A Communications Network for Cislunar Operations

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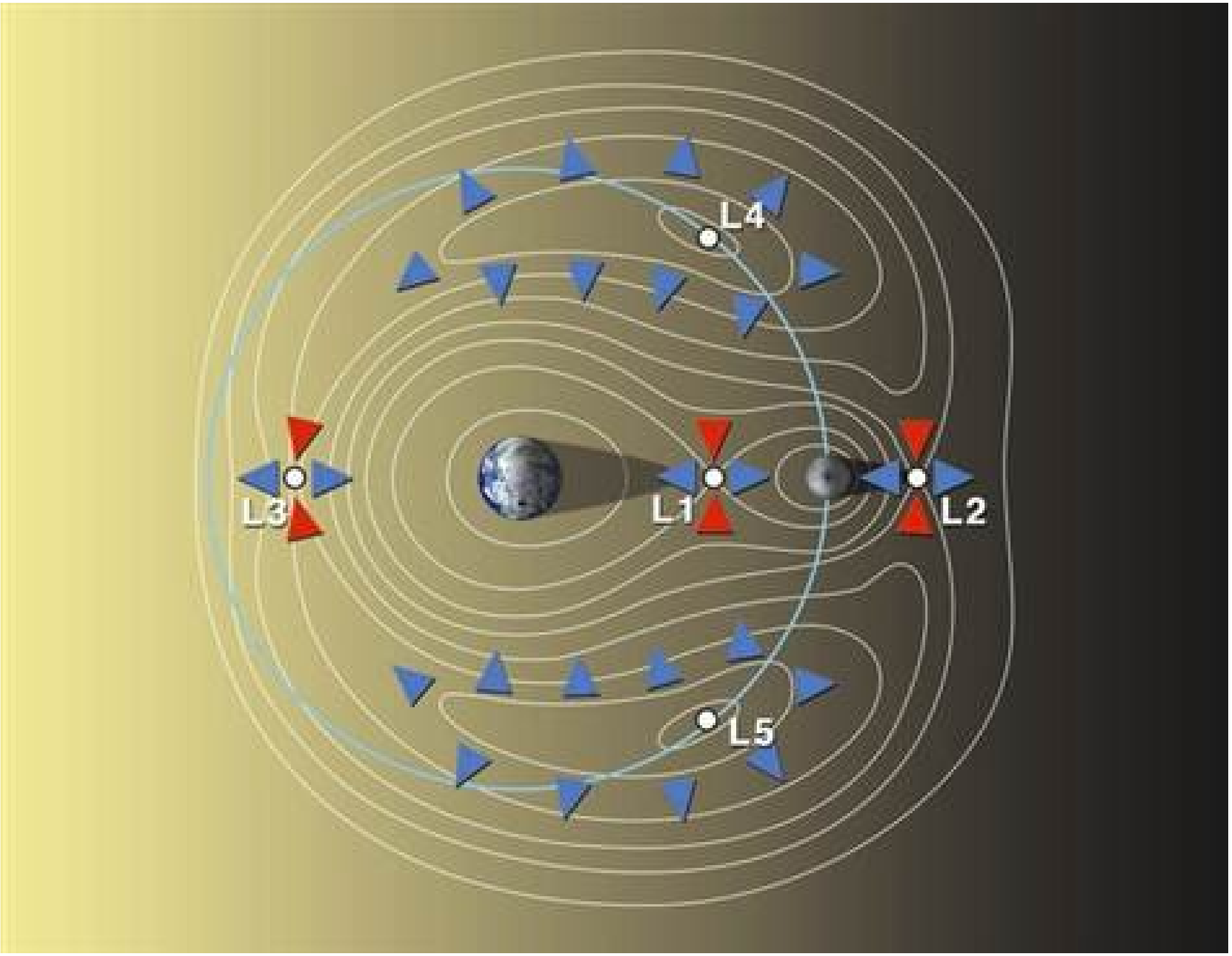
Cislunar Possibilities

- International Space Station: science laboratory, stepping stone to further exploration.
- Constellation studies:
  - Up to five 28-day extended-stay missions at rim of Shackleton Crater, South Pole.
    - Study assumed at least one lunar relay satellite in orbit.
- Newest NASA concept: Outpost at EML-2.
  - Gateway to near-lunar space, asteroids, Mars and its moons. Astronomy, telerobotics, vehicle assembly.
- Surface ops: mining, drilling for water (RESOLVE).

EML-2 Outpost



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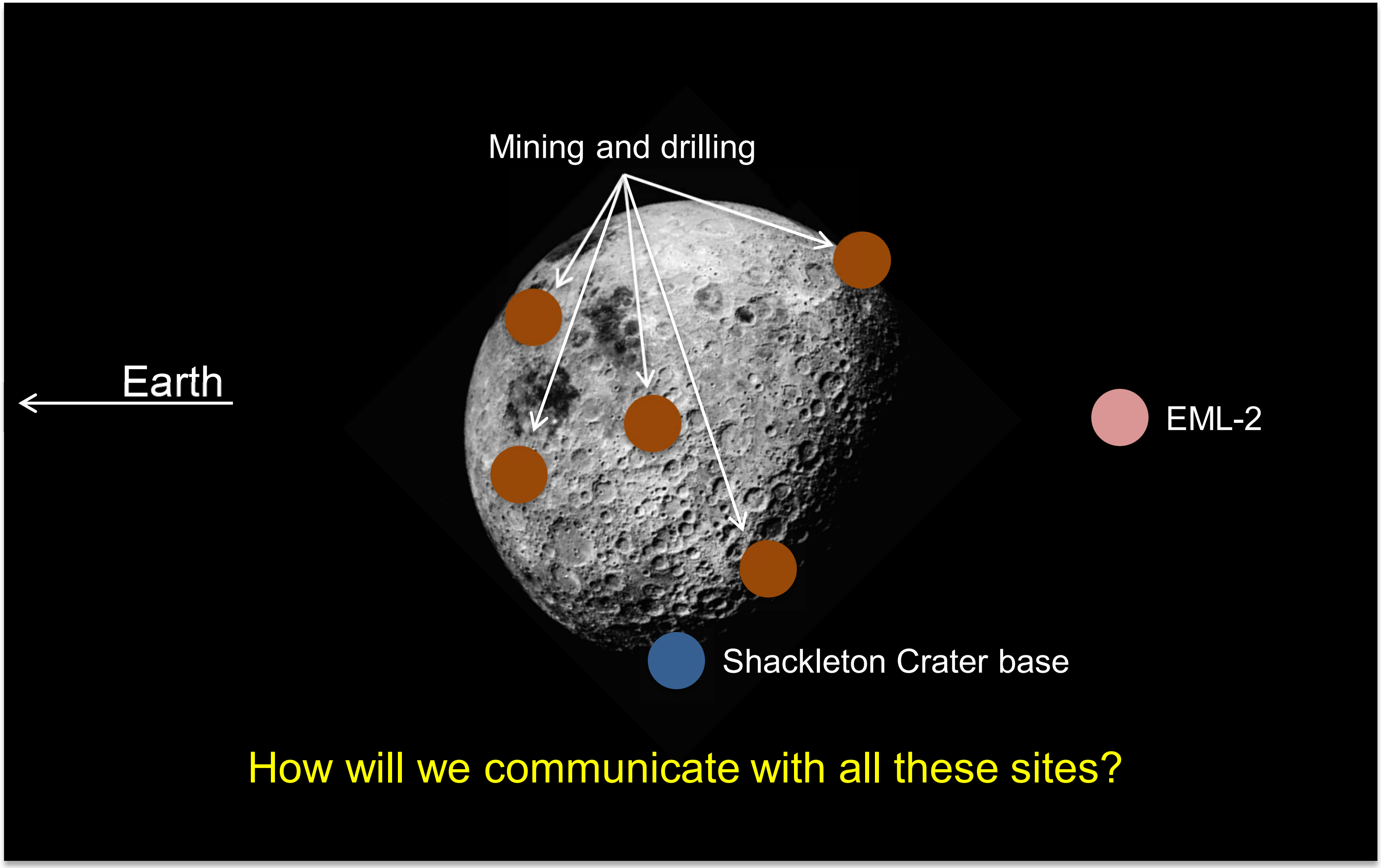
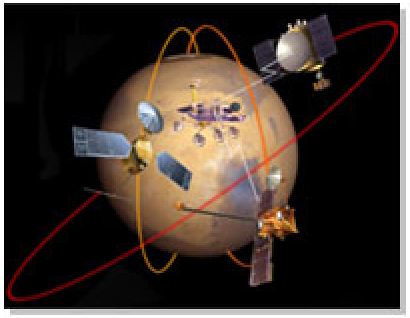
Strawman Lunar Operations



Interplanetary Communications Today

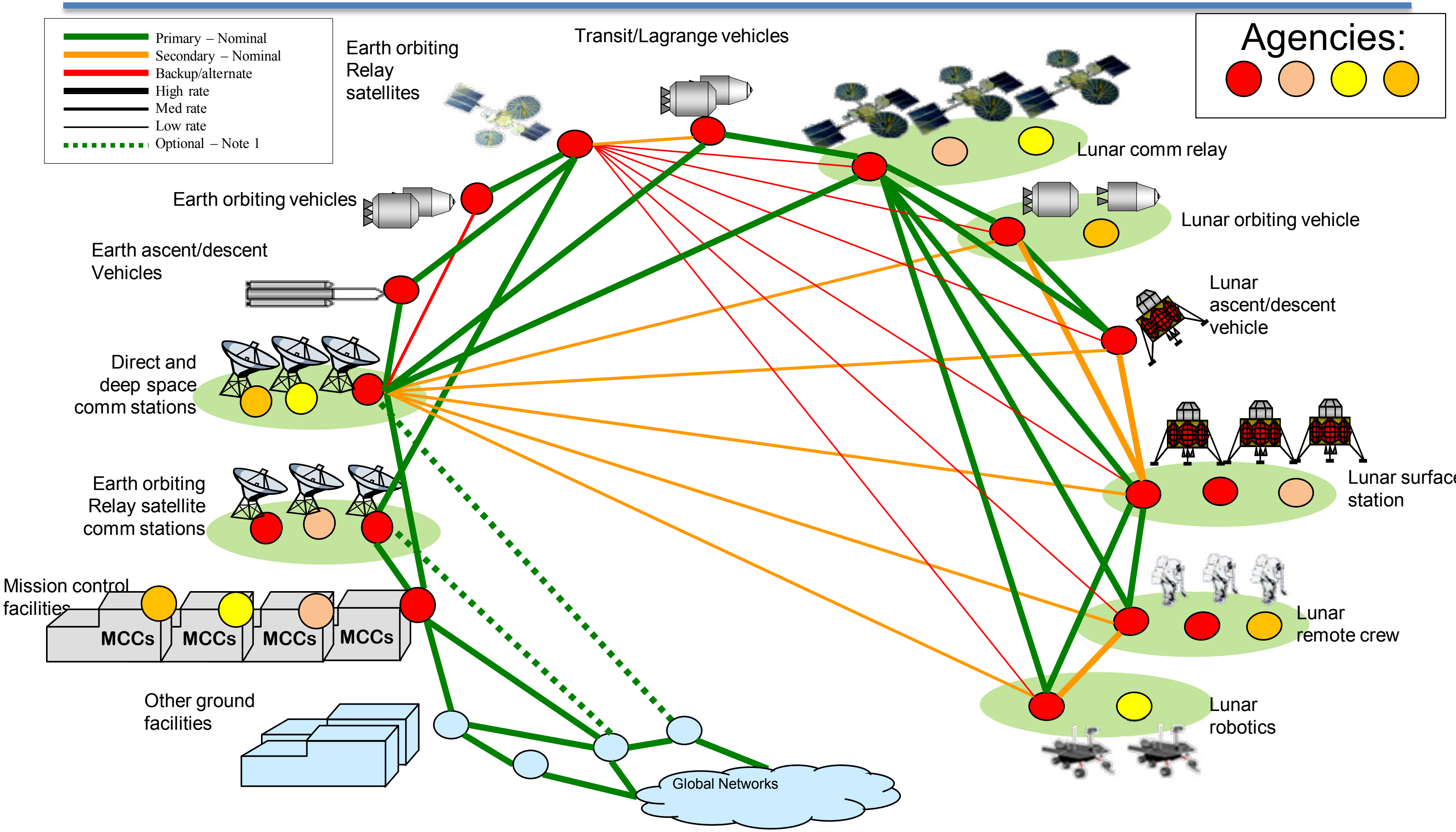
- Communication opportunities are scheduled, based on orbit dynamics and operations plans.
- Transmission and reception episodes are individually configured, started, and ended by command. S/C to ground.
- Reliability over interplanetary links is by management: on loss of data, command retransmission.
- More recently – MER, Phoenix – we have had managed forwarding through a relay point: TM and some TC via Odyssey and MRO.

What's Wrong With That?



- This mission communications model has worked fine for over forty years; we've done a lot of good science.
- But the status quo is:
  - Labor-intensive
    - Communication operations cost is a large fraction of the budget for each mission.
    - Risk of human error mandates mitigations that further increase cost.
  - Program-limiting
    - Cost and risk increase with the number of links between communicating entities.
    - As cross-links among spacecraft become more common (e.g., cislunar operations), cost and risk increases are non-linear with increase in the number of spacecraft.

Lunar Manned Mission Profile



Note 1 – Session data from other facilities may or may not be required to go through MCC "gateway". Architecture supports both options.

An Alternative

- The Internet is very widely used on Earth, not only for commerce and social networking but also for science investigations and engineering operations.
- So why not use it for cislunar operations and interplanetary science missions too?
  - Minimize cost (automation, COTS).
  - Minimize risk (huge installed base).

It Works Fine in Near-Earth Orbit

- Space Communication Protocol Standards (SCPS)
  - TCP options that improve performance on satellite links, where data loss is more often due to corruption than to congestion
  - International standard (CCSDS and ISO as well as DoD)
- Operating Missions as Nodes on the Internet (OMNI)
  - UoSAT-12, an HTTP server in orbit
  - CHIPSat, used Internet protocols on all communication links
  - CANDOS on STS-107, used mobile IP
- IP stack would also work well in surface networks on other planetary bodies.

So What's the Problem?

- Interplanetary space is a qualitatively different environment.
  - Internet, near-Earth, and planetary surface networks are all characterized by:
    - Very short distances between communicating nodes, therefore very brief signal propagation delays (up to a few hundred milliseconds).
    - Continuous end-to-end connectivity. A network partition is treated as an anomaly and allowed to terminate communication.
  - Any network spanning interplanetary space would be characterized by:
    - Long distances between communicating nodes, lengthy signal propagation delays (e.g., 1300 milliseconds from Earth to the Moon, 4-20 minutes from Earth to Mars).
    - Routine network partitioning due to lapses in connectivity on one or more links of the end-to-end path.

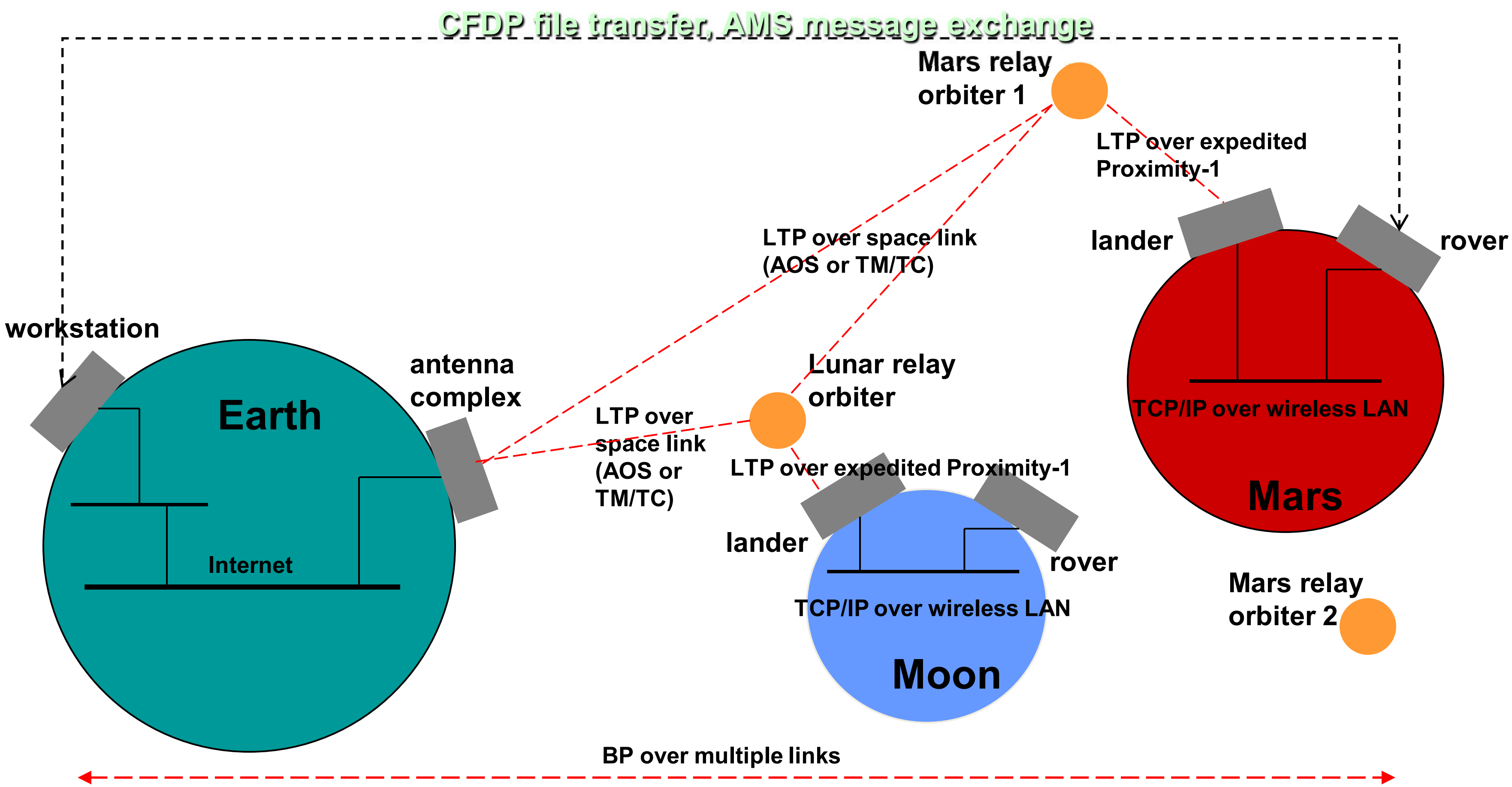
Ruling Out the Internet Architecture

- TCP isn't suitable, for a variety of reasons.
- There's no alternative Internet standard for reliable transmission that would work over interplanetary links.
- So no standards for flow control and congestion control.
- None of the standard routing protocols would work.
  - BGP relies on TCP. Others rely on timers that won't work right.
  - Transient network partitioning would be interpreted as topology changes, an error.
- And no COTS routers would work.
  - Interruption of outbound link must cause outbound traffic to be queued rather than discarded.
- All that's left is UDP/IP with static routing: just a less bit-efficient packaging alternative to raw CCSDS packets.

Delay-Tolerant Networking (DTN)

- An overlay network.
  - DTN "bundle protocol" (BP) is to IP as IP is to Ethernet.
  - A TCP connection within an IP-based network may be one "link" of a DTN end-to-end data path; a deep-space R/F transmission may be another.
- Reliability is achieved by retransmission between relay points within the network, not end-to-end retransmission.
- Route computation may have temporal as well as topological elements, e.g., a schedule of planned contacts.
- Forwarding at router is automatic but not necessarily immediate: store-and-forward rather than "bent pipe".
- DOS attacks contained: reciprocal inter-node suspicion.

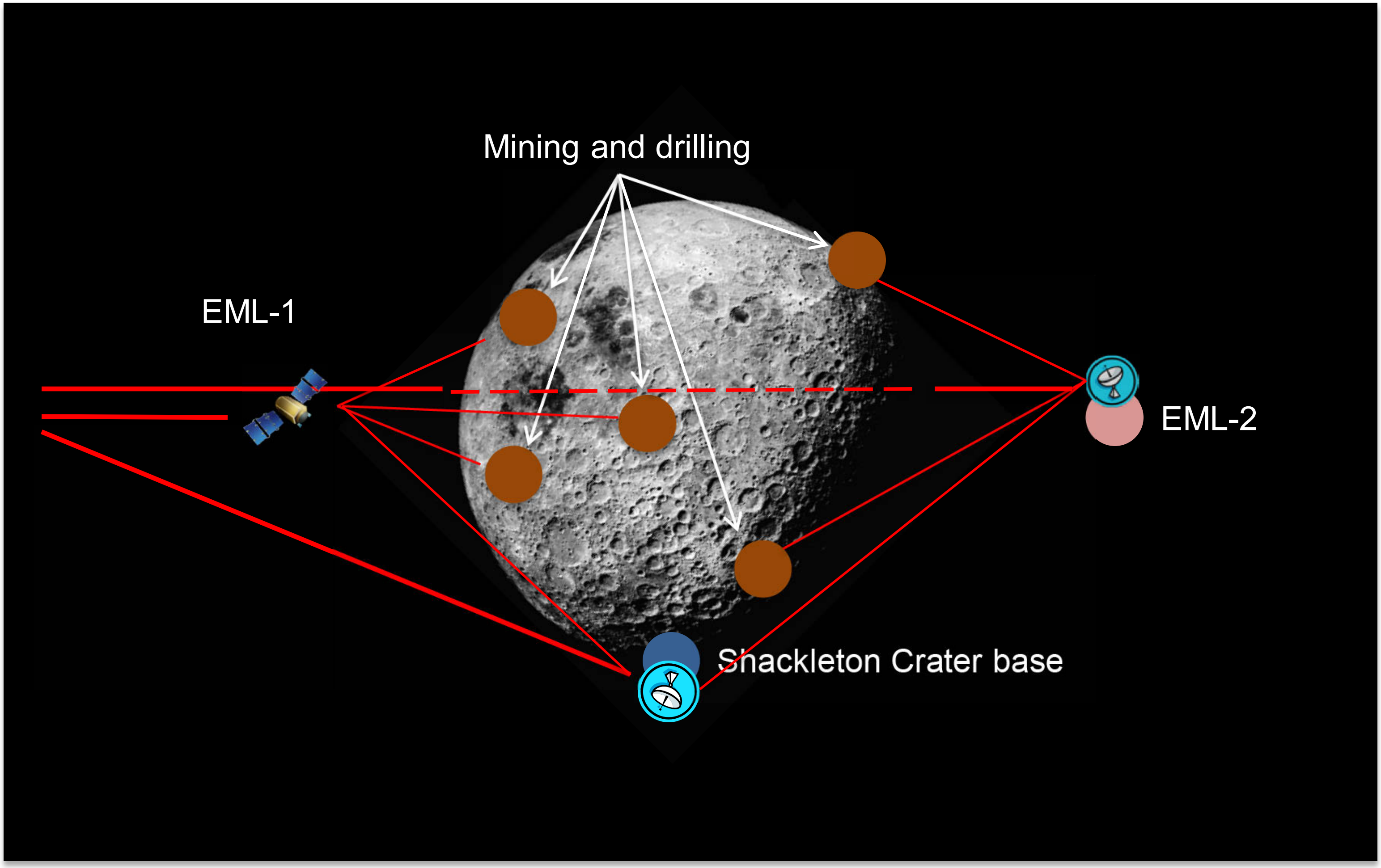
DTN Operations in space



DTN for Mission Communications

- Automatic **relay** operations.
  - Retain data until outbound link is available.
  - Then transmit until link is no longer available.
- Fine-grained **routing**: automatic selection of (possibly parallel) links to transmit over, based on the final destination of the data.
- Automatic selection of data to transmit, based on mission-specified **priority**.
- Automatic **retransmission** of lost or corrupted data.
- Automatic **aggregation** of data into blocks, to limit acknowledgment traffic.
- **Custodial forwarding**, for early release of retransmission buffer space.
- Automatic **congestion control**, based on rate management.
- Automatic **data aging and purging** based on bundle's "time to live".
- Optional status reports for detailed **tracing and data accounting**.
- Support for **file transfer**, **message exchange**, **multi-point delivery**.
- Support for **security**: authentication, encryption.

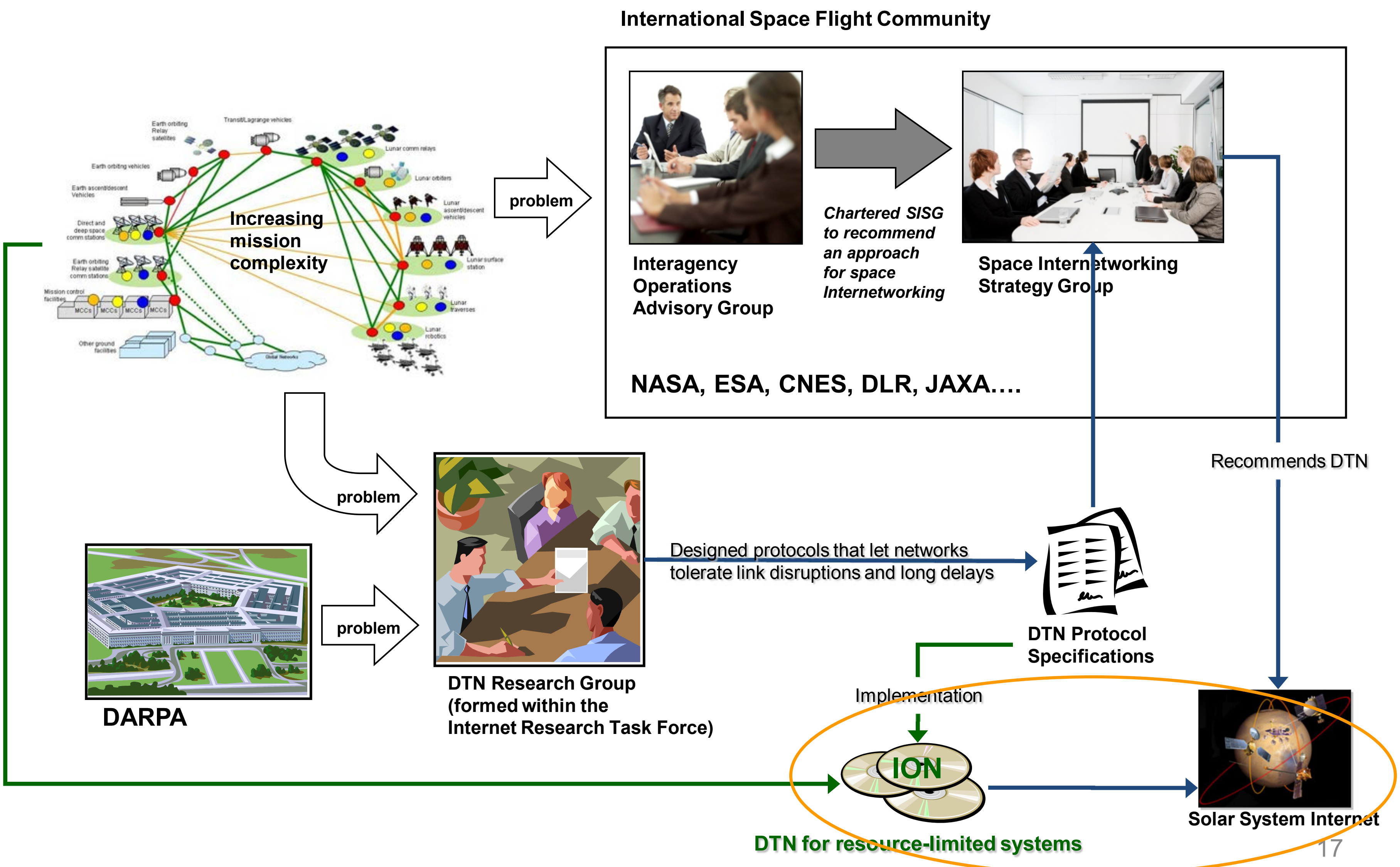
DTN for Cislunar Operations



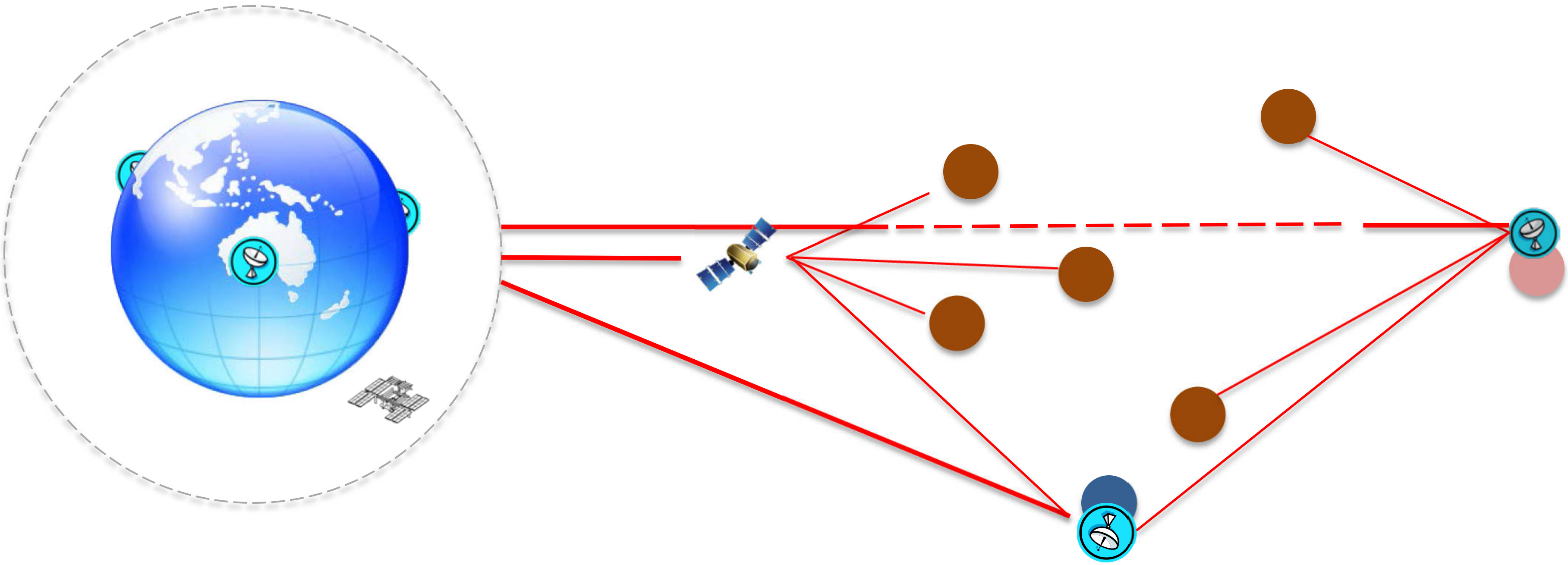
Operations Notes

- The EML-1 relay can be used for communication among the mining sites on the "near side" – and with the Shackleton Crater site – as well as linking with Earth. So the EML-1 node and the Shackleton node offer alternative data paths to Earth.
- The EML-2 outpost similarly enables communication among the "far side" sites and with Shackleton, and from there back to Earth.
- EML-1 altitude from lunar surface is 56,000 km; EML-2 altitude is 67000 km. Halo orbit at EML-2 has angular extent larger than the moon's disk as seen from Earth, so direct-to-Earth links from EML-2 should be possible, offering another alternative data path to Earth.

How Will It Be Implemented?



First Stage of Deploying the SSI



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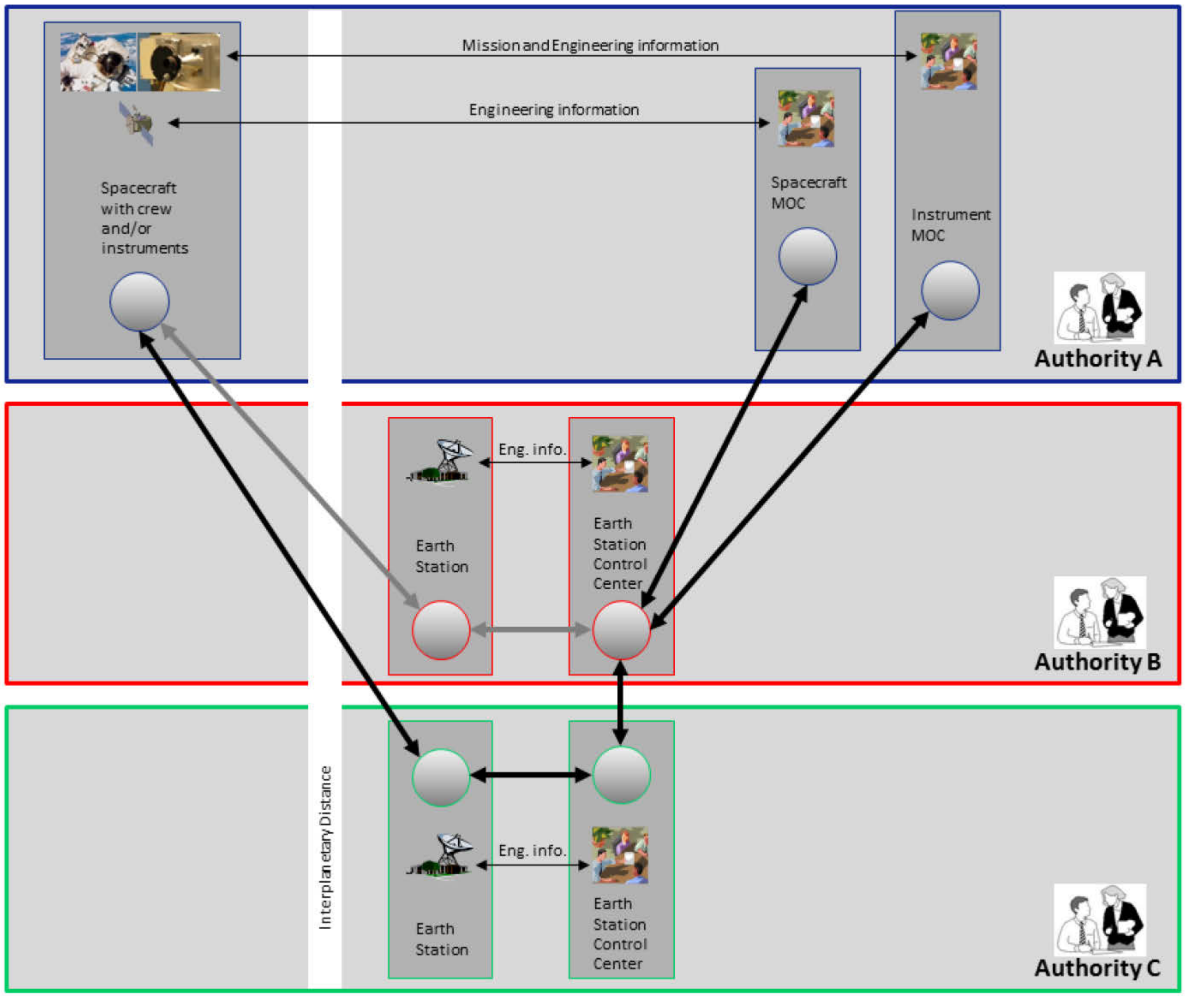
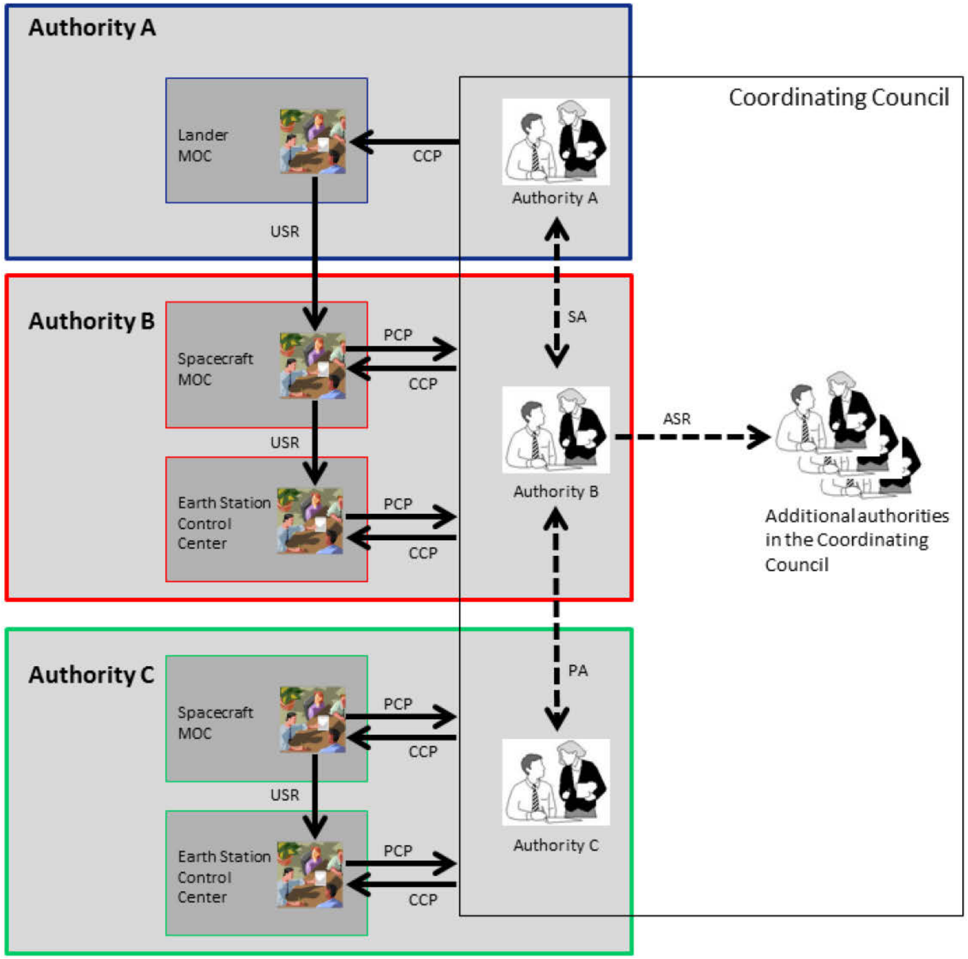
SSI Architecture: Operations Model



SSI Architecture: Coordination Model



Protocols

- Bundle Protocol (RFC 5050)
  - Delay-tolerant forwarding, quality of service, congestion control, tracing and data accounting
  - Data aging and purging
  - Route computation based on contact graphs
- Licklider Transmission Protocol (RFC 5326)
  - Delay-tolerant retransmission of lost data
- Bundle Security Protocol (RFC 6257)
  - Authentication, encryption, integrity protection
- CCSDS File Delivery Protocol (727.0-B-4)
  - Delay-tolerant file transfer
- CCSDS Asynchronous Message Service (735.1-B-1)
  - Delay-tolerant message middleware

Technology

- Interplanetary Overlay Network (ION) implementation of the DTN protocols:
  - Designed to be suitable for use in flight computers.
    - Small footprint, efficient use of processor
    - Private management of a fixed memory allocation
    - Ported to real-time operating systems (VxWorks, RTEMS) as well as Linux, OS/X, FreeBSD, Solaris, Windows
  - Demonstrated on a flying spacecraft (EPOXI) in 2008, acting as an in-space router 15 million miles from Earth.
  - Configuration-managed by the NASA ION Working Group since 2009.
  - Freely available to all national space agencies and commercial space flight providers: http://sourceforge.net/projects/ion-dtn/.

Summary

- Reliable and efficient communications will be critical to the success of commercial flight operations in cislunar space.
- The Internet is not well-suited to meeting this requirement. But the Delay-Tolerant Networking (DTN) architecture is.
- The DTN protocols are well-documented and implementations are mature.
- We think DTN will be ready to support low-cost, low-risk cislunar networking by the time the vehicles are in place.