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Building the Solar System Internet using Disruption Tolerant Networking: NASA's Vision and Deployment Progress

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Abstract

NASA Headquarters began evolving a vision for the Solar System Internet (SSI) in 2005 when JPL was asked by NASA to develop a space networking roadmap for the Agency. This roadmap led to the formation of a NASA-wide project to develop Disruption Tolerant Networking (DTN) protocols and initiated standardization activities within both the Consultative Committee on Space Data Systems (CCSDS) and the Internet Engineering Task Force (IETF). Fast forward to now and DTN has been flight validated in deep space, near-earth and tested in numerous flight and ground demonstrations. DTN has been an operational service on the International Space Station since 2016 and has been used by more than a dozen ISS payloads as a way to more effectively manage precious communications bandwidth. While DTN on ISS is a server-based application for data management and not the protocol used in the space links, it continues to be a powerful use case. Moreover, DTN is operational in NASA's PACE mission for engineering telemetry, which marks the first operational infusion into a NASA Class B science mission. DTN is also a multi-mission operational service within NASA's Deep Space Network. With these and other activities, critical infrastructure components of the solar system internet are beginning to be deployed. Enabling protocols are largely standardized within CCSDS and IETF, and flight and ground system products are available at varying levels of maturity. Adopting DTN benefits most mission types, even single missions, and quantitative assessments of benefit across multiple mission classes have been compiled. Through continued strategic mission adoptions, elements of solar system internet infrastructure will become operational. Over the next few years, the first major instantiation of the SSI is likely to occur in the Lunar vicinity as NASA, industry, and other space agencies begin adopting elements of the LunaNet operations concept and architecture to achieve interoperability among Lunar spacecraft. This paper will describe the vision for a solar system internet and how it differs from the terrestrial internet, the architecture, operational capabilities to date, and the latest roadmap.

Keywords: store-and-forward, bundle protocol, intermittent connectivity, planetary missions, Lunar networks

Acronyms/Abbreviations

APL	Applied Physics Lab
BP	Bundle Protocol
CCSDS	Consultative Committee for Space Data Systems
cFS	Core Flight Software
DSN	Deep Space Network
DSOC	Deep Space Operations Center
DTN	Delay and Disruption Tolerant Networking
ESA	European Space Agency
FY	Fiscal Year
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
ILLUMA-T	Integrated LCRD Low Earth Orbit User Modem and Amplifier Terminal,
IOAG	Inter-Agency Operations Advisory Group

ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KPLO	Korean Pathfinder Lunar Orbiter
LCRD	Laser Communications Relay Demonstration
LEO	Low Earth Orbit
LOS	Loss of Signal
LTP	Licklider Transmission Protocol
LuCCI	Lunar Surface Comm and Autonomy Architecture Project
MSFC	Marshall Space Flight Center
NSN	Near Space Network
O&M	Operations and Maintenance
SCaN	Space Communications and Navigation
SMD	Science Mission Directorate
HEOMD	Space Operations Mission Directorate

1. Introduction

The primary objectives of this paper are to describe the vision of space networking, the advantages that have been achieved through NASA's deployments to date, and the readiness of Delay and Disruption Tolerant Networking (DTN) for use in space missions now. DTN can refer to the concept of space networking or the protocol suite that is key for implementing it. The DTN Protocol Suite extends the terrestrial Internet capabilities into highly stressed data communication environments where conventional Internet protocols do not work. These environments may experience frequent disruptions, long delays, and/or high error rates. In the Internet, each received packet is forwarded immediately if possible, deleted if immediate forwarding is not possible. With DTN, each received packet is forwarded immediately if possible, stored for future transmission if forwarding is not currently possible but is expected to be possible in the future. Using these protocols, we can have a "Disruption Tolerant Network" for space system communications.

2. NASA's Vision for Space Networking

2.1 Towards a Solar System Internet

The initial idealized vision for a Solar System Internet depicted a richly interconnected solar system with long-haul communication links and relay nodes in deep space, as shown in Figure 1. While it was immediately recognized that standalone relay nodes in deep space in the near term would likely be infeasible from a cost standpoint, the main takeaway from this early view was the notion of a "network of internets" where highly connected delay/disruption tolerant communications would be available in the places in the solar system where the most space assets would be concentrated, such as the Moon and Mars. Another key understanding of this vision is that it would surely be implemented incrementally such that the network would be gradually built with each mission launch. [1] Needed capabilities were then identified for development, standardization, demonstration, flight validation, mission adoption, and infusion. The worldwide community was engaged and a multi-center NASA team was formed to develop software for NASA's communication networks and for use in NASA missions. The next major update to this vision likely came with the creation of the LunaNet architecture. DTN is viewed as the key enabler of the LunaNet concept for networked communications in the Lunar vicinity. [2]

In summary there are three components to NASA's vision for Space Networking. One is the view of an interconnected solar system to improve exploration and improve efficiency of operations. Another has been the notion of building the necessary components and transitioning them to operations. At this point, development of minimum core capabilities is complete and DTN has become operational. Additional capabilities will continue to evolve over time. The third driving component of the Solar System Internet is the LunaNet architecture and operations concept which is currently influencing NASA and industry plans for Lunar exploration in the near-term. This will likely culminate in a richly connected network that allows secure networking supported by a wide range of industry and government providers.

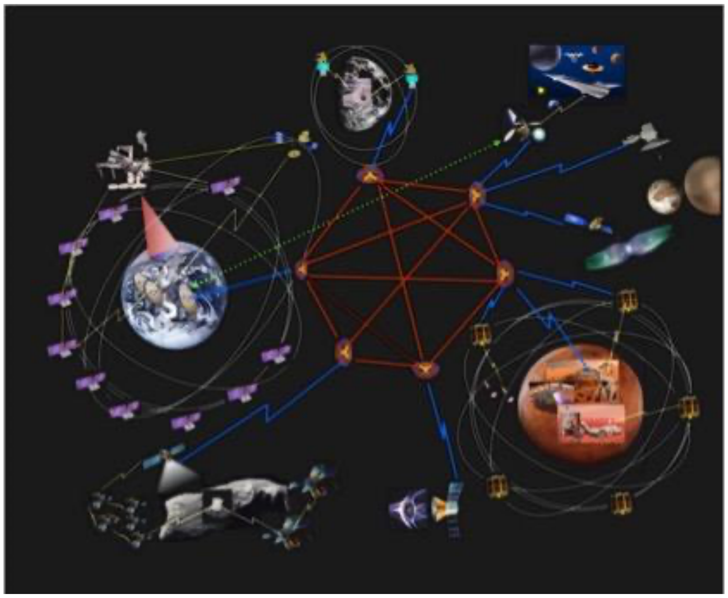


Fig. 1 Solar System Internet as a network of internets.

2.2 Key Drivers

Development and operational deployment of DTN capabilities is especially timely due to the increasing number of missions and growth in mission complexity. Key mission drivers include the trend towards an increasing number of smaller missions, increased reliance on relay operations with limited relay capabilities, and major campaigns for human exploration which involves complex operational in-situ topologies. Similarly, the increasing number of missions, human missions, and overall mission complexity increase the loading on ground networks. More efficient use of bandwidth, reductions in time required to support each communication contact, and reductions in mission planning activities are all needed to maximize mission benefits within funding available.

Benefits of space networking for multiple spacecraft or even use of DTN for a single spacecraft have been realized through many activities in the life of the project. Table 1 summarizes benefits by mission class. Throughout the remainder of this paper more detailed assessments of mission benefits are described.

Table 1: Mission Benefits by Mission Class

Mission Class	Mission Benefits
Single Spacecraft	Improves ground-based planning and data management, Automatic recovery from unexpected data dropouts
Multi-Spacecraft Missions	Rate buffering, Simpler commanding, Reduction in downlink planning
Optical Communications	Risk mitigation due to weather, etc.
Server-Based Onboard Operations (i.e. ISS Payload Data Management)	More effective use of available bandwidth
Constellations and Fleets	Can enable coordination for constellations More efficient use of onboard autonomy

2.3 DTN Benefits by Mission Class

2.3.1 Single Spacecraft Missions

While one may initially attribute disruption tolerant networking to multi-spacecraft scenarios, even a single spacecraft mission system consists of multiple connected computers when considering the end-to-end information flow. As such, there are advantages to using DTN protocols even for single missions, such as to eliminate the need to manually adjust file sizes and plan retransmissions, to reduce operations team workload, and to enable downlink to span the entire length of an antenna pass since data will be reliably transferred. This has been found to increase data throughput by roughly 3-5% per pass. Additionally, file transmissions can be spread across multiple passes, further reducing time required to manage data. [3]

2.3.2 Multiple In-Situ Elements

For missions involving multiple coordinating in-situ elements, DTN can be viewed as a key enabler to secure interoperability among a diverse set of spacecraft. This could include incremental launches of varying mission types that build-up networking capabilities. This network could include a mix of industry provided missions as well as international partner missions. Operating relay networks with shared assets securely becomes paramount with DTN and DTN-based Security being seen as important solutions. DTN can also enable critical data, such as astronaut health data, to be downlinked as soon as possible.. The NASA LuCCI Project is developing operational concepts that include DTN for scenarios involving in-situ Lunar spacecraft communicating via store-and-forward relays to Earth ground stations as shown in Figure 2. [4]

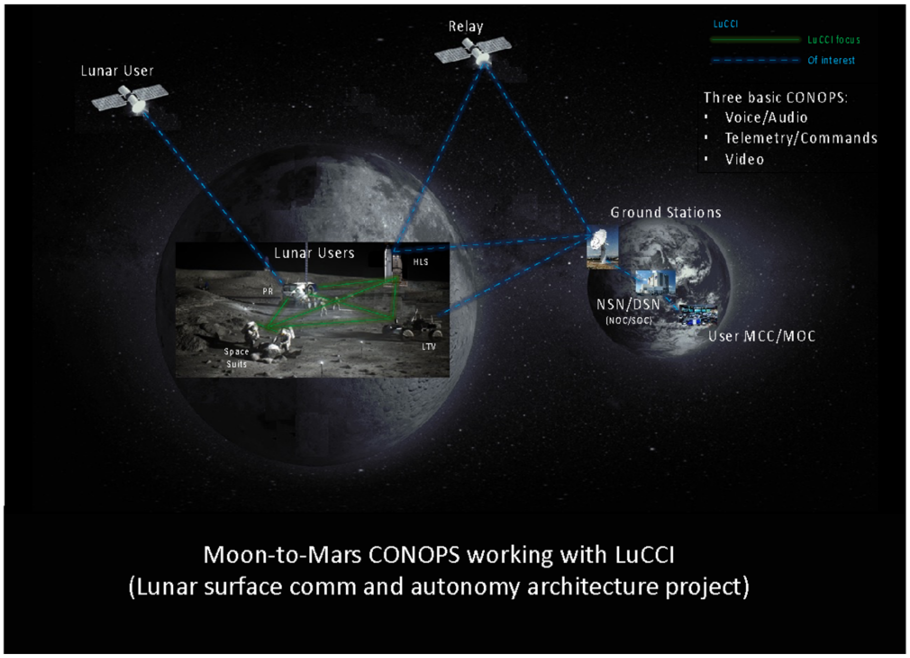
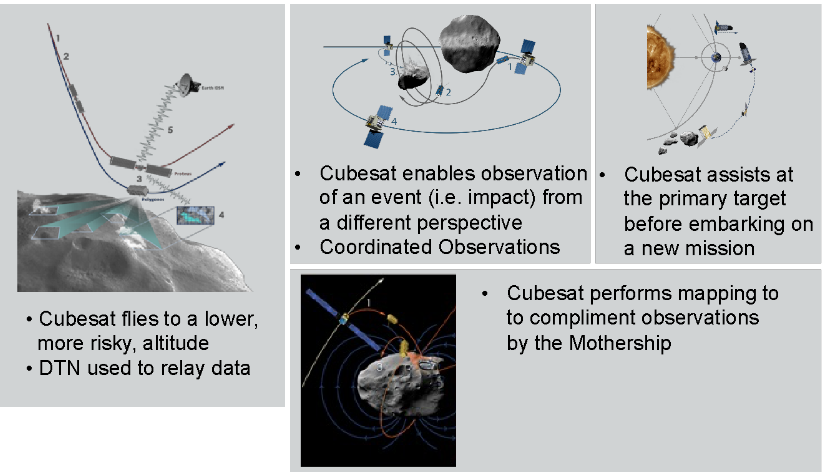


Fig. 2. Example topology for Lunar Communications

2.3.3 Planetary and Small Body Missions

DTN can enable automated store-and-forward data relays, additional redundancy and robustness in communications, automated coordination among autonomous assets, and more efficient operations for each spacecraft. DTN can also enable new mission concepts involving multiple coordinating spacecraft. Some recent examples from actual mission designs are shown in Figure 3. In these examples, small spacecraft deployed from the parent spacecraft perform more risky encounters, observe events from multiple perspectives, are tasked with unique science objectives, or assist with mapping small bodies [5]



- Cubesat flies to a lower, more risky, altitude
- DTN used to relay data

- Cubesat enables observation of an event (i.e. impact) from a different perspective
- Coordinated Observations

- Cubesat assists at the primary target before embarking on a new mission

- Cubesat performs mapping to to compliment observations by the Mothership

Fig. 3. Example Small Body Networking Designs

2.3.4 Constellations and Multi-Spacecraft Robotic Missions

In studies involving scientists working with networking and autonomy experts, several mission concepts involving multiple coordinating elements were studied in detail to evaluate the benefit of space networking to enhance or even enable the mission concept to be proposed. [6] In a 32 small spacecraft constellation study for an interferometric observatory behind the Moon to study galactic centers, DTN can facilitate data sharing among the network nodes for science coordination, simplify operations and improve communications efficiency. [7] In the case where there is surface armada for autonomous exploration of Mars, DTN can facilitate autonomous coordination among heterogeneous rovers. [8] In another study for lunar or Mars lava tube exploration, science data management, mobility, and basic health monitoring cannot be performed via ground control in an environment with possibly frequent disruptions due to obstacles between rovers. DTN also better enables rovers to take excursions outside communication range in order to take science observations, extending the range of exploration. [9] These concepts are illustrated in Figure 4.

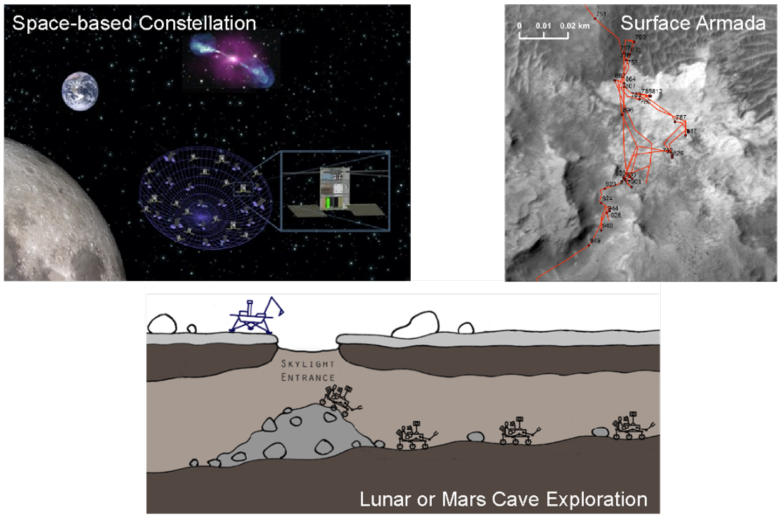


Fig. 4 Constellation and other Multi-Spacecraft mission concepts

2.3.5 Future Human Exploration

Human exploration missions as embodied in the current Artemis architectural vision will include many coordinating elements to support both human exploration and science activities associated with those missions. DTN offers many advantages, such as making most efficient use of available bandwidth, facilitating quality of service through prioritization of the most important or urgent data, automation for space-based relay services, and to make most effective use of limited ground tracking resources by enabling data to be queued for transmission when a link is available. Networking capabilities developed for Lunar Exploration should be usable at Mars. Figure 5 hints at the complexity involved in larger scale Lunar and Mars exploration, both due to the number of assets and networked coordination, but also communication link complexity with substantial loading on ground antennas.

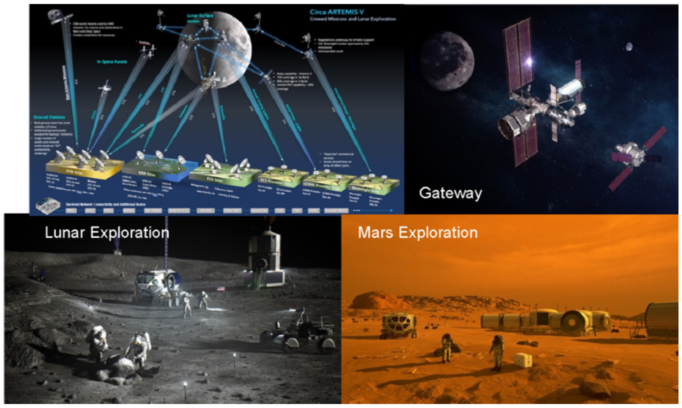


Fig. 5. Future Human Exploration

2.4 Operations and Governance [10]

In the introduction to this paper, a brief summary of differences between DTN protocols and the terrestrial Internet protocol suite were outlined. In this section, the key differences are elaborated. In the Internet, present and historical operation has been relatively low latency. Much of the operation of the applications has relied on this for real-time audio and video conferencing, flow control, network management, domain name resolution, web page rendering and a number of other purposes and applications. In the DTN environment, latencies can be very long and highly variable. Connectivity is commonly discontinuous for many cases, though predictable, through orbital and trajectory data associated with planets, moons, asteroids and spacecraft in transit. The current version of the Bundle Protocol that implements DTN concepts is found in [11]. Unlike the Internet, in which symbolic destinations such as Uniform Resource Locators (URL), like http://nasa.org are resolved through the Domain Name System to Internet Protocol (IP) addresses *before* a User Datagram Protocol packet is sent or a Transmission Control Protocol connection is set up, the Bundle Protocol system may bind End Point Identifiers (destinations in the Bundle Protocol Suite) to local destinations only after arriving at the destination network where the destination node is situated. Security is an integral part of the Bundle Protocol including encryption, integrity verification among other important features such as validation of nodes (e.g. through digital signatures and certificates).

The evolution of the DTN architecture has benefited from many lessons learned from the 50 year history of the Internet. Multistakeholder processes that draw on a wide range of participants have been adopted and used by the Consultative Committee on Space Data Systems [12] based on the experience of the Internet Engineering Task Force [13] along with the Internet Corporation for Assigned Names and Numbers [14] and the Internet Society [15]. These same models of collaborative work have informed discussions about the governance of a potentially collaborative implementation and operation of the Solar System Internet in which the private sector, governments, academia and the technical community work together to establish norms and principles of operation of the Solar System Internet.

As commercialization of cis-Lunar and more distant space becomes a reality, new governance principles and possibly new institutions may need to be established. While the Outer Space Treaty of 1967 [16] does not permit private ownership of extra-terrestrial bodies, it may be important to establish mechanisms by which some claims can be established, such as might be needed for the operation of a mine on the Moon, for example. The Artemis Accords [17] offer a nascent framework in which new treaty mechanisms might be established. We stand on the early threshold of a new and partly commercial exploration of space and it seems important to keep in mind the likely technical and policy implications of this enterprise will have to be worked out as we experience this new human enterprise.

3. DTN Deployment Progress

DTN development was initially funded by DARPA in 2000. NASA's DTN Project grew out of a roadmap for space networking that was created in 2005. This roadmap detailed capabilities that would be needed for Lunar and Mars networking as well as the concept of a Solar System Internet and a concept for a "network of internets" around the places where we want to be in the solar system. The roadmap led to the formation of a NASA multi-center DTN project in 2006. Some of the primary goals of NASA's DTN Project since its inception include::

- Providing most any mission, even single spacecraft missions, with more reliable communication protocols to improve operations efficiency, lower risk, and/or lower cost.
- Transitioning SCaN from being a link service provider to a network service provider
- Championing incremental creation of the Solar System Internet by accreting interoperable assets with each mission launch.
- Offering a secure multi-hop relay service at the Moon and elsewhere via DTN's security protocols that can enable spacecraft from multiple organizations to securely interoperate
- Advocating for deployment of a networking capability at the Moon using the same architecture needed for Mars.

The project has successfully conducted numerous DTN demonstrations which have led to current work infusing DTN operationally. Current project objectives include infusing DTN operationally into the SCaN networks, making DTN software available open source for infusion into missions, and continuing operational support for mission users, such as ISS and PACE. Additional objectives include promoting/facilitating industry adoption, and coordinating with standards bodies, other space agencies. Upgrades to existing DTN software products are ongoing to include security, network management, and select DTN-enabled software applications.

DTN is an operational capability for NASA. The first operational DTN service started in 2016 as a server-based application for managing payload bandwidth onboard the International Space Station (ISS). Within the past few years, a Deep Space Network DTN multi-mission operational service has been created. The PACE mission has become the first Class B NASA mission to use DTN operationally, which also brought the first operational implementation of DTN within NASA's Near Space Network (NSN). NASA's investment in DTN has evolved from technology development to demonstrations to implementations for operations. Now the majority of activities are operations focused with incremental improvements released as new implementations of DTN software evolve.

3.1 Protocol Implementations

NASA has invested in developing multiple software implementations of the DTN protocol suite for various purposes. The most complete, tested, and operationally used DTN flight and ground implementation today is called Interplanetary Overlay Network (ION). ION operational deployments include:

1. NASA's Deep Space Network (DSN) – ION BPv7 currently operational as a multi-mission service. ION was used by the DSN to support the KARI mission and used in interoperability/operational readiness tests with ESA.
2. NASA's Near Space Network (NSN) – ION BPv6 currently operational for 6 ground antennas supporting PACE. Nodes could be moved to support missions using other NSN antennas as needed. Longer-term vision for the NSN is evolving.
3. PACE – ION BPv6 currently operational for the PACE Ground System in the Mission Operations Center
4. ISS – ION has been operational onboard ISS since 2016 for server-based payload data management, supporting dozens of experiments to date.
5. APL – utilizing ION BPv7 for several ongoing activities
7. Other Space Agencies – KARI used ION on the KPLO mission as one example

8. Academia – ION deployed at the Morehead State University DSN-affiliated DSS-17 21m antenna and available for mission use as needed. ION is also used in various research activities.

BPLib is another SCaN-funded implementation of DTN. The primary focus of BPLib is to serve as a DTN module for the Core Flight Software system. The PACE mission is currently flying BPLib BPv6 as an operational capability for spacecraft engineering telemetry. While the initial focus for BPLib has been the Bundle Protocol, current work is aimed at updating the software to include APL's BPSec Open Libraries scheduled for release later this year as well as other elements of the DTN protocol suite. BPLib is viewed as strategic for promoting infusion into Core Flight System (cFS) missions, which are likely to include Gateway and other Artemis missions. The software is progressing towards NASA Class A certification and can be adapted for use outside of the Core Flight Software architecture.

HDTN was developed to maximize data throughput for use in mission applications with high data rates. This software implementation has been used extensively in recent technology demonstrations. In 2024 HDTN running on a laptop onboard ISS transmitted 4k video for the first time from ISS in a manner that passed through the Illuma-T optical communication payload, the LCRD spacecraft to an optical ground station. Through this and other tests and demonstrations, HDTN met performance objectives and demonstrated DTN benefits in a variety of mission scenarios.

3.2 International Standards

The DTN Project has long participated in both CCSDS and IETF standardization activities. SCaN funds CCSDS Standardization through its system engineering organization. The DTN multi-center team provides technical inputs to ongoing standardization activities. DTN Project participation in IETF led to the formation of a DTN Working Group and the Time-Variant Routing Working Group. IETF serves as the international commercial Internet standards body. Standards and activities are coordinated between IETF and CCSDS as needed. At this point standardization of the core DTN protocols is essentially complete with the focus now on completing standardization of network management and security standards.

3.3 Network Management (NM)

To operate a mission system involving DTN, it is important to have a way to manage the network. The DTN project has defined 5 high-level functional network management categories that need to be addressed to operate a DTN-based network. These include:

1. Mission Planning: System level information that DTN users and DTN providers will need to build, design and share, to achieve end-to-end data through the DTN during the service execution phase.
2. Node Configuration: Encompasses all DTN pieces regarding NM that involves creating, updating and managing a DTN node's configuration.
3. Node Monitoring: Encompasses all DTN systems answering the health question of the node/network.
4. Node Troubleshooting: Includes all DTN pieces required to fix and troubleshoot the node/network.
5. Miscellaneous purposes: Includes additional systems that may need to be needed for future advancements (e.g., automation or autonomy systems that allow the network to self-detect faults and/or self-correct them).

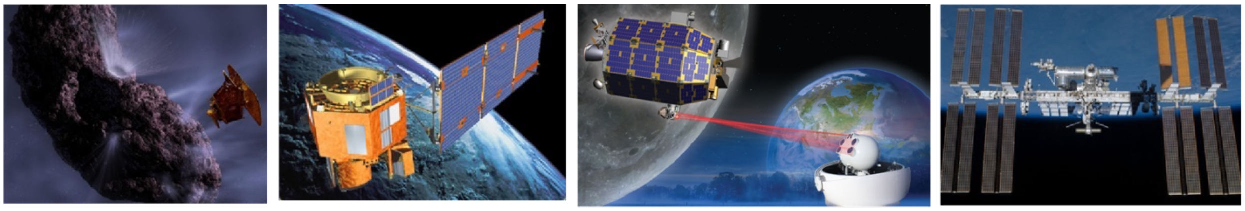
A very important consideration in space networking is to have a standard way to share information relating to managing a network. Toward that end, the work focus has been on defining the set of managed information for each element of the protocol suite. This Management Information Base (MIB), sometimes also called Application Data Model (ADM) can then be shared and incorporated by the appropriate implementing organization into mission system software. It is also likely the specification for managed information will become a standard within CCSDS.

3.4 Security

DTN-based security has the potential to improve the three tenets of cybersecurity, which are confidentiality, integrity, and availability. This is especially timely given emphasis on secure space communications and when considering multi-hop Lunar or Mars scenarios with multiple providers such that data would need to be relayed across NASA, industry, and other space agency assets. Confidentiality is improved because with heterogenous networks, securing bundles are more flexible and useful than utilizing full stream encryption. DTN improves integrity by protecting and tracking bundles and by having the ability to store or re-route them as needed. Availability is improved because of the ability of DTN to store and forward, track, and reroute data delivery in complex mission topologies. At the core of DTN security is the BPSec protocol which is in the final stages of standardization with an SMD AMMOS-funded open BPSec library in the final stages of development. [18]

3.5 Early Demonstrations

The very first experiments using DTN were led by the University of Colorado onboard an ISS payload soon after the NASA project began [19]. The first major flight validation of DTN occurred onboard the EPOXI Spacecraft in 2008 [20, 21]. That was followed by a demonstration of DTN onboard the Earth Observing One (EO-1) mission in 2010 [22]. In 2013, transmission of DTN bundles over optical links was demonstrated by the Lunar Laser Comm Demo (LLCD) mission. In 2016, the ISS began an operational service for ISS Payloads. While not in the communication links, this server-based capability was put in place to more efficiently manage ISS bandwidth and automate elements of payload mission operations. The early flight demos are summarized in Figure 6. All of the early flight demonstrations utilized NASA's ION implementation, which at the time was the only available NASA implementation of DTN protocols.



EPOXI
First DTN flight validation
Deep Space (2008)

EO-1
First DTN flight test in
Earth Orbit (2010)

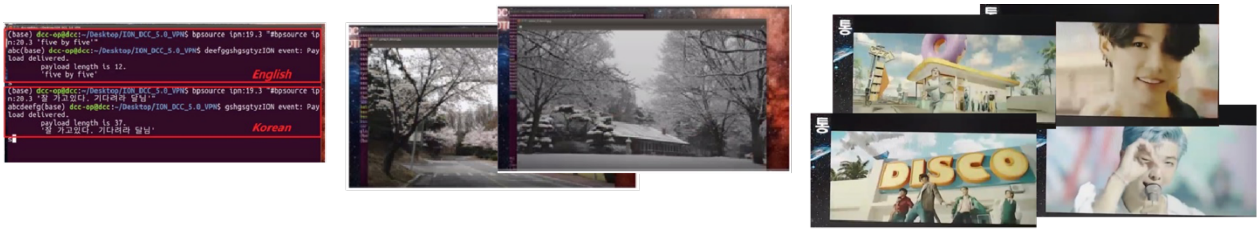
Lunar Laser Comm DTN Demo
(2013)

International Space Station
Fully Payload Data Management
Service (2016)

Fig. 6. DTN Early Flight Demonstrations

3.6 Recent Demonstrations

Two key recent demonstrations have helped to pave the way for operational capabilities within the SCaN networks. In 2022 the Korean Pathfinder Lunar Orbiter successfully conducted demonstrations of Bundle Protocol Service (BPS) and Bundle Streaming Service Protocol (BSSP). This demonstration successfully performed data transfer between the KPLO flight DTN Node/Payload and ground nodes (DSN and KPLO MOC). Specifically, message transfer, image transfer, and video streaming via BSSP were demonstrated as summarized in **Figure 7**. NASA's ION implementation was used for flight and ground nodes. This demonstration also was a validation test for the DSN Phase 1 Operational DTN Implementation. [23]



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n:20.3 'five by five'"
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load delivered.
        payload length is 12.
        'five by five'
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n:20.3 '잘 가고있다. 기다려라 달님'"
abcdeefg(base) dcc-op@dcc:~/Desktop/ION_DCC_5.0_VPN$ gshgsgtyzION event: Pay
load delivered.
        payload length is 37.
        '잘 가고있다. 기다려라 달님'
$
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1: Message Transfer
English: five by five
Korean (rough English translation):
I'm on my way. Wait there, moon.d

2: Image Transfers
Winter and Spring Images of ETRI Campus

3: Video Streaming via BSSP
BTS Music Video (scenes from K-pop Video)

Fig. 7. KPLO Demo Summary

In 2024, a comprehensive demonstration of DTN over optical links was conducted. This utilized NASA's HDTN implementation running on a laptop onboard ISS. The data was routed through the externally mounted ILLUMA-T

ISS payload which acted as an optical relay to the LCRD spacecraft for relay via a second optical link to Earth. The many different topologies and DTN features demonstrated were focused on informing an envisioned future NSN DTN-based architecture that could improve operations efficiency through link diversity by switching to RF communications during a disrupted link. Many DTN features were demonstrated including 4k streaming video. [24] A summary of this demo is shown in Figure 8. This demonstration is also significant as the last planned major demo of DTN prior to transition to operations within SCaN.

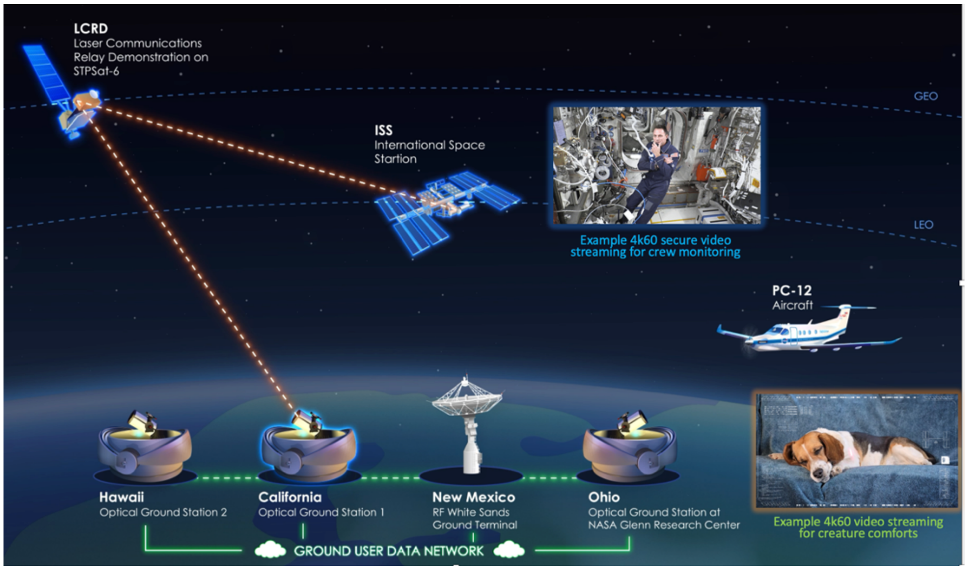

Fig. 8. 2024 Optical Comm DTN Experiments

3.7 Current Operational Capabilities

3.7.1 PACE Mission

In 2024 NASA's PACE mission became the first NASA Class B mission to use DTN operationally for housekeeping telemetry. Over 26 million bundles have been successfully transmitted to date with a 100% success rate. Downlinks occur via S-band communication links from the spacecraft running NASA's BPLib BPv6 implementation as a module within the flight system core Flight Software (cFS) environment. In the Mission Operations Center, ION version 3.7.0 is used. The four primary and two backup NSN antennas also run ION software. The configuration is summarized in Figure 9. PACE is also an example of DTN adoption for Single Spacecraft missions. Utilizing DTN has improved efficiency of operations by automatically initiating transfer of bundles when a communication contact occurs, enables retransmission, and handling of unplanned disruptions in communication gracefully by resuming downlink when the link becomes available again. [25]

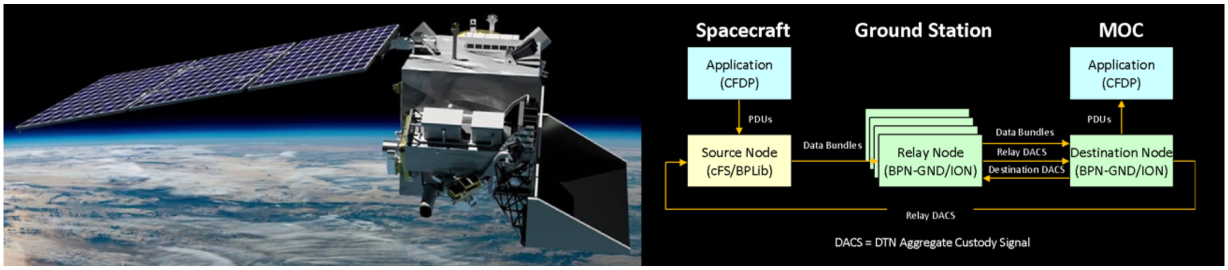

Fig. 9. PACE Mission DTN Data Flow Diagram

3.7.2 ISS Payload Operations

DTN has been used successfully as an operational service onboard ISS for Payload Operations since 2016 and supports roughly 17 experiments. For ISS, DTN is a server-based capability for managing payload experiment bandwidth. DTN is not in the communication systems for ISS. Onboard operations are managed by the Johnson Space Center and the Marshall Spaceflight Center oversees ground operations and dissemination of experiment data to PI's. One of the most significant advantages of using DTN onboard ISS is the ability to spread bandwidth allocations for experiments across 24 hours instead of just during day shift since DTN enables automation of data transfers. Another advantage of DTN is reduction in coordination among operations personnel to plan retrieval of ISS experiment data. Also, when downlinking large files, DTN (and CFDP) enable file transmissions to resume automatically after a Loss of Signal (LOS) period.

3.7.3 Deep Space Network

NASA's Deep Space Network (DSN) has implemented an operational capability for supporting DTN missions. The initial motivation for this was the requirement to support the Korea Pathfinder Lunar Orbiter (KPLO) project in 2022. The DSN implementation utilizes NASA's ION BPv6 implementation and while the KPLO mission was conducting a DTN demonstration, the DSN capability was the first phase of an operational DSN Service. In this demo, DTN-based bi-directional communication occurred between the KPLO spacecraft, the KPLO Mission Operations Center (KMOC) DTN node, the Korean Electronics and Telecommunications Research Institute (ETRI) ground system DTN node, and the DSN DTN node. Since supporting the successful series of KPLO DTN flight demonstrations, the DSN has completed the second phase of the implementation, which consists of a muti-mission service and upgraded the capability to BPv7 which is the current worldwide DTN standard protocol implementation. Phase 2 was delivered in mid-2024. Phase 3, which is nearly half completed, adds the ability to support missions that operate with the DTN security solution known as BPSec. Phase 3 also includes some initial implementations of network management capabilities to improve operations efficiency. Phase 3 is planned for completion in FY26. It should be noted that the DSN architecture places the DTN node in the Deep Space Operations Center (DSOC), which is located at JPL and essentially provides the DTN capability for communication links with any DSN antenna. In addition, the Morehead State University (MSU) DSN-affiliated antenna (DSS-17) has a DTN capability that was implemented to support flight demonstration of DTN on the Lunar IceCube mission and has since been upgraded to ION BPv7. Figure 10 summarizes this architecture.

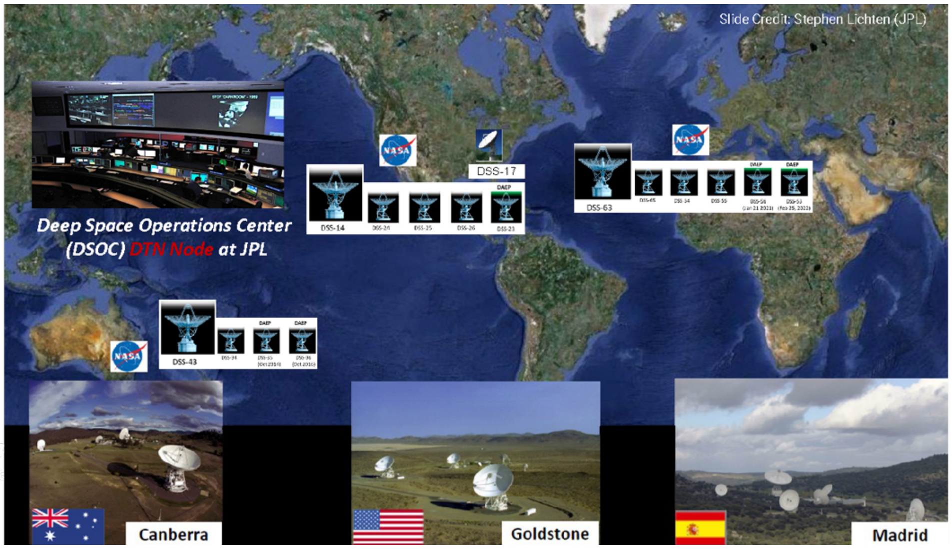

Fig. 10. DSN DTN architecture

3.7.4 Near Space Network

The NSN currently has a limited operational capability with 6 NSN ground stations supporting the PACE mission shown in Figure 11. If necessary, the NSN DTN nodes can be replicated and installed in other NSN ground station locations to support other missions. The NSN plans to fully infuse DTN into its networks in time to support mission needs. Early lessons-learned were gained through various DTN experiments using the ISS, ILLUMA-T, and ground networks, and these experiences will be used to help shape future NSN ground system infusion of DTN. Lunar Relay and Lunar DTE communication plans include DTN and are under the NSN umbrella. These industry-provided solutions will provide DTN service in a timeframe that is in the planning stages.

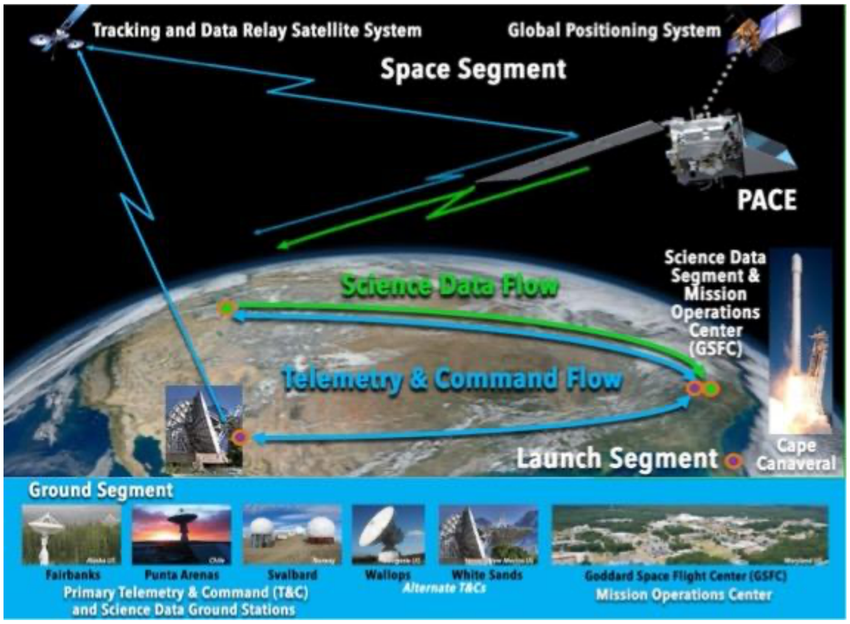

Fig. 11 NSN DTN Ground System implementation for the PACE mission

4. Conclusions & Next Steps

The capabilities and activities described in this paper provide evidence that a Solar System Internet is taking shape. DTN protocols and supporting infrastructure have become operational, lowering the barrier to entry from cost, risk, and schedule perspectives. The demonstrations and operational use cases provide insights into advantages for DTN to be used on most any type of mission. DTN adoption is timely given the emphasis on Lunar and Mars exploration, the increasing number of missions to be supported with limited ground resources, and the need for interoperability.

NASA's DTN project is working now to complete the remaining upgrades to DTN software through FY27. This is timely for Lunar Relay, Lunar Direct to Earth (DTE), Gateway, and other infusion activities. Late in 2027 program integration into the various organizations within SCaN should be possible. Like the Internet, capabilities will continue to evolve going forward as capabilities for network management, security, quality of service, and DTN-enabled applications mature and are standardized as necessary.

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