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Implementing Delay/Disruption Tolerant Networking for NASA's Plankton, Aerosol, Clouds, ocean Ecosystem (PACE) Mission

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Abstract

NASA's Plankton, Aerosol, Clouds, ocean Ecosystem (PACE) mission will be the first NASA science mission to use Delay/Disruption Tolerant Networking (DTN) for routine operations. The DTN Bundle Protocol (BP) is being integrated into the core Flight Software (cFS) for the transfer of house-keeping files. DTN nodes will also be integrated into the Near Space Network (NSN) ground stations and the PACE Mission Operations Center. This paper will describe the DTN implementations, the PACE DTN operations concept and how this mission is a significant step towards the Solar System Internet.

Keywords: space internetworking, internet, delay/disruption tolerant networking

Acronyms/Abbreviations

Aggregate Custody Signal	ACS
Advanced Orbiting Systems	AOS
Acquisition of Signal	AOS
Bundle Protocol	BP
Bundle Protocol Node – Ground	BPN-GND
Command and Data Handling	C&DH
Consultative Committee for Space Data Systems	CCSDS
Core Flight Software	cFS
CCSDS File Delivery Protocol	CFDP
Data Acquisition Processing and Handling Network Environment	DAPHNE
Data Storage	DS
Delay/Disruption Tolerant Networking	DTN
Earth Observing-1	EO-1
Ground Station	GS
Internet Protocol	IP
Interplanetary Overlay Network	ION
Monitor & Control Subsystem	MCS
Mission Operations Center	MOC
Near Space Network	NSN
NSN Initiative for Ka-Band Advancement	NIKA
Plankton, Aerosol, Clouds, ocean Ecosystem	PACE
Protocol Data Units	PDU
Programmable Telemetry Processor	PTP
Signal Processing Subsystem	SPS
Space Communications and Navigation	SCaN
Spacecraft	SC
SpaceWire	SpW
Telemetry Output	TO
Tracking and Data Relay Satellite	TDRS

1 Introduction

The internet on Earth has revolutionized the way humanity communicates with one another. We as a species have evolved from writing letters on pen and paper to shooting off a quick text or email that can reach its destination in seconds or minutes rather than days and weeks. The introduction and advancement of the terrestrial internet, built upon the Internet Protocol (IP), has transformed business, connected cultures, and expanded our knowledge all by connecting us to a network. A similar transformation is beginning within the space communications community through Delay/Disruption Tolerant Networking (DTN). Engineers at NASA's Goddard Space Flight Center are developing and refining DTN for implementation into mission and network architectures.

2 Delay/Disruption Tolerant Networking (DTN)

DTN is a foundational technology that will bring internetworking capabilities to space and create the solar system internet. Space communications are subject to frequent delays and the unavailability of contemporaneous end-to-end links. These latency and disruption challenges result in the need for additional networking protocols.

DTN is a suite of standard protocols that use information within the data stream, headers attached to data units, to accomplish end-to-end data delivery through network nodes. The essential protocol that enables DTN is the Bundle Protocol (BP). The DTN bundle is the network data unit. Unlike a terrestrial IP network, DTN uses a store-and-forward approach, storing data at intermediate nodes until the next node in the path is available. This enables DTN to operate in scenarios with disrupted communications, where a continuous, full-bandwidth, end-to-end path between source and destination nodes may not exist for the duration of a communication session [1].

The store-and-forward approach is also used for optional hop-by-hop data acknowledgements and retransmissions for reliable data delivery. Therefore, DTN can successfully operate in scenarios with communication delays, where timely and stable feedback from data destinations is not always available. In addition, DTN enables successful data delivery in situations where there are data rate mismatches — for example when a high-data-rate science downlink is delivered to a ground station with lower uplink rate capabilities.

The DTN protocols provide transport and network layer functionality. That is, they provide the means for the delivery of data across multiple links. The data can be reliably or unreliably delivered, and users can select the reliable option to guarantee data completeness.

DTN has been in use operationally by the International Space Station since May 2016 to deliver data from payloads and systems over the space station's communications links [2]. This human spaceflight experience has led to NASA planning to incorporate DTN as the network layer protocol for the expansion of exploration beyond low Earth orbit [3].

NASA's Science Mission Directorate has also recognized the benefits of DTN for robotic science missions [4]. Though it has not been used operationally yet for a robotic science mission beyond space station payloads, there have been multiple DTN flight demonstrations for robotic missions, including on the EPOXI mission in deep space [5], and the Earth Observing-1 (EO-1) in low Earth orbit in 2010 [6]. The EO-1 demonstration successful transferred data from an Earth science mission to ground stations, including real-time housekeeping telemetry that would have been lost due to a previous hardware failure. NASA's Plankton, Aerosol, Clouds, ocean Ecosystem (PACE) mission, anticipated to launch in 2022, will be the agency's first science mission to use DTN for routine operations.

3 Plankton, Aerosol, Clouds, ocean Ecosystem (PACE) Mission

The PACE mission, launching in 2024, will help NASA better understand how the ocean and atmosphere exchange carbon dioxide, uncover how aerosols might fuel phytoplankton growth in the surface ocean, and collect critical observations of Earth. PACE will be located in a polar orbit around the Earth with nominal spacecraft altitude of 676.5 kilometers with an inclination of 98° [7].

PACE will use ground stations located in Fairbanks, Alaska, Wallops Island, Virginia, Punta Arenas, Chile, and Svalbard, Norway. These ground stations are being developed through NASA's Near Space Network (NSN) Initiative for Ka-Band Advancement (NIKA) effort, which is a joint effort between NASA and Kongsberg Satellite Services (KSAT). KSAT is responsible for the development and installation of the Chilean and Norwegian antennas. The NIKA effort will enhance data return capabilities by establishing the four tri-band antennas, providing missions with the option of X-band, S-band, and Ka-band. Additionally, each antenna will incorporate DTN into its S-band system to provide robust data delivery services.

NASA's PACE mission will downlink science data to the ground nodes at 600 megabits per second over Ka-Band. Data that reaches these ground stations will then be forwarded on to an Amazon Web Services cloud-based data storage system through the NSN's Data Acquisition Processing and Handling Network Environment (DAPHNE), which does data capture, data processing, and data delivery services for high rate science data.

PACE command and telemetry services will be provided over S-Band links with each ground station. The S-band downlink data includes the transfer of housekeeping telemetry files. The transfer of these files will be performed using DTN.

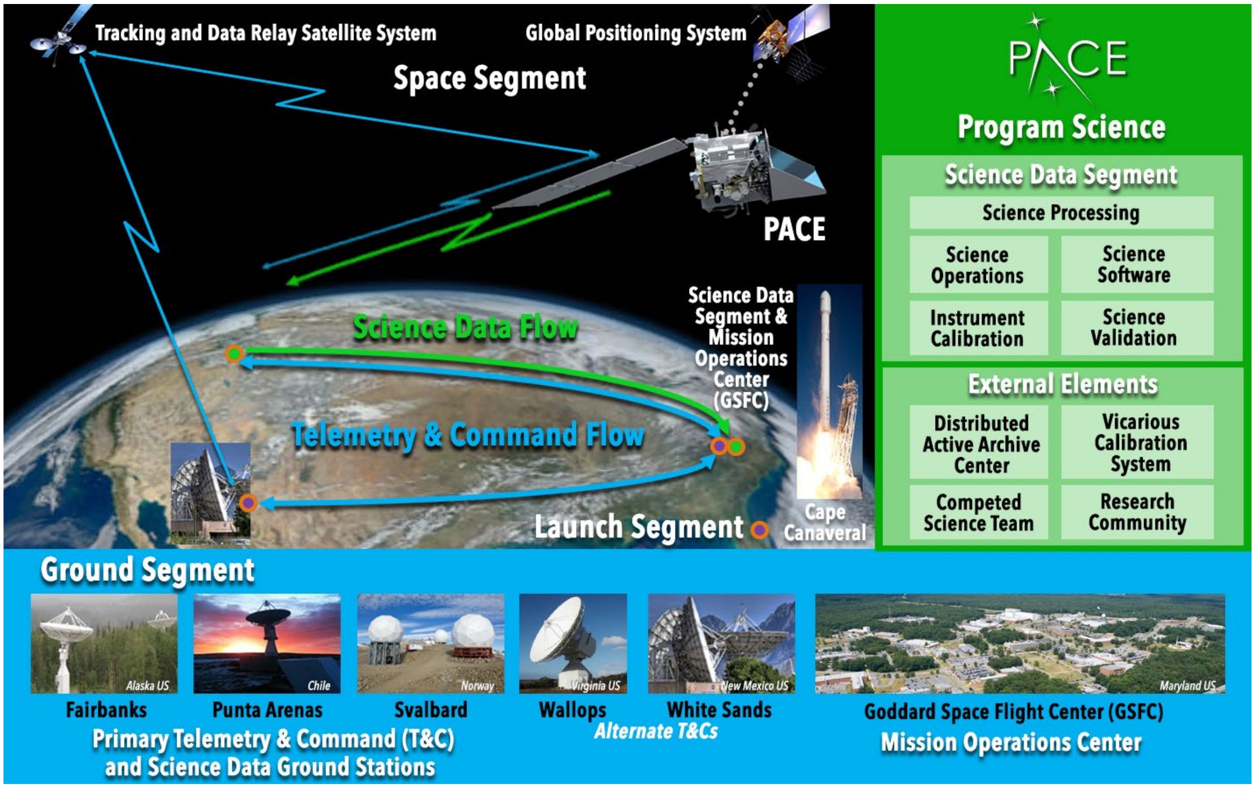

Figure 1. PACE Mission Architecture. Credit: NASA/PACE

4 Operational Concept

PACE's operational concept consists of DTN flight and ground nodes. The DTN flight node is integrated on PACE spacecraft and the DTN ground nodes are integrated at four ground stations and the PACE Mission Operations Center (MOC).

The PACE spacecraft stores housekeeping telemetry in files in an onboard flash file system on the Command and Data Handling (C&DH) board. The housekeeping files contain a stream of Consultative Committee for Space Data Systems (CCSDS) telemetry packets. The S-band downlink of housekeeping telemetry entails sending the housekeeping files to the MOC and deleting those files in the onboard flash file system after they are successfully received by the MOC. The CCSDS File Delivery Protocol (CFDP) is used to transfer the files. BP is used to transfer the CFDP Protocol Data Units (PDU) from the spacecraft to the ground station, and then from the ground station to the PACE MOC during a real-time space to ground contact. The files are never assembled at each ground station. The pieces of a single file may flow through any of the ground stations to be reassembled at the MOC.

As seen in Figure 2, the DTN bundles containing the pieces of the files are generated and queued prior to the start of the downlink to the ground station. Once the downlink has begun at the Acquisition of Signal (AOS), the bundles are sent to a DTN node located at the ground station. The DTN node at the ground station generates acknowledgements to be sent back to the spacecraft and initiates a second bundle transfer to the MOC. This process is detailed in the section below.

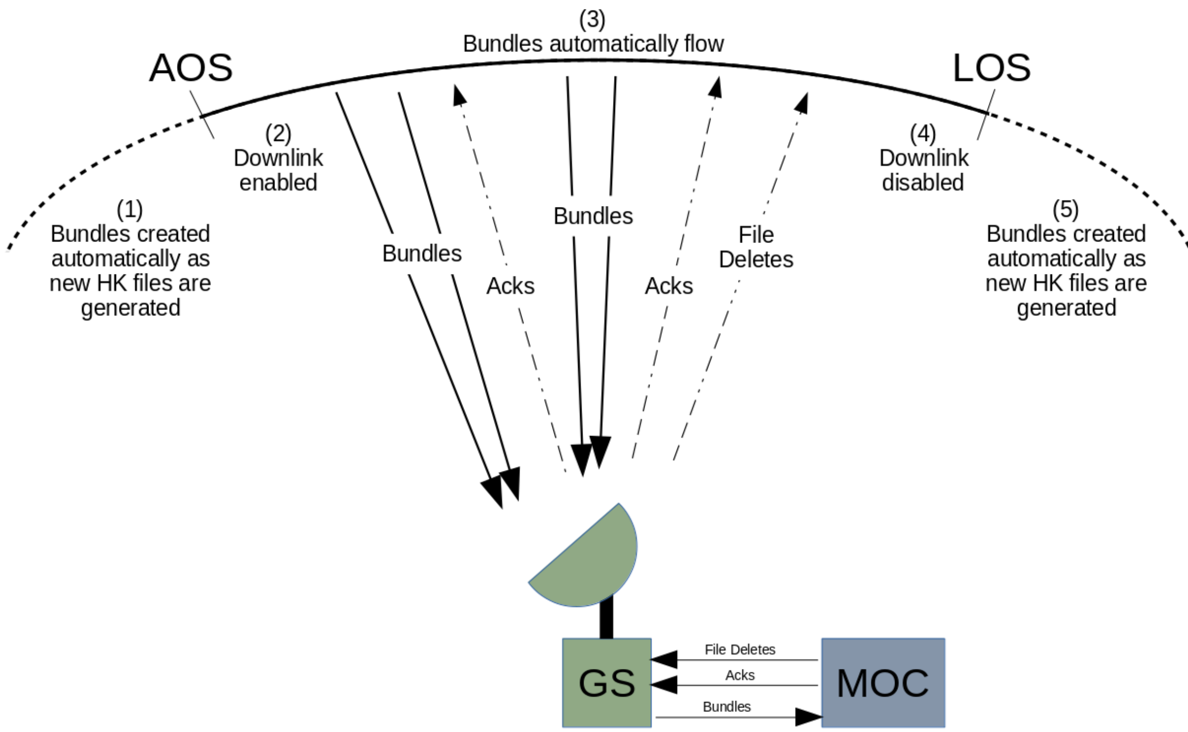

Figure 2. Bundle Protocol Downlink

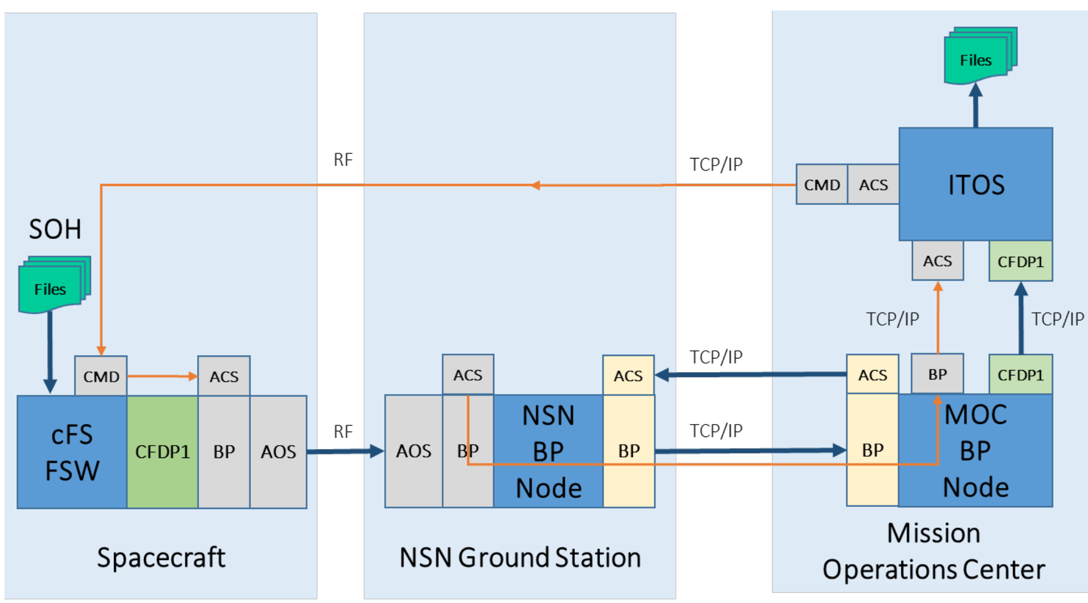

Figure 3. PACE DTN Elements

The diagram above depicts the flow of recorded housekeeping data passing through three distinct hops (note that “ACS” is used to represent a bundle acknowledgment (Aggregate Custody Signal) and does not specify the exact form of the acknowledgment):

1. The spacecraft bundles the CFDP PDUs containing the housekeeping data into bundles, which are then placed in encapsulation packets, and then inserted into advanced orbiting systems (AOS) frames and sent to the ground over S-band.

2. The ground station receives the AOS frames, extracts the bundles, and acknowledges receipt of those bundles back to the spacecraft through the MOC. Sending the acknowledgements through the MOC instead of directly back to the spacecraft was required due to the security architecture of the mission. At the same time, the ground station forwards the bundles to the MOC over a ground IP network.
3. The MOC receives the bundles and acknowledges receipt of the bundles back to the ground station. The MOC then extracts the CFDP PDUs from the bundles and forwards them to a CFDP engine running in integrated test and operations system (ITOS). The ITOS CFDP engine reconstitutes the files. The file accounting tool generates the necessary file delete and file retransmit commands which are then sent back to the spacecraft based on what files have been successfully reconstituted at the MOC. Transfers between the ground station node and the MOC can continue after the spacecraft pass is completed.

5 Implementation

The implementation of DTN flight and ground nodes conforms to the CCSDS Blue Book recommendation 734.2-B-1 [8], which is based on RFC 5050 [9]. The systems engineering and software development processes to implement DTN for PACE mission are compliant with NASA Procedural Requirements (NPR) 7123.1B [10] and NPR 7150.2C, Class B [11] respectively. The requirements and design for DTN implementation on PACE were approved at NSN, PACE, and DTN infusion project's system requirements reviews, preliminary design reviews, and critical design reviews.

The open source core Flight System (cFS) is an independent, reusable software framework and set of reusable software applications [12]. There are three key aspects to the cFS architecture: a dynamic run-time environment, layered software, and a component-based design. It is the combination of these key aspects that makes it suitable for reuse on any number of NASA, industry, or academia flight projects and/or embedded software systems. DTN flight software implementation is a cFS application compatible with the version of the core Flight Executive (cFE) used by PACE. The BP implementation on the spacecraft is fully contained within the flight software residing on the C&DH board; no hardware or other software components on the spacecraft are modified to handle bundles.

The cFS Bundle Protocol Application implements the high-level functions for receiving, bundling, and sending data. It is also responsible for processing MOC commands, configuring the BP settings, prioritizing data flows, and interfacing to the cFE for services like event logging and performance monitoring. The BP library is a bundle protocol implementation for memory constrained environments and is used by the cFS application to build and parse bundles. The high-level architecture of the flight software BP application is depicted in the diagram below.

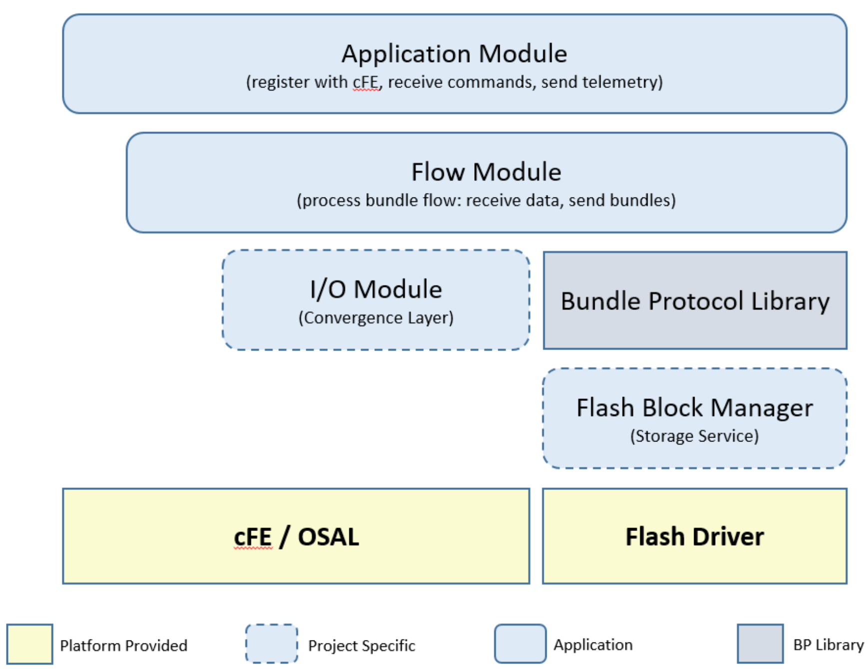

Figure 4. High-level architecture of the flight software BP application

The DTN ground node is being developed with Bundle Protocol Node – Ground (BPN-GND) software. This software will be used under different configurations at NSN ground stations and the PACE MOC. BPN-GND provides a generic node solution for development labs, integration facilities, ground stations, mission/science operation centers, and other environments using DTN BP. It offers the full set of bundle node capabilities for sending and/or receiving bundles, and configuring the nodes to support both data transfer and operations of NASA spacecraft, instruments, and projects that use BP within their internetworking environment. BPN-GND includes Application Agent (AA), Convergence Layer Adapters (CLAs), and Bundle Protocol Agent (BPA). The AA provides application and administrative services, CLAs sends and receives bundles on behalf of BPA, and BPA executes Bundle Protocol. BPN-GND currently uses Interplanetary Overlay Network (ION) [13] as BPA, which implements Bundle Protocol and supports all bundle processing for PACE mission.

The diagram below shows the high-level use of the BP Ground Node at both the NSN ground stations and the PACE MOC to provide their required DTN capabilities.

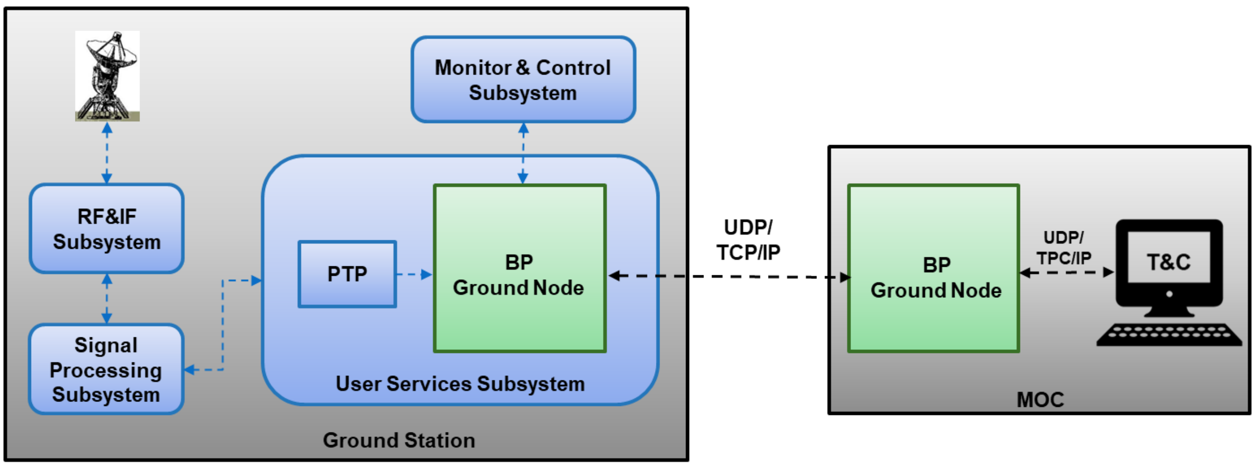

Figure 5. BP Ground Node at both the NSN ground stations and the PACE MOC

BPN-GND goes through build testing and system testing in DTN testbed at Goddard Space Flight Center. DTN ground nodes are currently being integrated and tested at four NSN ground stations. The DTN ground node for PACE MOC has completed successful site acceptance testing. After successful site acceptance tests at NSN ground stations and PACE MOC, PACE mission will conduct FlatSat, ground reading tests, observatory integration and test, and end-to-end tests to assess the flow of recorded housekeeping data using DTN.

6 Conclusion

At the time of this publication, May 2021, the PACE flight software team has successfully completed build testing of a recent DTN build, which implements complete DTN flight functionality for PACE. The PACE MOC team is in the process of integrating a recently released BPN-GND build, which meets all the DTN ground requirements. Additionally, they successfully completed site acceptance testing with the previous BPN-GND build. Sustainment of both flight and ground nodes will be performed in future builds, as needed. The NIKA team successfully integrated DTN nodes at ground stations in Alaska and Norway and is in process of integrating DTN nodes at the Punta Arenas, Chile ground station. The DTN team is on track to support the 2024 launch and operations of PACE.

The inclusion of DTN on PACE is a significant step in the evolution of the solar system internet [14]. Although DTN is only being used for low rate transfers of housekeeping files, the difference between demonstration and operational requirements are substantial. Operational flight and ground software systems must follow a rigorous quality assurance process, incorporate fault tolerance, include a wider set of interfaces for monitor and control, and undergo a much greater degree of documentation and testing. The resulting products are then available for future missions. The cFS implementation of BP has already been incorporated into the Lunar IceCube mission and will be the first implementation of DTN at the Moon [15].

Working through the requirements for an operational mission also identified areas that require further development. Most notable are the requirements and constraints driving fault tolerate operations and the implementation of protocol loops between the ground station nodes and spacecraft flowing through the MOC. This would not be an acceptable solution if that ground station node was a space relay instead. The implementations to support PACE also accommodate the necessary monitor and control of the various nodes, but the nodes are not yet being managed as part of a larger network. The development of network management tools, network level operations concepts, and related standards and policies are still required.

The NSN plans to incorporate a network operations center that will orchestrate services among a combination of commercial and government systems [16]. The NSN will be creating a DTN-based network through the management of DTN nodes providing the network layer services over a variety of space link providers. The ambitious plans for LunaNet [17] also drive the need for network management capabilities and other DTN components and systems.

The new BP version 7 standard [18] addresses the PACE lessons learned and brings additional DTN capabilities with the potential for greater interoperability between commercial, terrestrial, and space systems. It is not anticipated that PACE will switch to using BPv7, but the cFS and ground implementations will be upgraded to include BPv7 to allow the future network to be based on the latest version. Other foreseen implementation needs include operational implementations of DTN convergence layers, security protocols, and routing protocols. Operation at data rates higher than can be performed in software will drive the development of hardware accelerated implementations, especially for flight systems. Ground solutions will likely start to incorporate cloud-based implementations.

There will be no shortage of work before the solar system internet can become an ever-present system, depended upon like Earth's internet. When PACE launches and begins operations, it will be another "small step and giant leap." Perhaps not as significant or as visible as others in this category, but a historic milestone nonetheless.

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