Advanced Communications, Navigation and Technology Concepts for a Mars 2018 Orbiter

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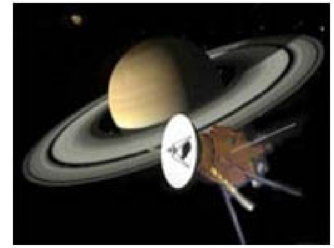
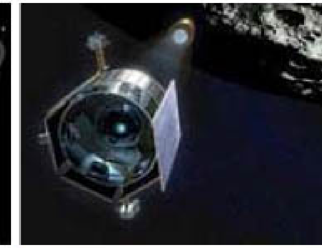
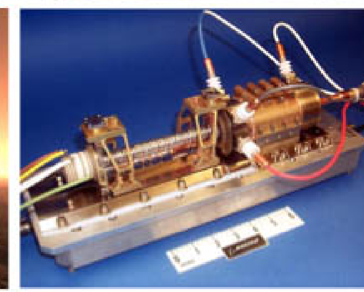
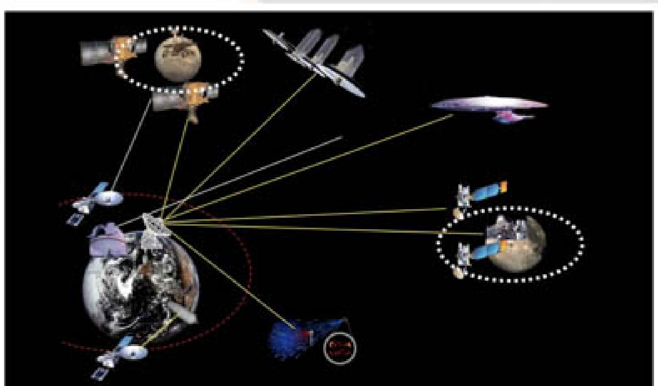
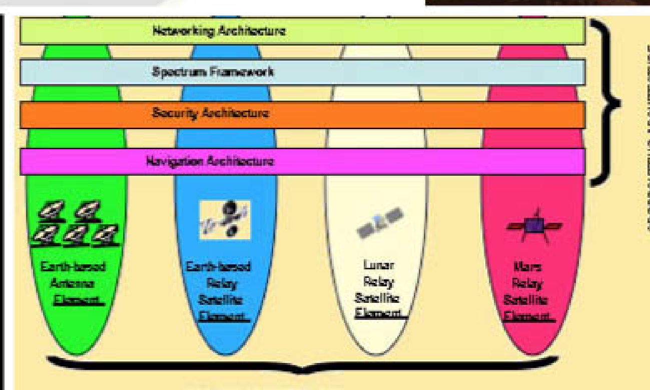



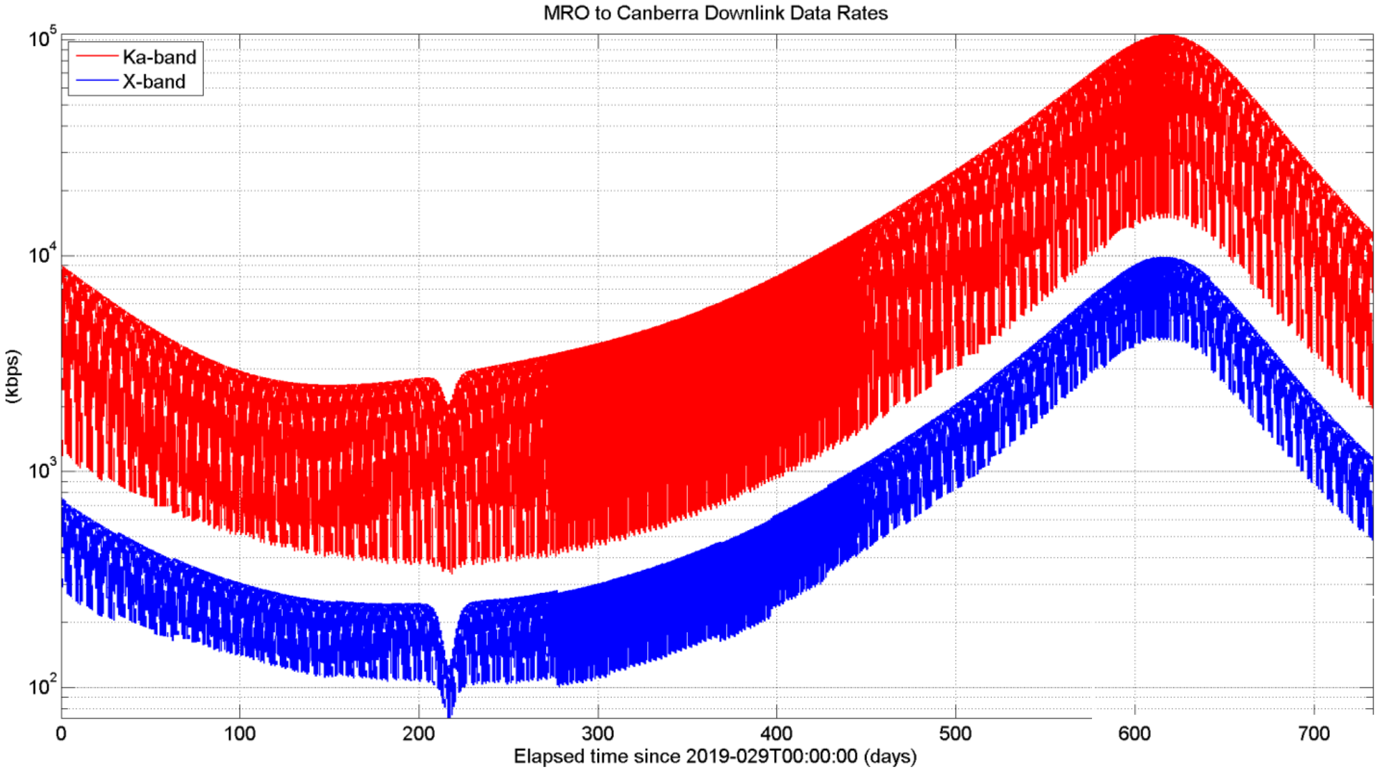


Overview

- High Rate RF Communications
  - Spacecraft System Bottlenecks
  - DSN Bottlenecks
- Optical Communications Technology Demo
- Navigation Technology Demo
  - Rendezvous in Mars orbit and related technologies
  - Autonomous aerobraking
  - ΔDOR at Ka-band
  - One-way radio metric tracking/Deep Space Atomic Clock
  - Ranging at optical frequencies
- Disruption Tolerant Networking (DTN) Demo & Avionic Requirements
  - Flight segment
  - Ground segment
- Summary

Orbiter to Canberra Data Rate Spans (2 Years)
(X-band and Ka-band)

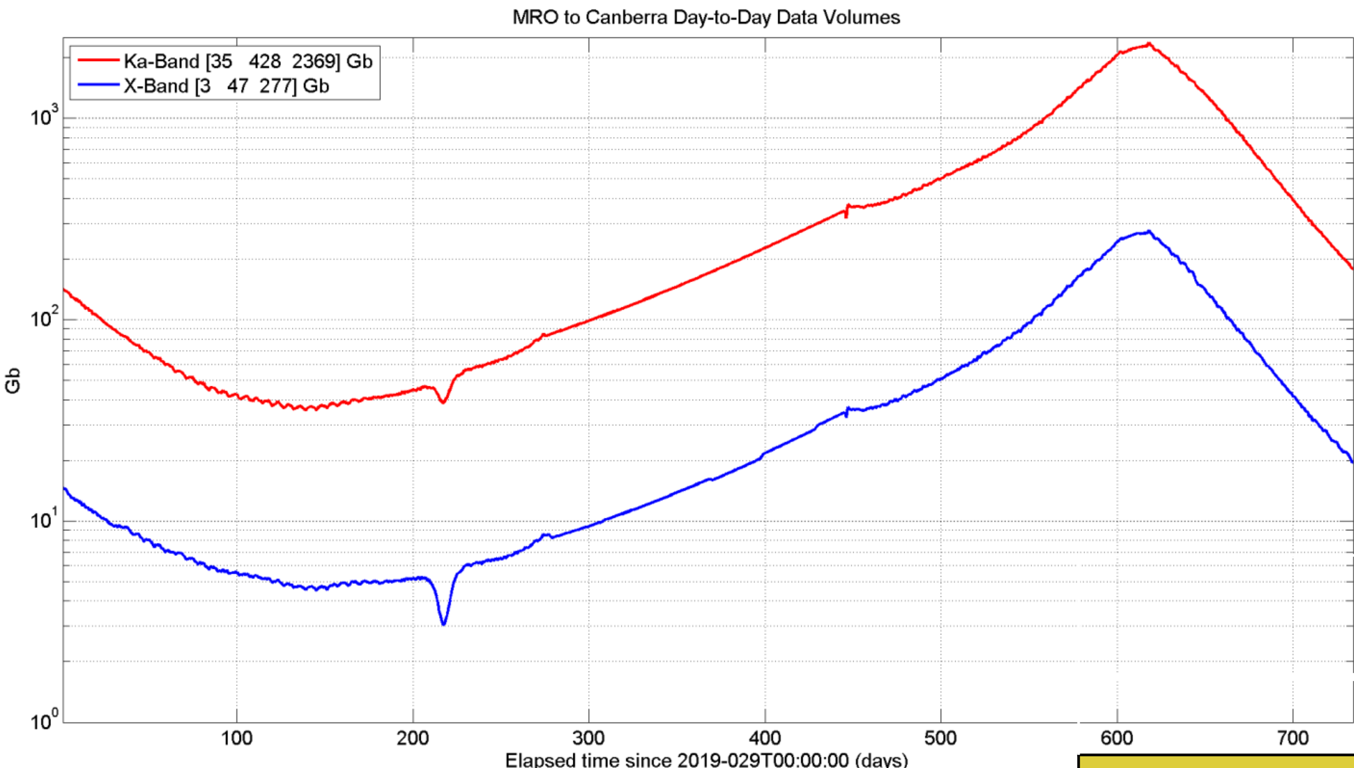


<u>Assumptions</u>:
- Science operations from 01/29/19 – 01/29/21.
- One 8-hour pass / day
- DSN 34-m Beam Wave Guide (BWG) antenna
- Coverage model for celestial body dynamics, spacecraft orbits and station locations
- RF model for signal / noise environment (link quality)
- End-to-end model for protocols and routing of network topology.

	Average Data Rate (kbps)		
	Min	Mean	Max
X-Band D/L	115.5	1756.5	9060.3
X-Band U/L	315	2604	13169.7
Ka-Band D/L	2127	22225	110505

- **Data rates are a strong function of the Mars–Earth range, which varies widely over the two-year synodic period.**
- **Downlink data rates at Ka-band are typically 10 times those at X-band**

Orbiter to Canberra Data Volumes (2 Years) (X-band and Ka-band)



<u>Assumptions</u>:
- Same as previous.

	Daily Data Volume (Gb)		
	Min	Mean	Max
X-Band D/L	3.8	56.1	344
X-Band U/L	9.9	83.4	505.0
Ka-Band D/L	68.7	691	4140

- **Data volumes are, again, a strong function of the Mars–Earth range.**
- **Downlink data volumes at Ka-band are typically ten times those at X-band**

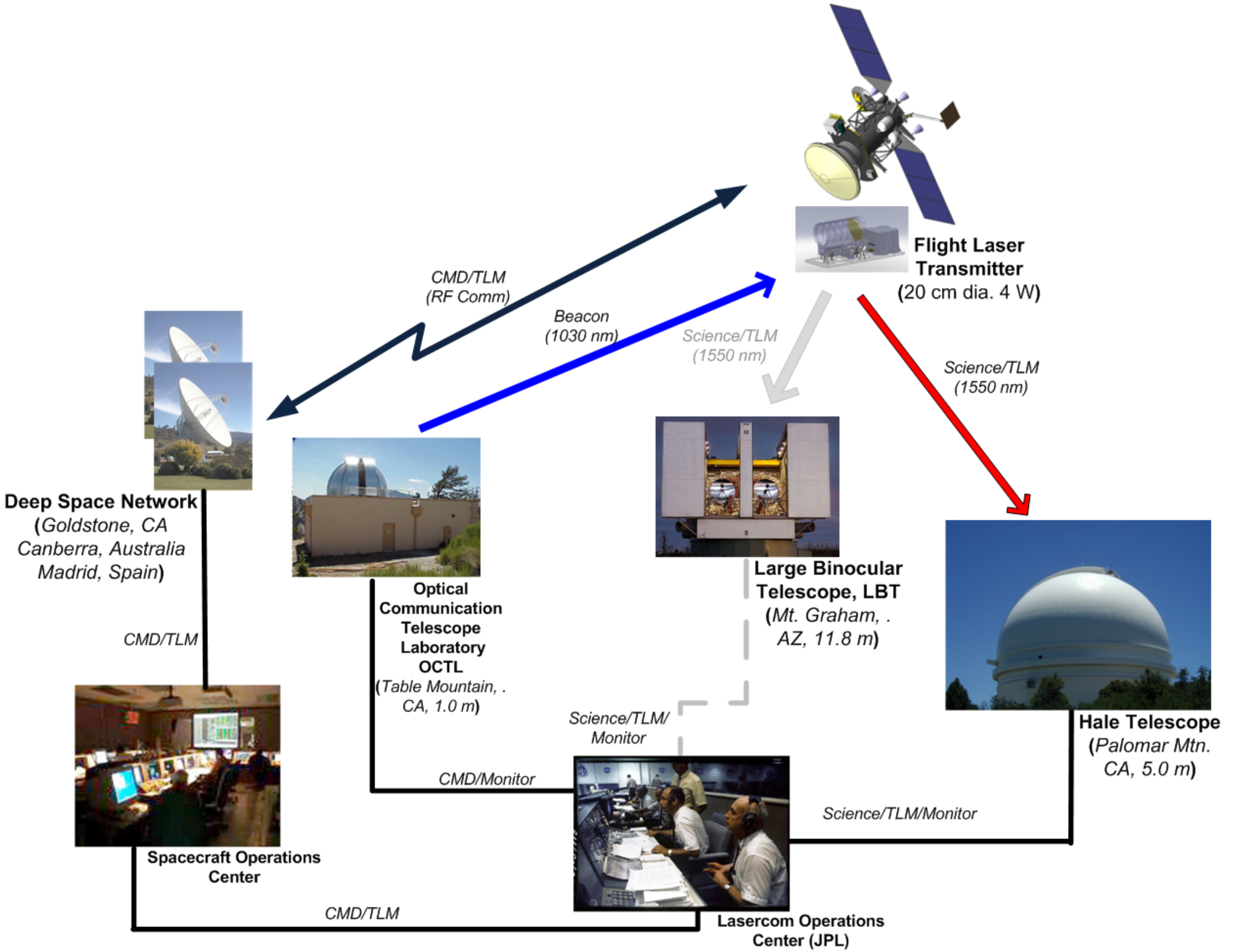
High-Rate RF Communications & Spacecraft System Bottlenecks

- Current Command & Data Handling (C&DH) avionics limited to ~6 Msps throughput
  - Limitations will have to be relieved to realize Ka-band data rates
- Current Solid State Recorders (SSR) have a capacity of ~160 Gb.
  - Will have to increase to accommodate daily Ka-band data volumes
- Current radio of choice is the *Small Deep Space Transponder* (SDST):
  - Frequencies: Deep space S- or X-band, Ka-band
  - Uplink: 4 kbps (uncoded)
  - Downlink: 6 Msps (typically coded)
  - Encryption/decryption: None
  - Operates at the required frequencies
  - Can support lower downlink rates for links at large Mars-Earth range
  - Becomes a flight-side bottleneck at closer ranges on the downlink
  - Can only receive a very limited uplink rate (<< X-band link can support)
- Next-Gen radio (albeit notional) is the *Universal Space Transponder* (UST):
  - Frequencies: Deep space S- or X-band, Ka-band
  - Uplink: 26 kbps (uncoded) up to 6 Msps (coded)
  - Downlink: ≥ 80 Msps (typically coded)
  - Bandwidth Efficient Modulation: Quadrature Phase Shift Keying (QPSK); Offset-QPSK or Gaussian Minimum Shift Keying (GMSK)
  - Encryption/decryption: Advanced Encryption Standard (AES)

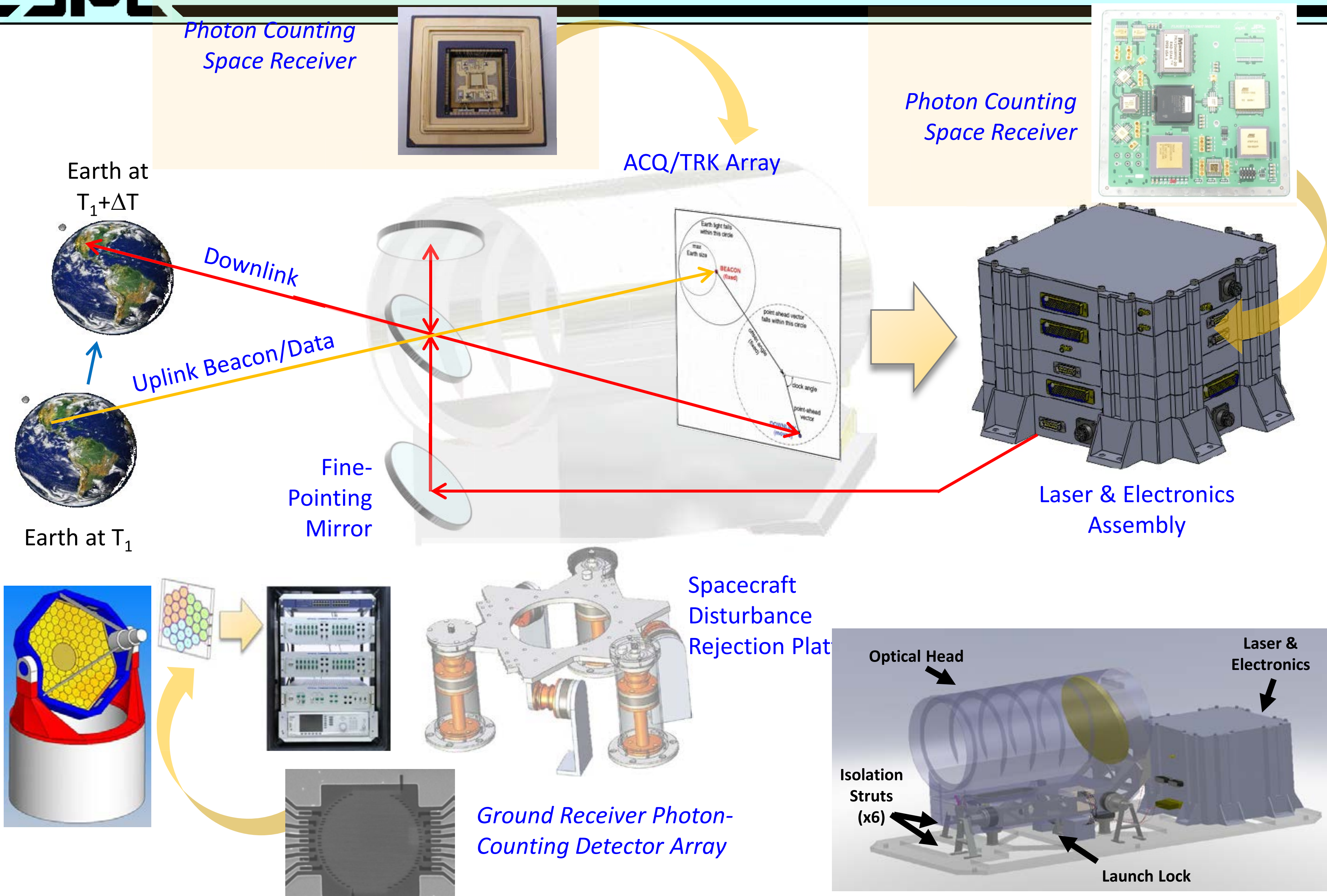
High-Rate RF Communications & Ground System Bottlenecks

- For downlinks ≤ 26 Msps, current system throughput is sufficient
  - To triple the downlink rates (as seems likely) augmentation is in order
- Deep Space Receiver/Telemetry Processor will need increased capacity
  - High-rate commercial receiver similar to the Near Earth Receiver/Telemetry Processor
  - Next generation wideband high-rate receiver being prototyped at JPL
- Demodulators and decoders
  - Missions currently utilize BPSK/QPSK with convolutional, Reed–Solomon or Turbo codes
    - DSN currently supports convolutional and Reed Solomon codes at high data rates
    - Turbo codes have more gain – but are complex and hard to decode (a few Mbps limit)
  - Low Density Parity Check (LDPC) codes enable high rate decoding with high coding gain
  - At higher rates, channel allocations become filled requiring bandwidth-efficient modulation.
    - A likely option is Gaussian Minimum Shift Keying (GMSK)
  - New modulation and decoding techniques are recommended by CCSDS
    - Enhance performance as well as interoperability with other missions or service providers
- Data received at DSN complexes must be sent back to JPL or some other specified destination
  - Commercial leased lines provided via NASA Integrated Services Network (NISN)
  - As data volumes increase, so must the leased line capacity – but no technology challenge
- Above upgrades assume a link between a Mars 2018 orbiter and a single DSN 34m antenna
  - If two antennas are arrayed, then all numbers increase by 2x, and so on . . .
  - Remote sensing spacecraft, with modern instruments, can far exceed downlink capacity
  - Project requirements for arrayed passes can significantly enhance downlink performance

Lasercom Demonstration Architecture

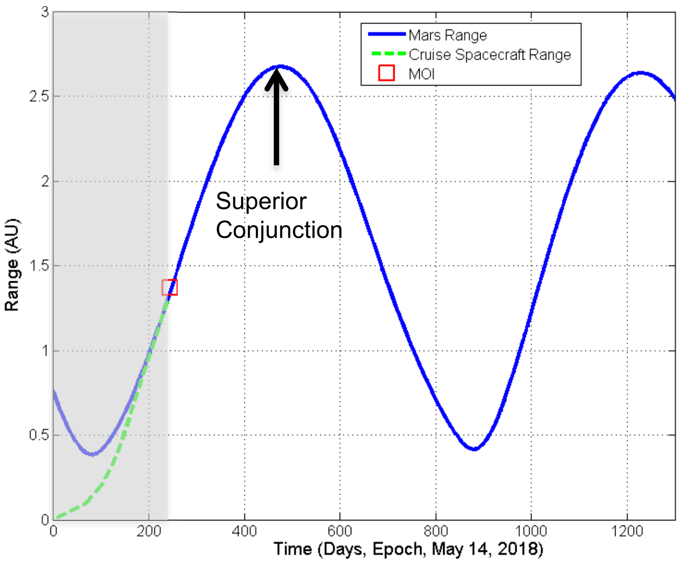


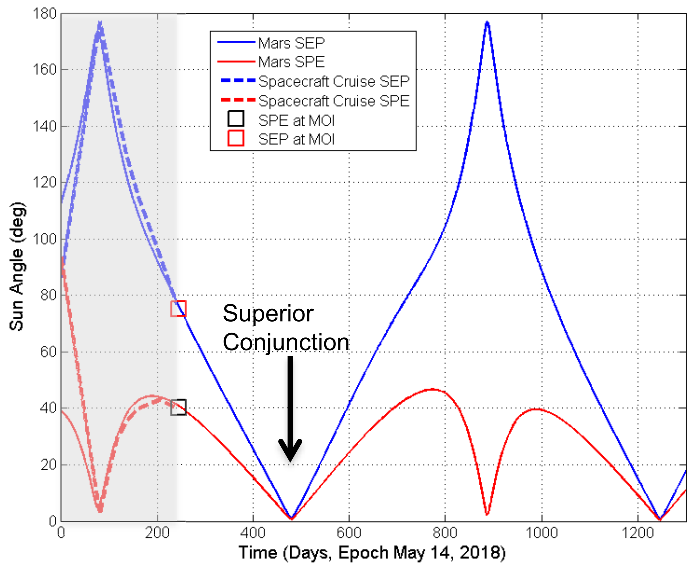
Key Technologies for Deep-Space Demo Under OCT Development



Mars 2018 Optical Comm Demo

- **Wide variety of ranges and deep-space link conditions during cruise (5-months) and following MOI (> 4 years)**
  - **Ranges from 0.2-1.37 AU during cruise and 0.42-2.64 AU following MOI**
  - **Sun angles**
    - **Minimum SEP angle supportable using the Hale telescope is 12-20°**
      - **Need new build to support operations at 3-5° SEP**
    - **Flight terminal designed for 2-deg SPE operation**





Link Outage Summary

Min SEP	Days of Outage	Min SPE	Days of Outage
20	120	2	19
12	72		
5	30		
3	17		

Diverse link conditions encountered during cruise and orbit phases of mission

Rendezvous in Mars Orbit
(and Related Technologies)

- **2018 Mars opportunity could demonstrate proximity operations, as well as rendezvous and docking in Mars orbit, all likely required for eventual Mars Sample Return**
  - Updated version of MRO optical navigation camera could demonstrate autonomous navigation in Mars orbit by imaging Phobos or Deimos against background stars or by tracking landmarks on Martian surface
  - Optical navigation camera might also be able to produce science-quality mapping images of Phobos and Deimos

- **Orbiter could deploy pop-out (university?) cubesat with COTS release mechanism**
  - Orbiter spacecraft would locate cubesat with optical navigation camera, to simulate search for sample capsule; rendezvous & docking would follow
  - Cubesat could demonstrate FEEP (field-effect electric propulsion)

Autonomous Aerobraking

- **Aerobraking atmospheric passes must occur at altitudes such that**
  - **Aerodynamic forces or heating rates are within spacecraft design limits**
  - **Aerodynamic effects are still sufficient to modify the orbit in a timely fashion**

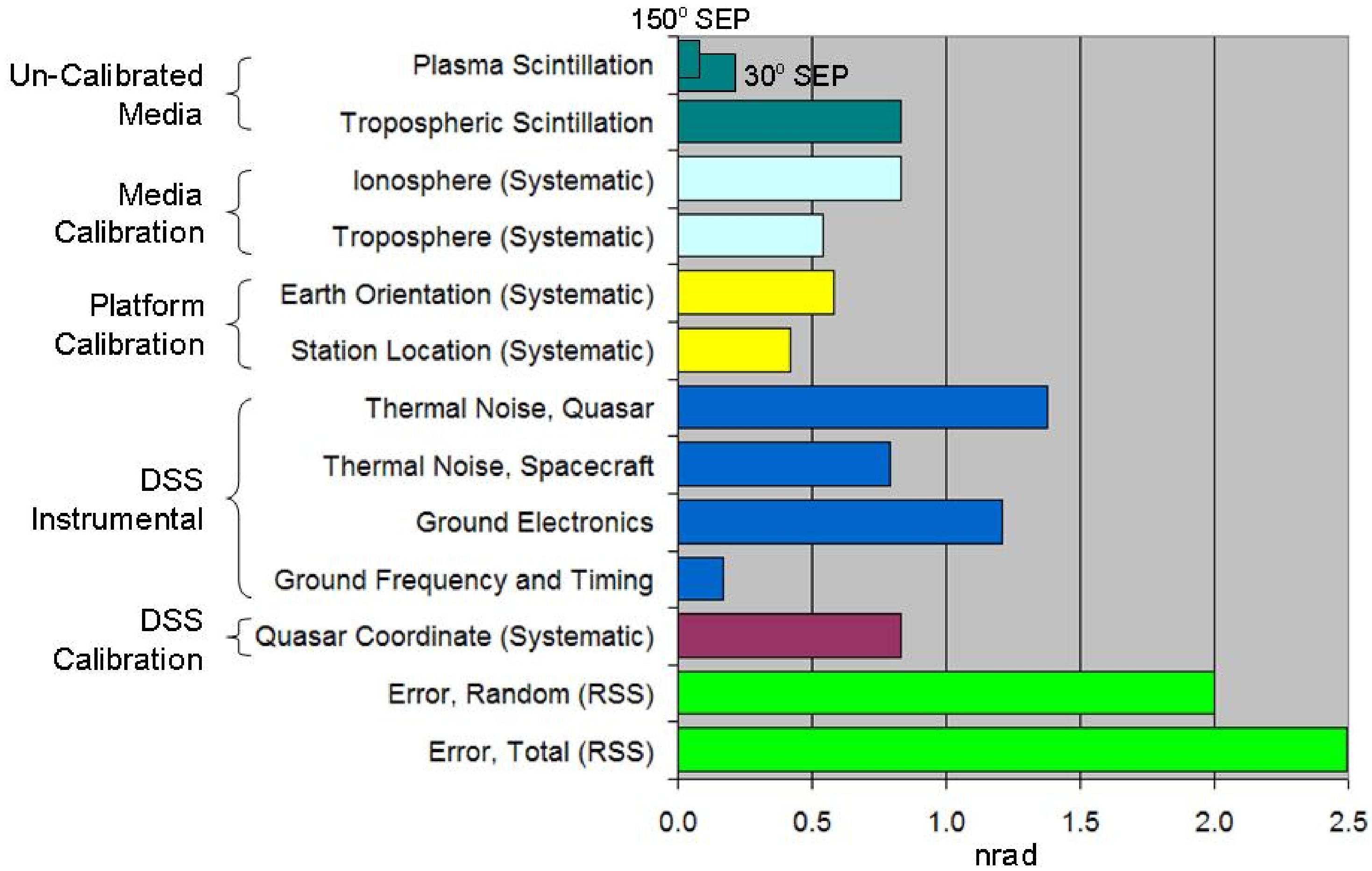
- **Given periapsis orbit accuracy requirements, along with the duration of the aerobraking process, an on board means of automating orbit determination and periapsis altitude control is desired.**
  - **Spacecraft accelerometer data will be an enabling capability**

- **NASA activity, led by LaRC with JPL participation, is developing autonomous aerobraking techniques**

Ka-Band ΔDOR Data

- ΔDOR performance has likely been pushed as far as possible at X-band
- Next significant advance will come by transitioning to Ka-band
- Important spacecraft feature is Ka-band DOR tone at 120 to 160 MHz
  - MRO Ka-band downlink demo (2005) used DOR tone of 76 MHz
  - Results indicated that higher frequency DOR tone was needed to get Ka-band performance that surpasses X-band
- Improved ΔDOR accuracy using Ka-band should be validated
  - When spacecraft enters Mars orbit, absolute accuracy of ΔDOR can be validated, using ephemeris of Mars as truth model
  - Future projects can then plan to use newly validated capability
- S/C-S/C ΔDOR demo opportunities may exist, for spacecraft near Mars
- 2018 orbiter might provide a Ka-band beacon for future Mars missions
- Ka-band ΔDOR reduces key error sources of X-band ΔDOR
  - Reduce charged-particle errors by 15x ($1/f^2$ frequency dependence)
  - Reduce thermal noise and ground electronics errors by 4x (increased B/W)
  - Reduce quasar position errors by 4x (more compact radio sources)
- ΔDOR and telemetry should migrate to Ka-Band contemporaneously

Typical DSN ΔDOR Error Budget at X-Band



From Border, J. S., Lanyi, G. E., and Shin, D. K., "Radiometric Tracking for Deep Space Navigation," in *Advances in the Astronautical Sciences: Guidance and Control 2008*, Vol. 131, edited by M. E. Drews and R. D. Culp, Univelt, San Diego, 2008, pp. 309-328.

Deep Space Atomic Clock (DSAC)

- Scheduled for Earth orbit flight (2015) as NASA Tech Demo Mission
- A deep-space follow-on demo could be done with 2018 Mars orbiter
  - Mass and power would be reduced for more fully flight-ready instrument
  - Long-haul, as well as in situ, links could be demonstrated
- Use of DSAC on Mars approach may reduce demand on DSN antennas
  - Tracking is typically continuous during last 45 days of Mars approach
  - Tracking in 2-way mode can accommodate single spacecraft per antenna
  - Tracking in 1-way (downlink only) mode can accommodate multiple spacecraft per antenna (MSPA), allowing antenna sharing among missions
- Use of DSAC in Mars orbit can take full advantage of MSPA, allowing more extensive tracking coverage of each orbiting spacecraft
  - Enables improved orbit knowledge, better gravity field determination, improved radio science, and more accurate and robust aerobraking
- 1-way Ka-band downlink (with DSAC) improves accuracy over 2-way, i.e., X-up/Ka-down tracking (eliminates higher intrinsic X-band error levels)
- 1-way uplink (with DSAC) allows on-board radio-metric-based '*auto-nav*'
  - Useful in various phases of general planetary missions
  - Radio-metrics, along with optical and inertial, would have broad applicability, desirable accuracy and robustness-to-mismodeling

Laser Ranging

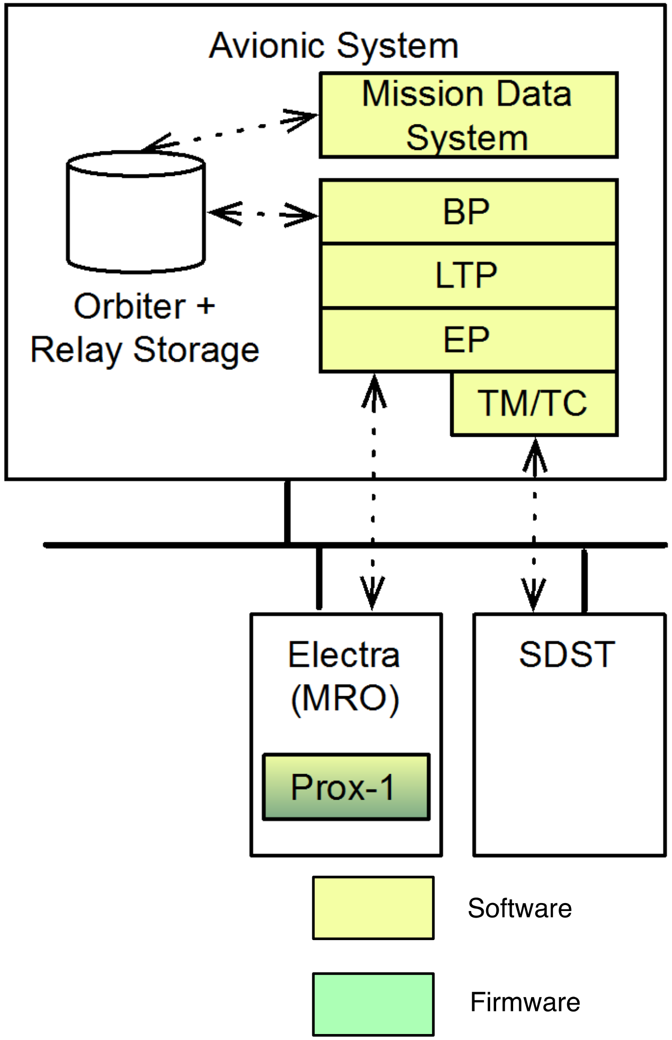
- Metric tracking for navigation should be derivable from deep space communication at optical frequencies
- Lasercom on 2018 Mars Orbiter could allow demonstration of S/C-Earth terminal ranging at optical frequencies
  - Ranging capability can be added to current lasercom development for a modest incremental cost
- S/C-S/C ranging demonstration could be done relative to other Mars orbiting S/C, if any are suitably equipped
  - Secondary spacecraft (e.g., cubesat) could be deployed for this purpose, with corner reflector
- Scientific experiments could be carried out also to obtain
  - Improved estimate of post-Newtonian parameter gamma
  - Improved estimate of Martian ephemeris and 10-20 asteroidal masses
  - Improved Martian gravity field, yielding information on crustal structure and seasonal CO_2 flow, from
    - 2-way laser ranging or 1-way laser range linked to DSAC
  - Note that latter gravity experiment could also be carried out with
    - 2-way Ka-band Doppler or 1-way Ka-band Doppler linked to DSAC
  - Inclusion of accelerometer could further improve gravity field determination

Flight Segment DTN Implementation

- **Integrate *Interplanetary Overlay Network* (ION) S/W with the avionic system (C&DH)**
  - **Re-use telecomm payload design**
    - **(no change from MRO and MAVEN)**
  - **Leverage existing ION software demonstrated on *Deep Impact Network Experiment* (DINET)**
  - **Require further integration with avionic S/W**
  - **Increased processing complexity and load on C&DH**
  - ***Performance can be improved by implementing better storage management and hardware/firmware acceleration on the most tasked processes***
- **Demonstrate DTN integration with avionic system**

Acronym Definitions:
BP = Bundle Protocol
LTP = Licklider Transmission Protocol
EP = Encapsulated Protocol
TM/TC = Telemetry/Telecommand
C&DH = Command & Data Handling

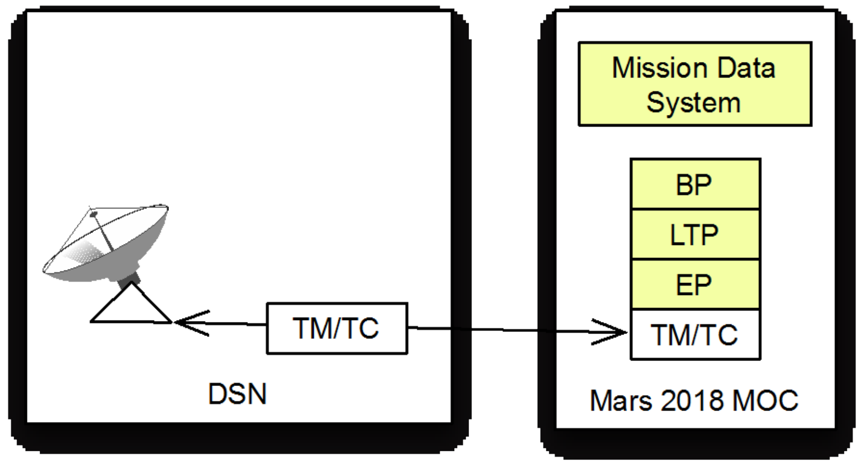
Option 1: DTN in the avionic system



Ground Segment DTN Implementation

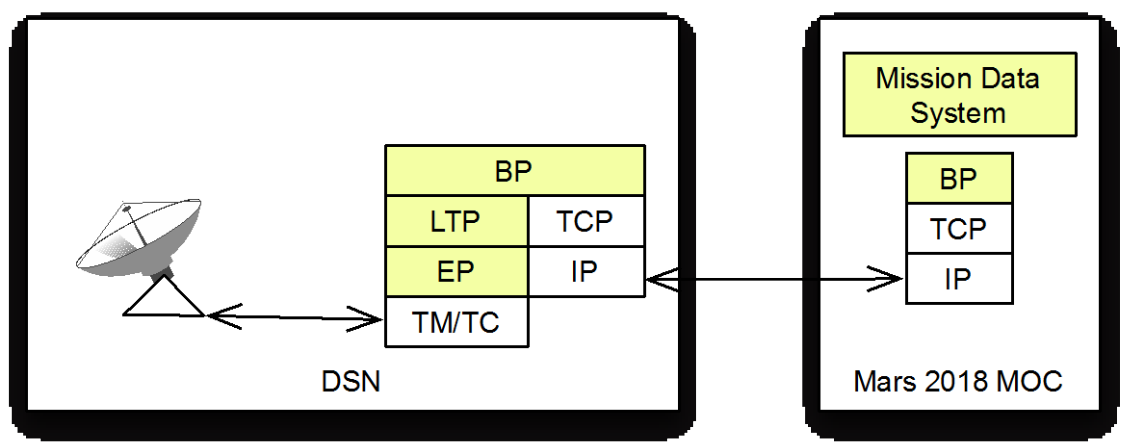
- Option 1: At the MOC only
  - EP, LTP and BP process done by MOC
  - LTP ARQ acknowledgement is generated at the MOC

OPTION 1: DSN PASS-THROUGH



Acronym Definitions:
MOC = Mission Operations Center
ARQ = Automatic Repeat Request

OPTION 2: DTN in DSN



- Option 2: LTP/BP at DSN; BP only at MOC
  - MOC processes Bundles that contain mission data
  - DSN performs framing, encapsulation, and LTP retransmission

Summary

- The paper surveys communications and navigation technology advancements relevant to the design and flight of a 2018 Mars orbiter.
  - Advancements in RF communications, for both the spacecraft and ground ends (i.e., DSN) of the link.
  - Importance of a deep space optical communications demonstration.
  - Advances in navigation techniques, both Earth-based and applicable to proximity operations.
  - Validation of space networking benefits, within the context of DTN.
- A 2018 mission is ‘made to order’ as a platform for advances described.
- These developments would materially contribute to NASA’s long-term goals in science, exploration and technology development.
- A 2018 Mars orbiter could reinvigorate the Mars program as well as provide a rationale for implementation of new capabilities that are important to future spacecraft as well as the future DSN.