
  - Provides for the use of high performance uplink FEC coding
- Provides a single protocol that can be used across all space links
- Allows direction insertion of other protocols (i.e. IP, DTN) into USLP frame, making internetworking more efficient.

NOTE: A single protocol for all space links (DTE, DFE, cross-links) will reduce the number of protocols required for space missions and provides for broader use of firmware needed developments to support security and increased data rates.

KRATOS

How USLP addresses the future needs (2-2)

- Provides a variable length frame capability for all Links
  - Duplicating TC and Proximity functionality
  - Added capability for TM and AOS type links
- Utilizes VC IDs for MAPs/Ports in both TC and Prox
  - Replaces TC Segmentation Mode
  - Replaces Proximity Output Ports
- Offers an Optional Insert Zone Service to be used as needed
  - For insertion of low latency commanding/status or ARQ reporting
  - Can be used to duplicate current AOS functionality if required
- Eliminates the need for insertion of Idle Frames when performing AOS type operations.
- Supports Mission Need for more agile use of Coding
  - Frame need not be coupled to code block allowing easy code change
  - Supports commanding of physical parameters via USLP

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USLP

- USLP is designed to optionally provide the Data Link Services while residing transparently above the Space Link Coding and Synchronization sub-layer.

CCSDS Data
Link Layer

| Upper Layer Protocol (Including Session Control and Reliable Delivery) |
| Data Link Protocol Sub-layer (USLP) |
| Coding and Synchronization Sub-layer |
| Physical layer |
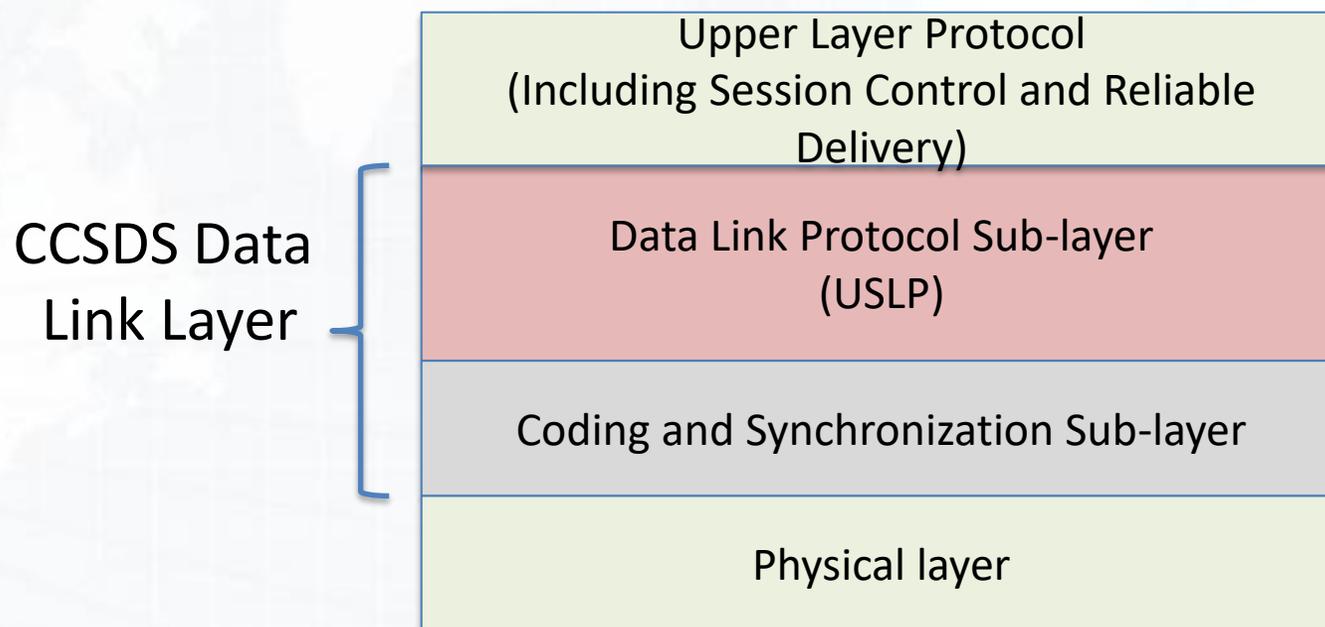
Note: USLP explicitly defines the frame length in all frames to optionally decouple the relationship of the Space Link C&S Sub-Layer from the Data Link Protocol Sub-Layer.

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Link Layer Services

Transmitting (sending) Side

Packet Service   *VCA Service*

Packets   **User Units**

Input Sub-layer
- VCS SAP — Form TFDFF_SDU
- VCA SAP — Form VCF_SDU
- Select VCF_SDU

TFDF_SDU (Transfer Frame Data Field)

OCF Service — OCF_SDU

Data Sub-layer
Virtual Channel (VC) Formulation
- Add VC Header and increment VC Counter
- Insert Received TFDF-SDUs
- Insert OCF
- Compute and Add Security Header and Trailer

Virtual_Channel_Frame

VC_Frame Service

Sync& Coding Sub-layer

Master_Channel_Frame

Merge VC Frames

MCF Service — MC_Frame

Master Channel (MC) Formulation
- Merge Received VC_PDUs
- Insert Insert_PDU into Frame
- FEC Coding and Randomization
- Add Attached Sync Marker

Insert SDU

MC_Frame

Link_Transmission_Unit

Physical Layer
Physical Channel (PC) Formulation
- Merge Received MC_PDUs
- Add Idle/Idle Frames as required

Merge MC Frames

Physical Channel
Symbol Stream

Receiving Side

VCA Service   *Packet Service*

User Units   **Packets**

- VCA SAP — Extract Octets
- VCS SAP — Extract Packets

VCS_SDU

Separate GVCS_Frames

Output Sub-layer

VC_Frame   *VC Frame (post security)*

Data Sub-layer
- Deliver Received and verified VC-Frames
- Check VC Continuity
- Perform Security Process
- Extract OCF

Virtual_Channel_Frame

Separate VC_Frames

Separate VC_Frames

Master_Channel_Frame
- Extract Insert SDU
- Separate MC_Frames
- Validate Frame using CRC when contained
- FEC Decoding and Derandomization
- Delimit code block(using ASM if required)

Sync& Coding Sub-layer

Link Transmission_Unit (ASM+VC_Frame)

Physical Channel
Symbol Stream

Physical Layer
Physical Channel (PC) Reception
- Acquire symbols

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Transfer Frame Data Field

TFDF Header					TFDF Data Zone
VC Data Structure and Protocol fields Identifier Mandatory			**Optional (only required for Stream Data) Streaming Data Pointer** • First Header Pointer For packets • Last valid octet for user defined data		• CCSDS Space Packets • Internet Datagrams • DTN Bundles/Fragments • User Octets
Data Inclusion Rules	Protocol ID	Extended Protocol ID			
3 bits	5 bits	8 bits	16 bits		Variable

The organization of data within a VC is signaled within a VC header. Header identifies both the type of data unit contained and the data delimiting rules that apply.

1. Identifies Protocol of User's data (i.e. CCSDS Space Packets, Internet Datagrams, DTN Bundles or bundle segments, user octets)
2. Streaming requires added header information for the VC service data unit.
I. First header pointer
II. Last valid user octet

Data Inclusion Rules	Streaming Pointer Field (Optional based on Data Rules)
'000' Complete User Data units	Not Required
'001' Streaming packets	First Header Pointer
'010' Streaming User Octets	Last Valid Octet in VC Data Field
'011-111' To be defined via SANA	To be defined per defined rules

Protocol ID	
'00000'	CCSDS Packets
'00001'	IP Datagrams
'00010'	DTN Bundle
'00011'	User Octets
'11111'	Field Extension

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Possible Modifications to USLP

- Add a "from" address field into frames to identify the source of the frame when Source/Destination set to Destination
  - o   To inform recipient of source
  - o   Possible use for a frame relay service

- Provide a Code Block Accountability capability for Link Analysis
  - o   Include a 1 or 2 byte incrementing counter in the beginning of the code block data field (reducing the size of the data contained within the code block) providing a better mechanism for clock calibration when code block and frame are uncoupled.
- Other suggestions:
  - o   Increase Version ID to 8 bits for compatibility with other format protocols (e.g. Internet, DTN) and allow all compatible formats to share the error free link provided by a CCSDS FEC code.
  - o   Utilize a protocol like HDLC to delimit all data units without knowledge of data unit fields

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Spacecraft Onboard Interface Services

Space Internetworking Services

Space Link Services

Mission Operations and Information Management Services

Systems Engineering

Cross Support Services
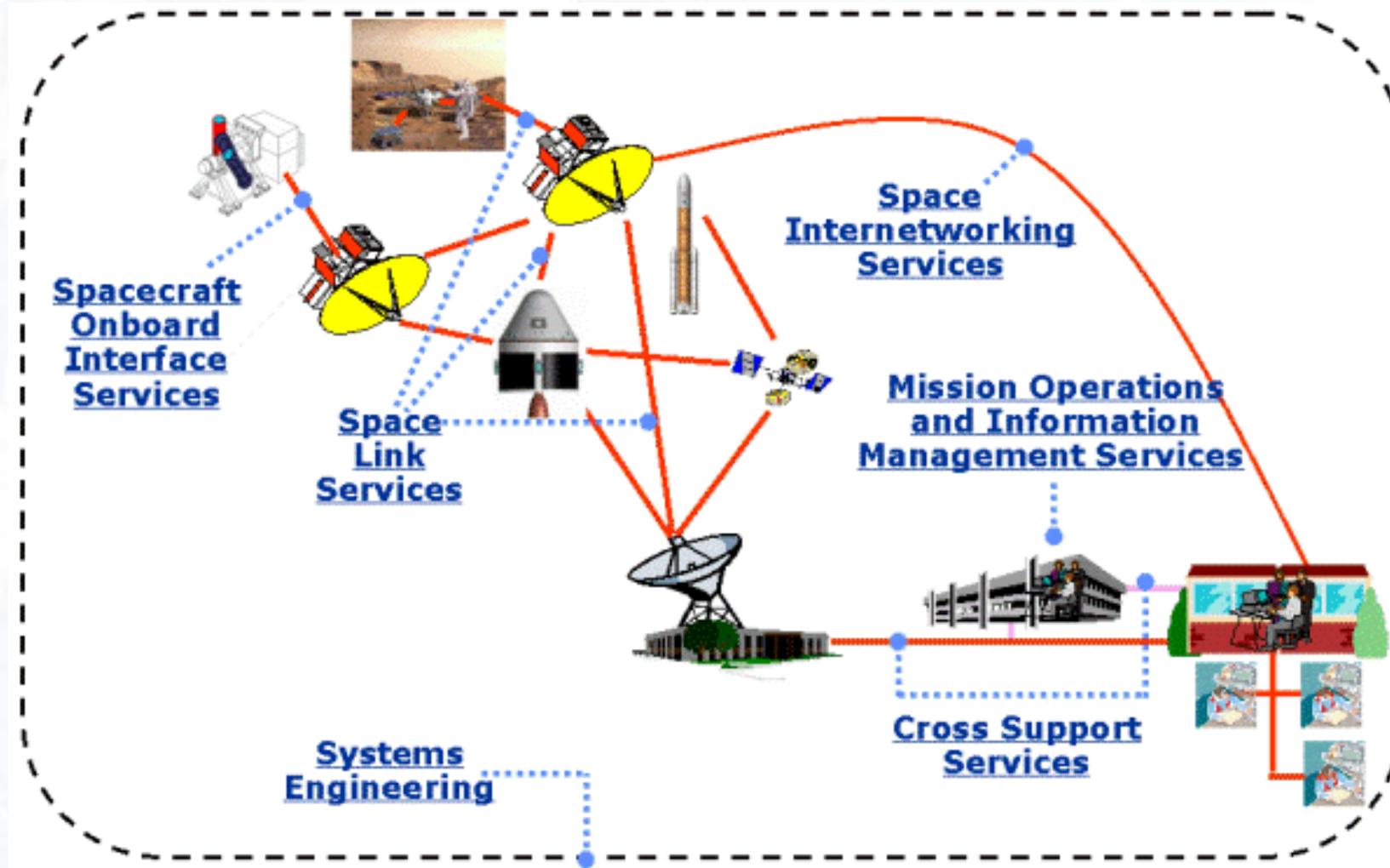
Mission Operations and Information Management Services (MOIMS) Area

- Objectives
  - Encourage interoperability and smooth transition of space missions from "mission operations" to "mission utilization."
    - Mission Operations – Functions that occur during the flight path
    - Mission Utilization – Functions required by mission users
- Standards
  - Mission Operations Message Abstraction Layer
    - Orbit, tracking, attitude data messages
  - Standard Formatted Data Units (SFDU)
  - XML Telemetric and Command Exchange (XTCE)
  - XML Formatted Data Unit (XFDU)
  - Many other informational formats…
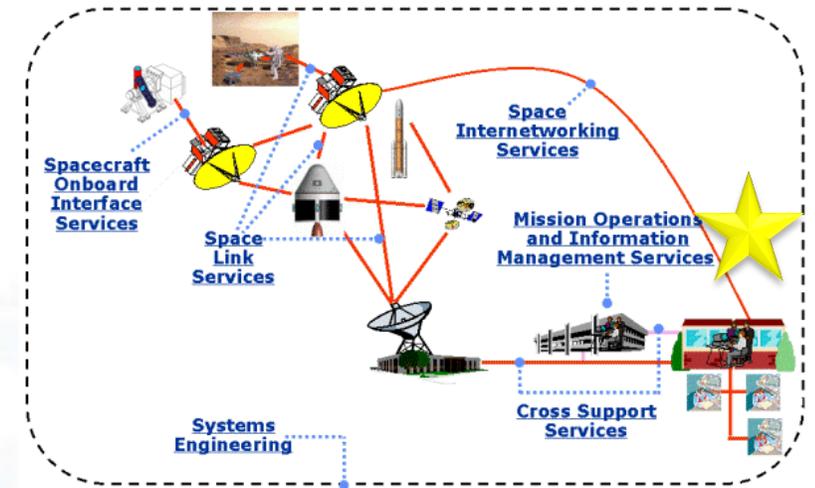
The objective of the MOIMS area is to address all of the flight execution phase applications that are required to operate the spacecraft and its ground system in response to mission objectives and their associated detailed information management standards and processes. The focus of this area is primarily on the "mission operations" functions that occur on a timescale driven by the flight path of the space vehicle. The MOIMS area ensures that application standards exist that facilitate the smooth transition of space mission information between the "mission operations" systems and the "mission utilization" systems.

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The Interoperability Challenge at the Information Level

- For going back to the moon, NASA selected common frequencies, so can all the spacecraft, instruments, and rovers interoperate?
  - Then they selected modulation schemes and then recommended CCSDS packet protocol. So can they interoperate now?
  - What if my space asset needs to announce an emergency to others?
  - If we all say we will coordinate activities, might there be a common activity schedule?

- Additionally, missions are getting more complex, cost pressures are increasing, and collaborations are being discussed even more.

- This is why standards need to get to the information-level needed by applications software. CCSDS has worked this area, but the solutions needed today may not be available. So now what?

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Mission Operations and Information Management Services (MOIMS) – 4 Work Areas

- Spacecraft Monitor and Control (SM&C)
  - Focused on service specifications for mission operations
  - One of the largest CCSDS working groups
  - Very limited adoption so far (nothing within NASA)

- Mission Planning and Scheduling
  - Activity-level planning and schedule formats and services
  - Fairly new working group
  - Promising, but not yet mature

- Navigation
  - Formats for exchange of data for flight dynamics
  - Broadly adopted

- Data Archive
  - Very long-term safe storage and retrieval

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MISSION OPERATIONS AND INFORMATION MANAGEMENT SERVICES

Spacecraft Monitor and Control

Note: In addition to Mission Operations (MO) Services discussed here, the SM&C working group standards also include the XTCE standard for describing a mission telemetry and command data base. It is a joint standards between CCSDS and the OMG with leadership from the OMG.

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CCSDS Mission Operations (MO) Services Concept

- In Space Data Systems, parameters may be accessed by:
  - A rover on Mars,
  - A satellite orbiting Mars,
  - Or mission operations centers on Earth

- ▸ Having a standard service for Parameters means:
  - ◦ A relay satellite can receive the rovers parameters and forward it to Earth
  - ◦ A Mission Control Centre can receive and process the Parameters of the satellite or rover
  - ◦ An external institution can receive and process the Parameters

- ▸ Basically, the same service can be used by completely different systems in completely different situations

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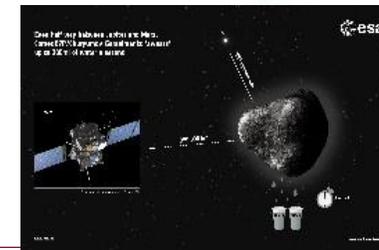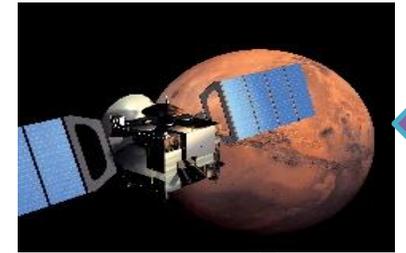
The MO Service Vision

- Let's define service standards for the primary mission ops capabilities of space and ground data systems

- First priority is to use them ground-to-ground (easier), but long-term goal is to use them on-board and on the space-to-ground link as well

- The project manager of a future mission will
    - Select the CCSDS MO services needed by his missions
    - Define bespoke (mission-specific) services using the MO Framework

- Benefits
    - CCSDS MO services: specs and related software already validated and available for immediate re-use
    - Bespoke services: all MO services benefits extend to them as well
    - Re-use of avionic software
    - Re-use of ground infrastructure software for mission operations
    - Re-use of ground operational concept and procedures
    - Easy maintenance for long duration missions

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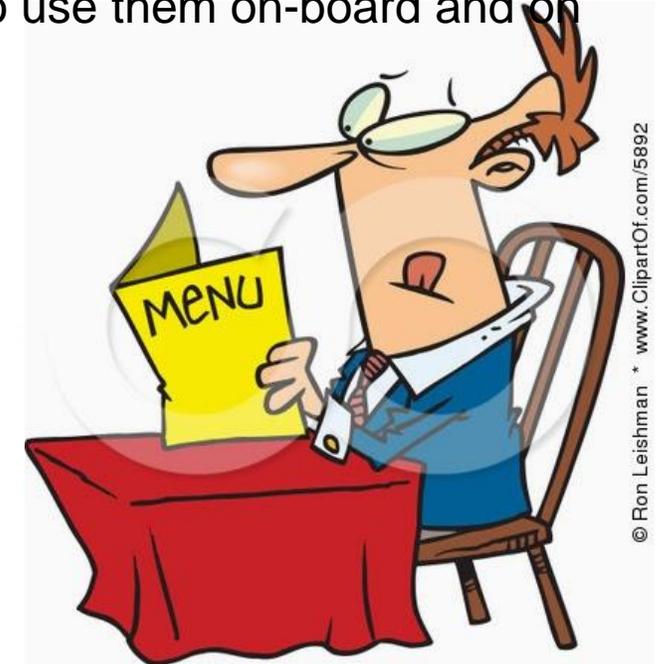
MO Services Concept

- CCSDS has defined an open architecture and framework that is:
    - Able to integrate new and legacy systems of different organizations
    - Service Orientated
    - Independent from technology
    - Designed to support the long lifetimes of space missions

- The framework allows different systems to communicate and interact together, independently from their
    - Location
    - Programming language
    - Hardware platform
    - Communications technology

- This independence allows an organization to choose
    - The technologies that are appropriate for them
    - Whilst still allowing bridging between these different choices where required

- It also increases long-term maintainability over the mission lifetime through replacement of both
    - Systems
    - Underlying technology

Your Systems

Standard MO Services

MO Framework

Technology

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The MO Framework

- **Central concept is the MO framework**
  - Defines the structure of an MO application
  - Provides generic model for data
    - Supports generic facilities such as archiving
  - Provides separation from technology

- **It is defined by three published specifications**
  - Reference Model
    - (CCSDS 520.1-M-1)
  - Message Abstraction Layer (MAL)
    - (CCSDS 521.0-B-2)
  - Common Object Model for data (COM)
    - (CCSDS 521.1-B-1)

Applications

Functional Services

Common Object Model

Message Abstraction Layer

Technology

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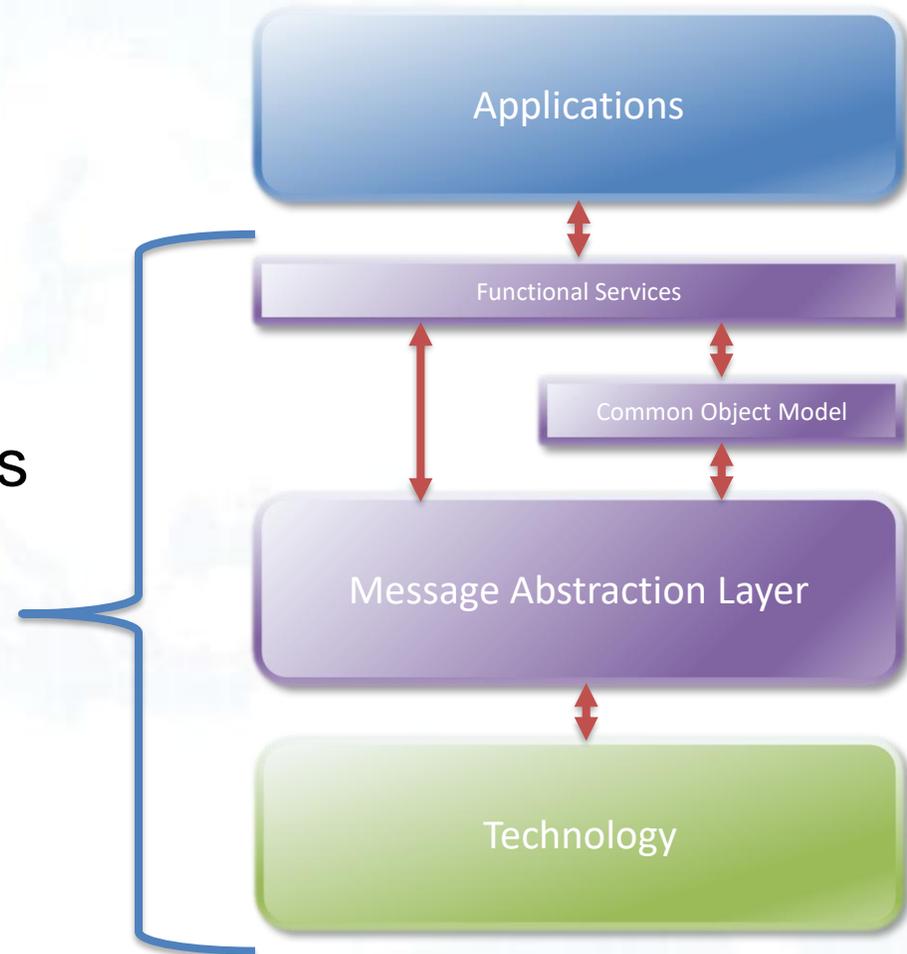
CCSDS Mission Operations Services

Services are defined and prototyped before being formally published as standards.

The categories shown on the right are at different stages of development – they are not all complete.

Vision is for the services to operate on any node – could be on the ground or on-board

- Monitor and Control
- Common Services
- Mission Data Product Distribution
- Archiving
- Planning
- Scheduling and Automation
- Navigation
- Software Management
- File Transfer and Management

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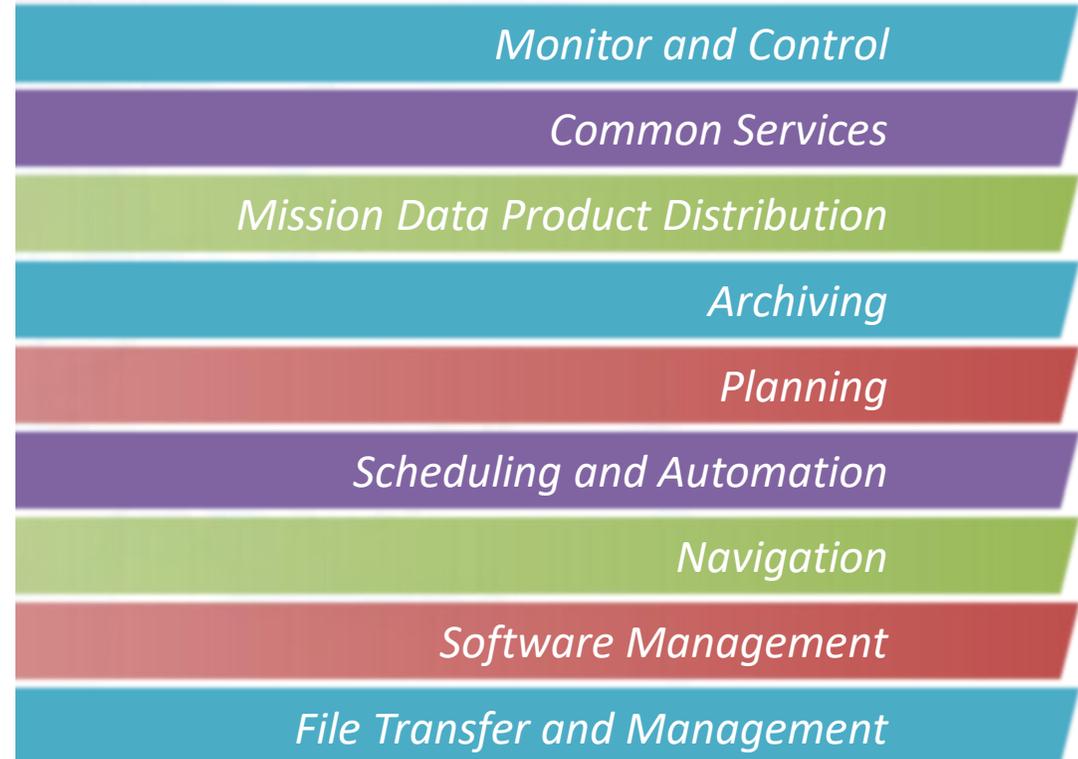
Parameter Service

- Parameters have an evolving value represented by a chronological sequence of value updates over an unbounded lifetime

- Parameters have a defined type
  - This is the data type of the value update, such as string or integer
  - Composition of parameters into complex structures supported by defining an Aggregation
    - See Aggregation service

- Value updates may be:
  - Periodic
  - Change-based
  - Or a mixture of the two

- It is also possible, when supported, to set the value of a parameter

- Parameter definitions are not defined in the service specification
  - Delegated to the runtime configuration of the provider

- Parameter definitions are managed using the operations of the Parameter service
  - They may also be managed via the Common Configuration service

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MO Example: Monitor and Control Services

- The M&C services also include extra services to extend the basic three services:
  - Check service
    - Provides online checking of Parameter values
  - Statistic Service
    - Provides online statistical evaluation of Parameter values
  - Aggregation Service
    - Provides aggregation of separate Parameter values in to coherent sets
  - Conversion service
    - Provides the specification of calibrations and conversions for Parameter values
  - Group service
    - Provides the ability to define groupings for simplifying the operations of the other services

- Note that many of these services are primarily for use within a control center (promotes re-use) and would not typically be used across interoperable interfaces.

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Are MO Services Ready Today?

- ESA launched OPSAT in December 2019
    - Once initial checkout of the cubesat is complete, several of the MO services will be tested
    - ESA sees great promise in the use of MO Services over a broad range of ground and space systems

- No acceptance within NASA so far
    - No available COTS product support
    - No U.S.-developed shareable software
    - Services have not been shown to scale up to large missions
    - Not sufficiently proven for consideration on Artemis/Gateway

- Philosophical issue with whether standards should delve so far into system design
    - ESA sees many benefits to defined functionality and common solutions
    - NASA prioritizes innovation and change over the "common solution" solution

- Where do we go from here?
    - Can the MO Service message structures be simplified and presented as a standard without the full MO Services framework and aspects of system design?

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MISSION OPERATIONS AND INFORMATION MANAGEMENT SERVICES

Mission Planning and Scheduling

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Space System

Mission Operations

Flight Dynamics

Ground Stations

Ground Stations

Science Planning

Science Planner

Science Planner

Science Planner

Mission Control Segment

Science Ground Segment
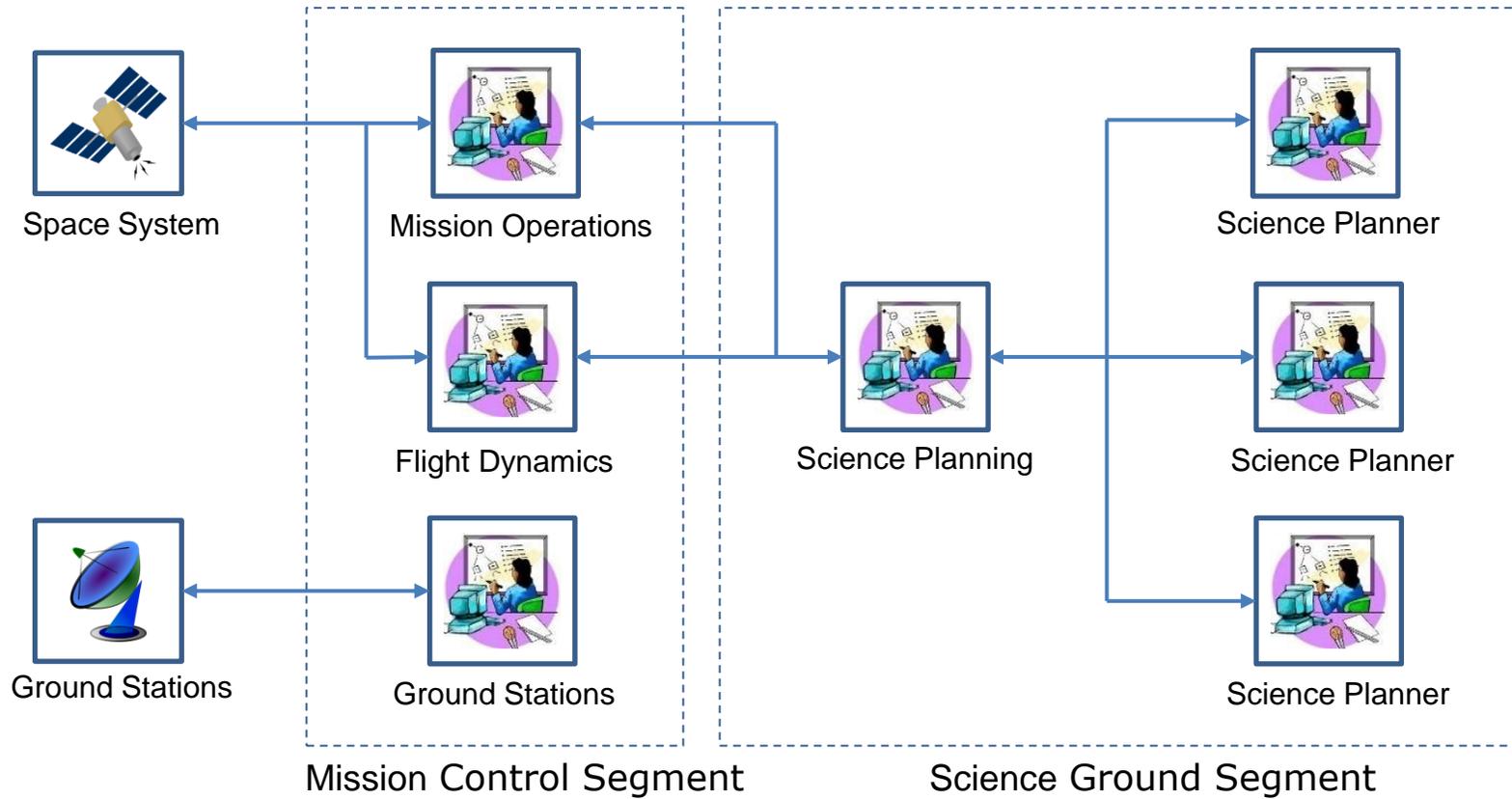
- The interactions within the scope of Mission Planning and Scheduling standardization can be grouped into four principal topics, potentially corresponding to services:

1. Planning Request
   - Asynchronous submission of Planning Requests, associated responses, and their subsequent management and status feedback
2. Plan Distribution and Retrieval
   - Distribution and access to the Plans generated by the planning function
3. Planning Process Management
   - Management of the planning process itself—initiation, monitoring and control, and configuration
4. Plan Execution Management
   - Management of the execution of Plans by a Plan Execution function - initiation, monitoring and control, editing of the currently executing Plan, update of Planning Events and resources, and configuration

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Functions Involved in Mission Planning

Scope of MPS Standardisation

Planning User

Planning Requests
Planning Process Management

Navigation — **Predicted Events** → Planning

Cross Support Scheduling

TT&C

Plans
Plan Execution Management

The specification of the services does not prescribe the planning process or algorithms used by the Planning application

Plan Execution

Monitoring & Control Automation

Mission Control

Mission Planning and Scheduling Services

- The Mission Planning and Scheduling working group is one of the newest CCSDS groups – 2 or 3 years old

- Plan is to address two full, but aligned, concepts
  1. Full set of service specifications compatible with MO Service framework
  2. Set of data formats to allow exchange of planning and scheduling products for those that do not adopt the full MO framework

- A descriptive "GREEN Book" has been published, actual specifications are not yet complete

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MISSION OPERATIONS AND INFORMATION MANAGEMENT SERVICES

Navigation

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CCSDS Navigation Data Standards

- There are currently six published standards for the exchange of spacecraft navigation data, each defined in its own Blue Book
  - Orbit Data Message (ODM)
  - Tracking Data Message (TDM)
  - Attitude Data Message (ADM)
  - Conjunction Data Message (CDM)
  - Re-Entry Data Message
  - Pointing Request Message (PRM)

- CCSDS Navigation standards are <u>format-based</u> standards and are independent of transport mechanisms or service specifications. MO services to utilize (wrap) these formats may be defined in the future.

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- Orbit Data Message (ODM) Blue Book
  - Specifies message formats for use in transferring spacecraft orbit information between space agencies and commercial or governmental spacecraft operators. Version 2 defines a new message, the Orbit Mean-Elements Message (OMM), and adds capabilities to the messages specified in the original issue.

- *Tracking Data Message (TDM).* Blue Book.
  - Specifies a standard message format for use in exchanging spacecraft tracking data between space agencies.

- *Attitude Data Messages (ADM).* Blue Book.
  - Specifies two standard message formats for use in transferring spacecraft attitude information between space agencies.

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Navigation Blue Books (2 of 2)

- *Conjunction Data Message (CDM).* Blue Book.
  - Specifies a standard message format for use in exchanging spacecraft conjunction information between data originators of conjunction assessments, satellite owner/operators, and other authorized parties. Such exchanges are used to inform satellite operator(s) of conjunctions between objects in space to enable consistent warning by different organizations employing diverse conjunction assessment techniques.

- *Re-entry Data Message.* Blue Book.
  - Specifies a standard message format to be used in the exchange of spacecraft re-entry information between Space Situational Awareness (SSA) or Space Surveillance and Tracking (SST) data providers, satellite owners/operators, and other parties. These messages can be used to inform spacecraft owners/operators of predicted re-entries or warn civil protection agencies about potential ground impacts.

- *Pointing Request Message (PRM).* Blue Book.
  - Defines a standardized format that allows space agencies and operators to exchange information about requested (sequences of) changes to the attitude of the spacecraft or to an articulated spacecraft component.

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MISSION OPERATIONS AND INFORMATION MANAGEMENT SERVICES

Data Archive

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Data Archive

- *CCSDS has created a unique data archive suite of standard to allow the very long-term storage of data. Assume you must store information on the data formats themselves along with the data. What if WORD is not the standard format 25 years from now?*

- *Used in many library systems across France.*
- *GOOGLE has been very interested and sends a representative to the meetings.*
- *Has not been used for mission operations data.*

- *Data Entity Dictionary Specification Language (DEDSL)—Abstract Syntax* - Blue Book

    - The Data Entity Dictionary Specification Language (DEDSL) standardizes of the expression of semantic concepts that are to be carried with data.

    - DEDSL--Abstract Syntax provides the abstract definition of the semantic information that is required to be conveyed and presents the specification in a layered manner (attributes, entities, dictionaries). As such the actual technique used to convey the information is independent of the information content; therefore the same abstract standard can be used within different formatting environments, and the semantic information may be translated to different representations as may be needed when data are transferred across different domains.

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Important References

Reference	URL
RF Link	http://standards.gsfc.nasa.gov/reviews/453-133/453-133.pdf
RF Link Study	http://deepspace.jpl.nasa.gov/advmiss/docs/phase1.pdf
LDPC Codes	http://cwe.ccsds.org/sls/docs/SLS-CandS/Meeting%20Materials/2008/200803.CrystalCity/NASA.JPL.Spring08-CCSDS%20ldpc.pdf
Current Blue Books	https://public.ccsds.org/Publications/BlueBooks.aspx
CCSDS Library	https://public.ccsds.org/Publications/default.aspx
SCPS	www.scps.org
SANA GMSEC	sanaregistry.org https://gmsec.gsfc.nasa.gov/
And, of course	www.ccsds.org

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THE PREMIER TELEMETRY EVENT

Q & A

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Thank you

**Robert Ritter
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