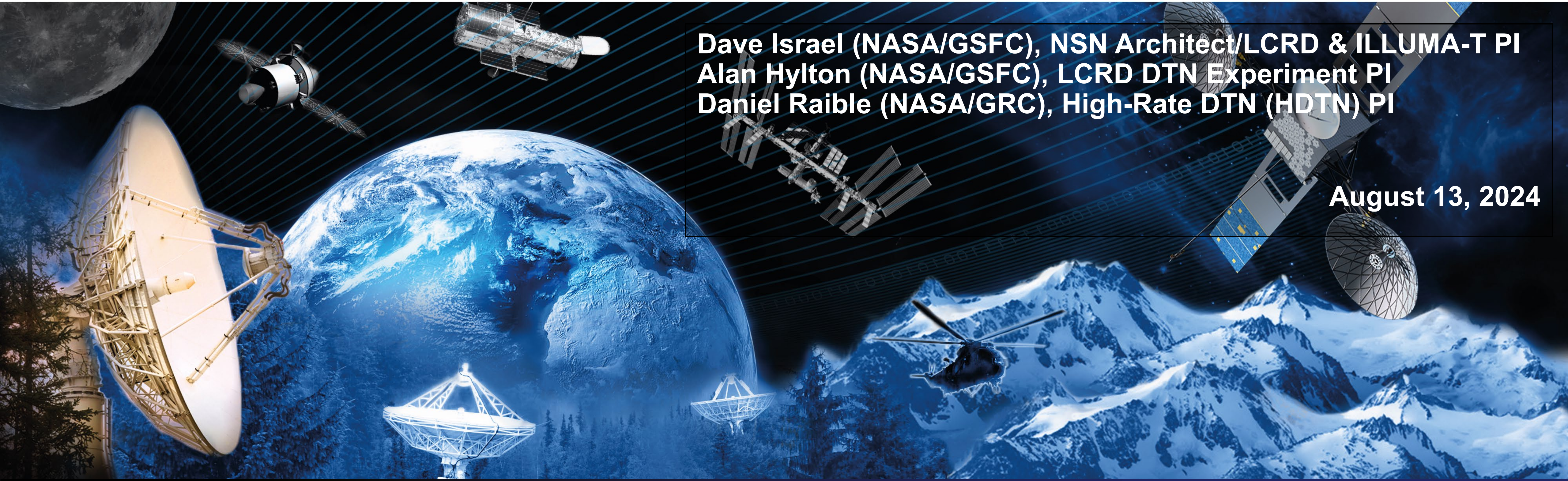
National Aeronautics and Space Administration

ESC Exploration & SPACE Communications

More than you ever imagined...

IPNSIG Keynote: DTN Over Lasercom Relay



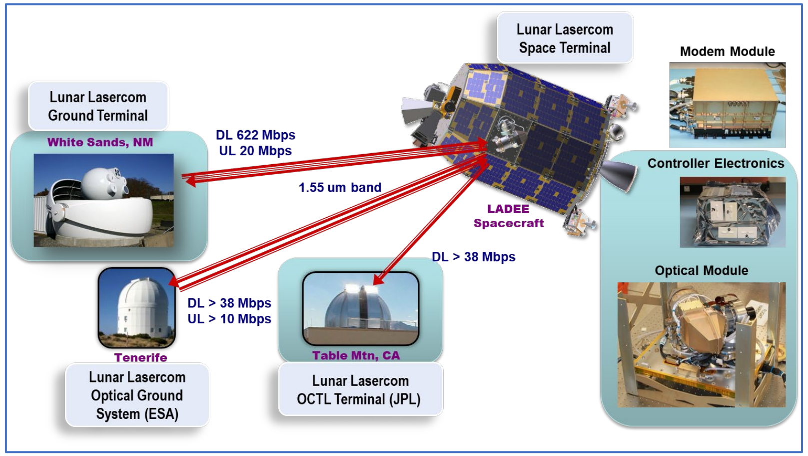
Dave Israel (NASA/GSFC), NSN Architect/LCRD & ILLUMA-T PI
Alan Hylton (NASA/GSFC), LCRD DTN Experiment PI
Daniel Raible (NASA/GRC), High-Rate DTN (HDTN) PI

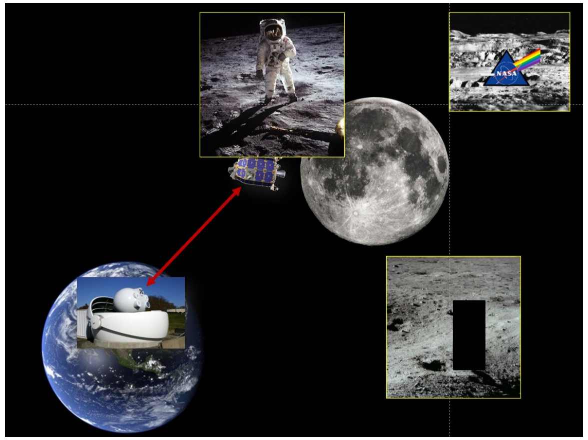
August 13, 2024

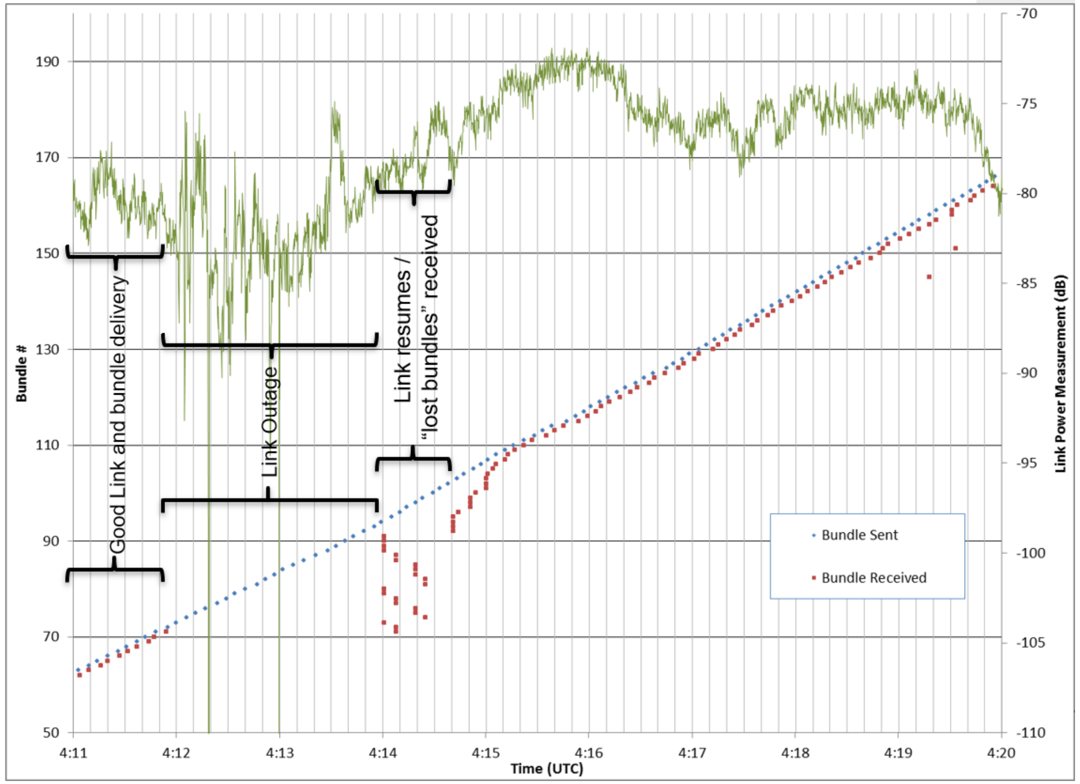
Introduction

- Demonstration of DTN over lasercom links were first performed with the Lunar Laser Communications Demonstration (LLCD) in Fall 2013
- The International Space Station (ISS) has been using DTN operationally since May 2016 through the Near Space Network (NSN) Tracking and Data Relay Satellite System (TDRSS)
- The Plankton, Aerosol, Cloud ocean Ecosystem (PACE) has been using DTN operationally through NSN ground stations since launch in February 2024
- DTN Experiments and Demonstrations were performed with the ISS over laser communications links in June 2024
- These experiments and demonstrations highlighted a variety of DTN capabilities in an operational scenario and architecture aligned with plans for the NASA Near Space Network and LunaNet

Lunar Laser Communications Demonstration (LLCD) DTN Experiments







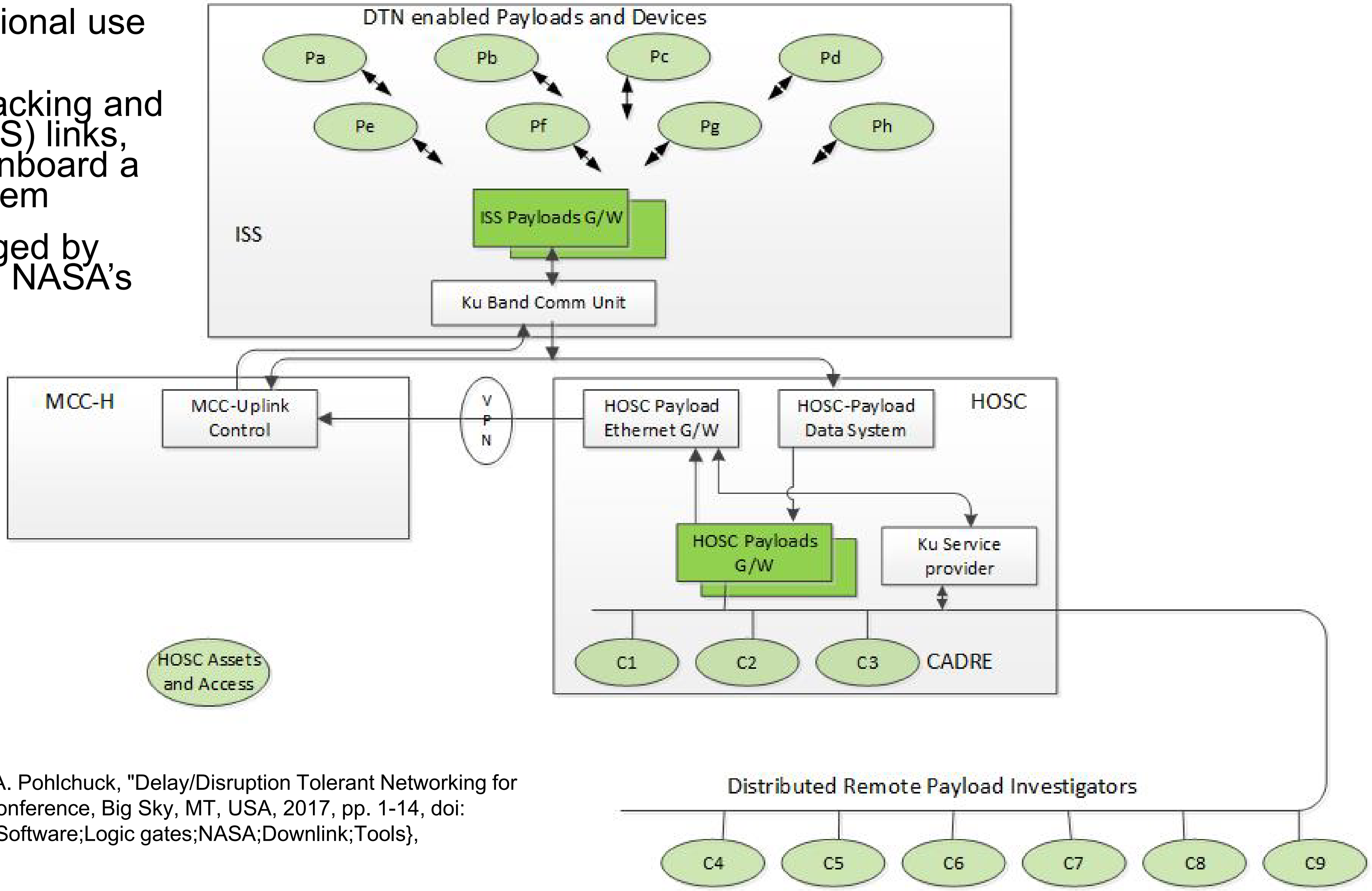
- The LLCD experiment demonstrated high-rate bi-directional optical communications to a spacecraft in lunar orbit in 2013
- DTN capabilities were demonstrated over the optical links*
  - Reliable communications over varying length outages due to atmosphere or clouds
  - Rate buffering
  - Multiplexing and de-multiplexing data over trunklines

*No DTN implemented onboard spacecraft (LLCD looped back DTN data over optical links)

David J. Israel, Donald Cornwell, Gregory Menke and W. John Guineau. "Demonstration of Disruption Tolerant Networking across Lunar Optical Communications Links," AIAA 2014-4481. *32nd AIAA International Communications Satellite Systems Conference*. August 2014.

Operational Use of DTN on ISS

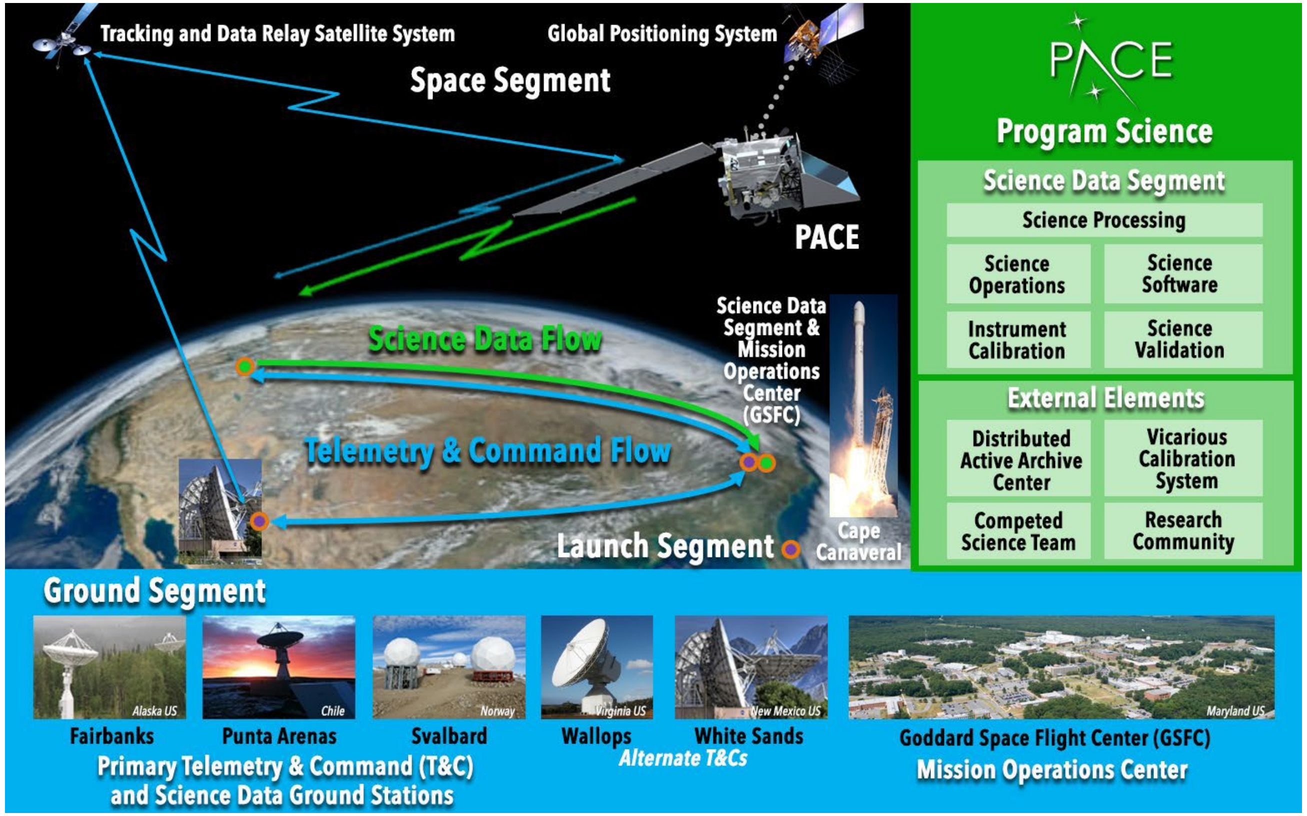
- DTN has been in continuous operational use on the ISS since 2016
- DTN traffic travels over the NSN Tracking and Data Relay Satellite System (TDRSS) links, however there are no DTN nodes onboard a TDRS or in the TDRSS ground system
- The space station network is managed by NASA's Johnson Space Center and NASA's Marshall Space Flight Center

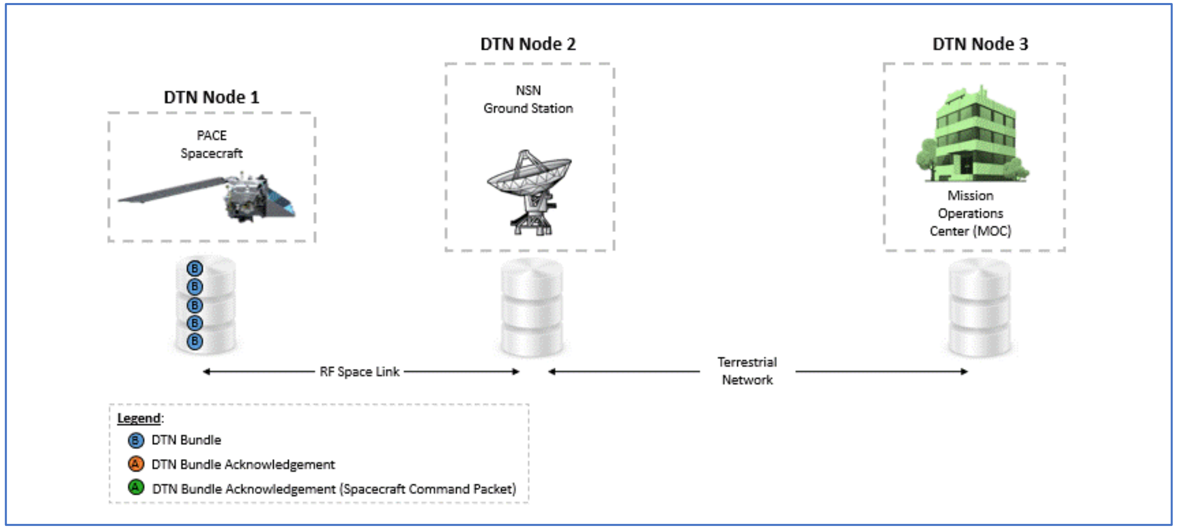


A. Schlesinger, B. M. Willman, L. Pitts, S. R. Davidson and W. A. Pohlchuck, "Delay/Disruption Tolerant Networking for the International Space Station (ISS)," 2017 IEEE Aerospace Conference, Big Sky, MT, USA, 2017, pp. 1-14, doi: 10.1109/AERO.2017.7943857. keywords: {Payloads;Protocols;Software;Logic gates;NASA;Downlink;Tools},

PACE Mission DTN Operations

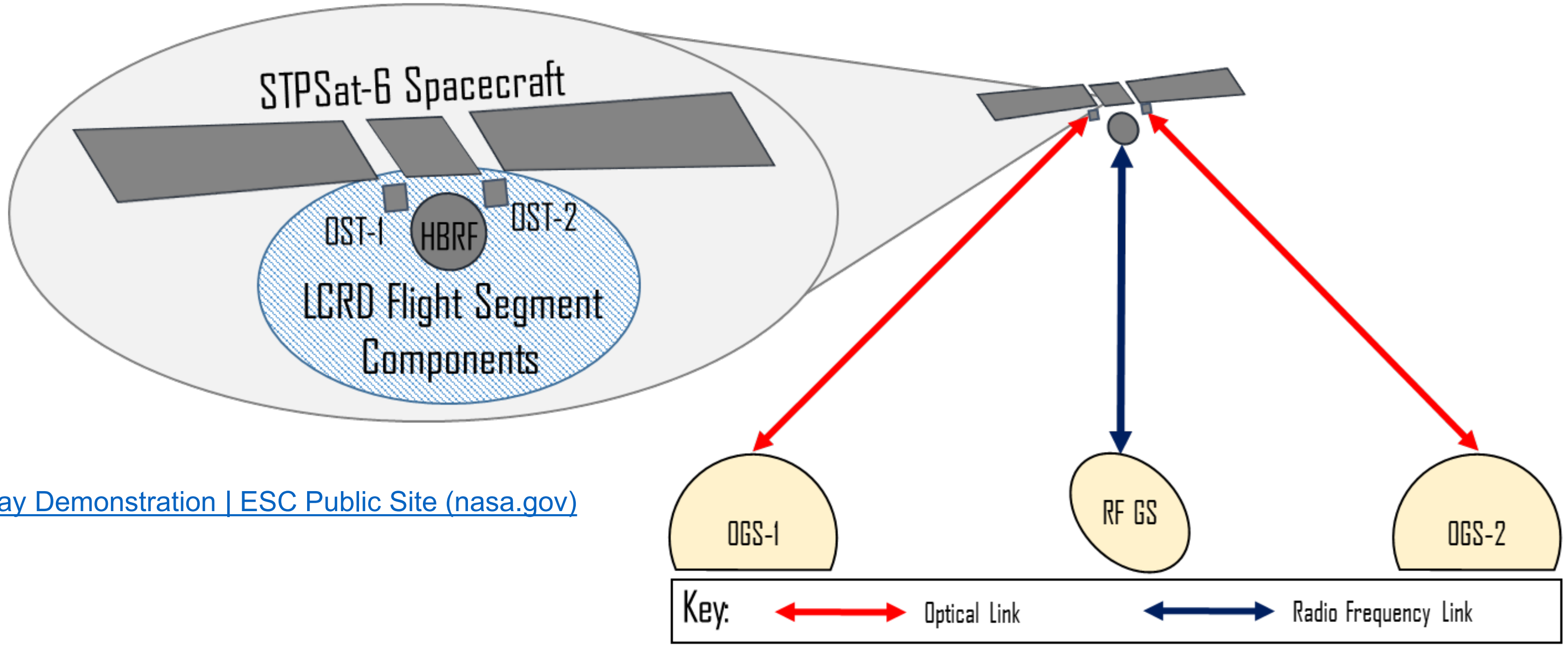
- PACE uses DTN to transfer all housekeeping files over S-Band links at 2 Mbps
- First operational use by non-HSF science mission
- PACE connects with DTN nodes at four NSN ground stations
  - PACE Mission Ops Center connects separately with each ground station
  - All custody signaling from ground stations are passed back through the MOC to be uplinked back to the spacecraft





Israel, D. J., Swinski, J. P., Wilmot, J., Strege, S., Anderson, B., Jain, P., & Matusow, C. (2021, May). Implementing delay/disruption tolerant networking for NASA's Plankton, Aerosol, Clouds, Ocean Ecosystem (PACE) mission. In The 16th International Conference on Space Operations (SpaceOps 2021) (No. SpaceOps-2020, 1, 1, 3, x1326).

LCRD Mission Experiment Architecture



[Laser Communication Relay Demonstration | ESC Public Site (nasa.gov)]

- **The Laser Communications Relay Demonstration (LCRD) launched in December 2021 and experiments began June 2022**
- **Flight segment is on board the Space Test Program Satellite-6 (STPSat-6) spacecraft in geosynchronous Earth orbit (GEO)**
  - **Two optical space terminals (OST), OST1 and OST2 (maximum rates of 1.244 Gbps)**
  - **High-bandwidth Radio Frequency (HBRF) terminal**
  - **Data switch**
- **The ground segment**
  - **Optical Ground Station 1 (OGS-1) in Table Mountain, California**
  - **Optical Ground Station 2 (OGS-2) in Haleakalā, Hawaii**
  - **Radio frequency ground station (RF GS) in White Sands, New Mexico**

Israel, D. J., Edwards, B. L., Butler, R. L., Moores, J. D., Piazzolla, S., Du Toit, N., & Braatz, L. (2023, March). Early results from NASA's laser communications relay demonstration (LCRD) experiment program. In *Free-Space Laser Communications XXXV* (Vol. 12413, pp. 10-24). SPIE.

ILLUMA-T: First LEO User of LCRD

LCRD at GEO
Launched Dec 7, 2021

ILLUMA-T on ISS at LEO
Launched Nov 9, 2023
Jettisoned Jun 29, 2024

ILLUMA-T

(Integrated LCRD LEO User Modem and Amplifier Terminal)

Develop an optical communications user terminal to demonstrate data transfer between low Earth orbit and the ground through a geosynchronous relay

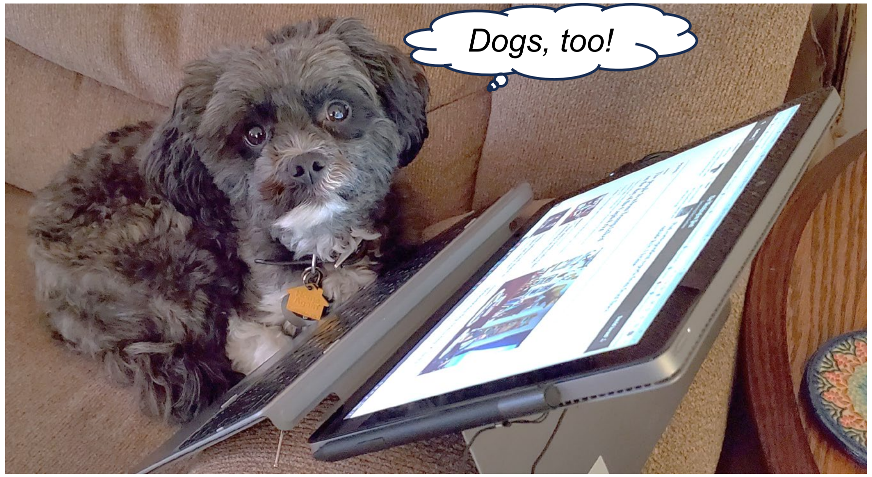
- **Provides 1.2 Gbps return link for ISS**
- **Provides 50 Mbps/155 Mbps forward link**
- **Demonstrates optical relay utility with LCRD**

Seas, A., Robinson, B., Shih, T., Khatri, F., & Brumfield, M. (2019, July). Optical communications systems for NASA's human space flight missions. In *International Conference on Space Optics—ICSO 2018* (Vol.

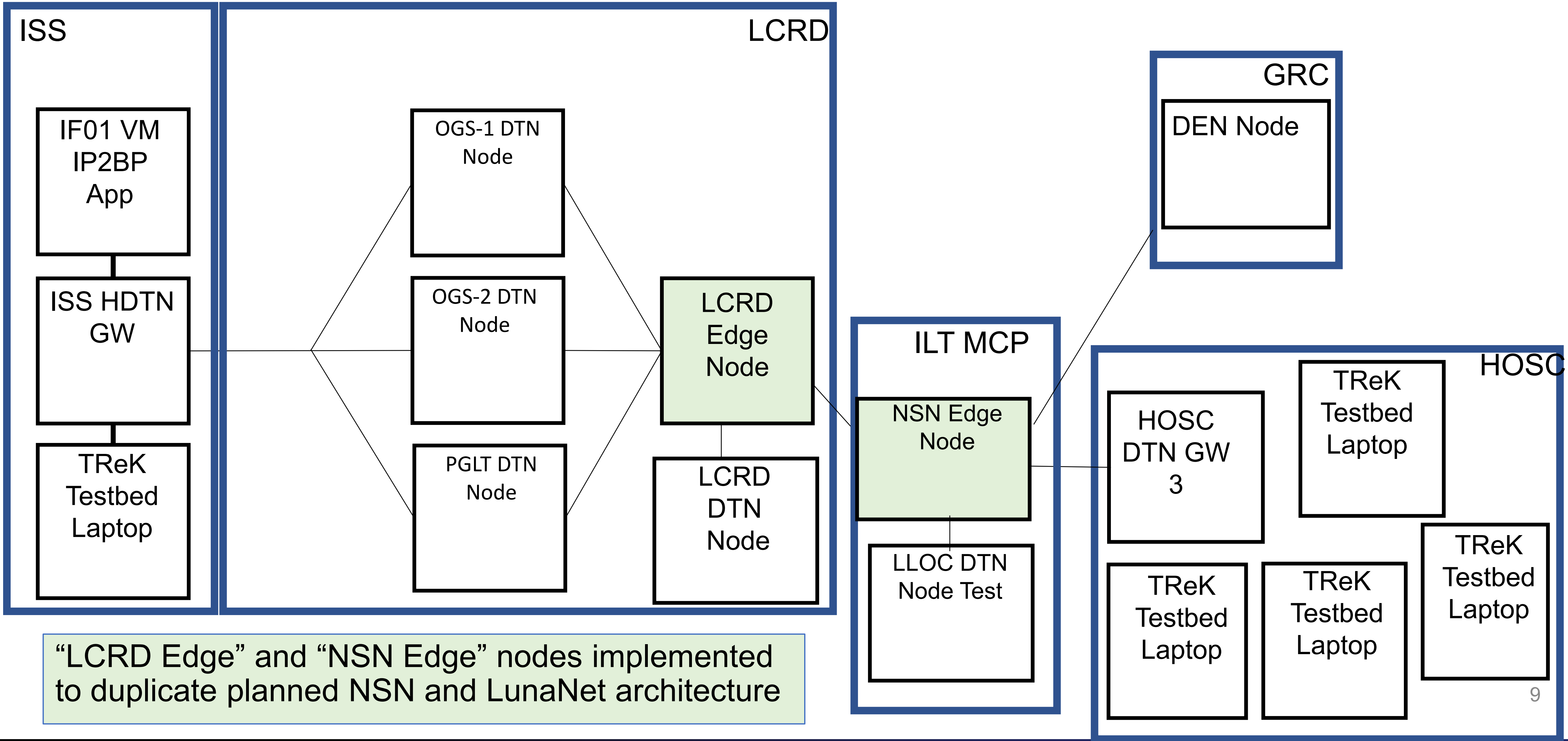
LCRD Experiment Goals and Ground Rules

- LCRD DTN Experiment Goals
  - Demonstrate BP at max data rates over all paths
  - Use BPv6 and BPv7
  - Demonstrate BPSec for end-to-end security thru an intermediate provider
  - Demonstrate complete data delivery thru link outages, across multiple passes and trunkline handovers
  - Demonstrate streaming video using BP
- Ground Rules
  - Must use the prescribed network provider architecture (See next slide)
  - All end-to-end data delivery must be done using BP
  - End users shall not have to reconfigure to reroute data in the case of a trunkline handover

"It's really all about the cat pictures"



LCRD Network Architecture



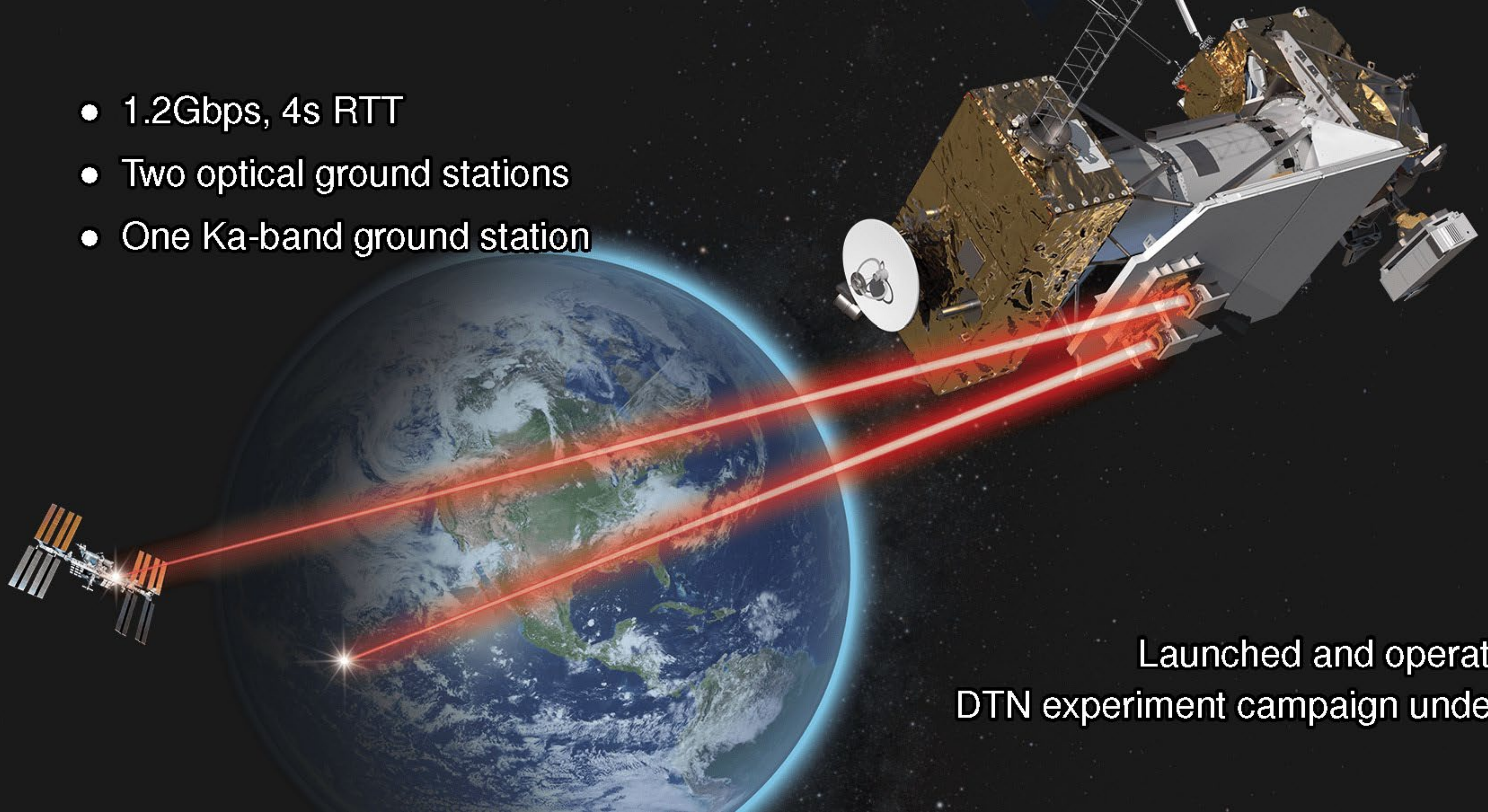
“LCRD Edge” and “NSN Edge” nodes implemented to duplicate planned NSN and LunaNet architecture

Alan Hylton ∈ NASA

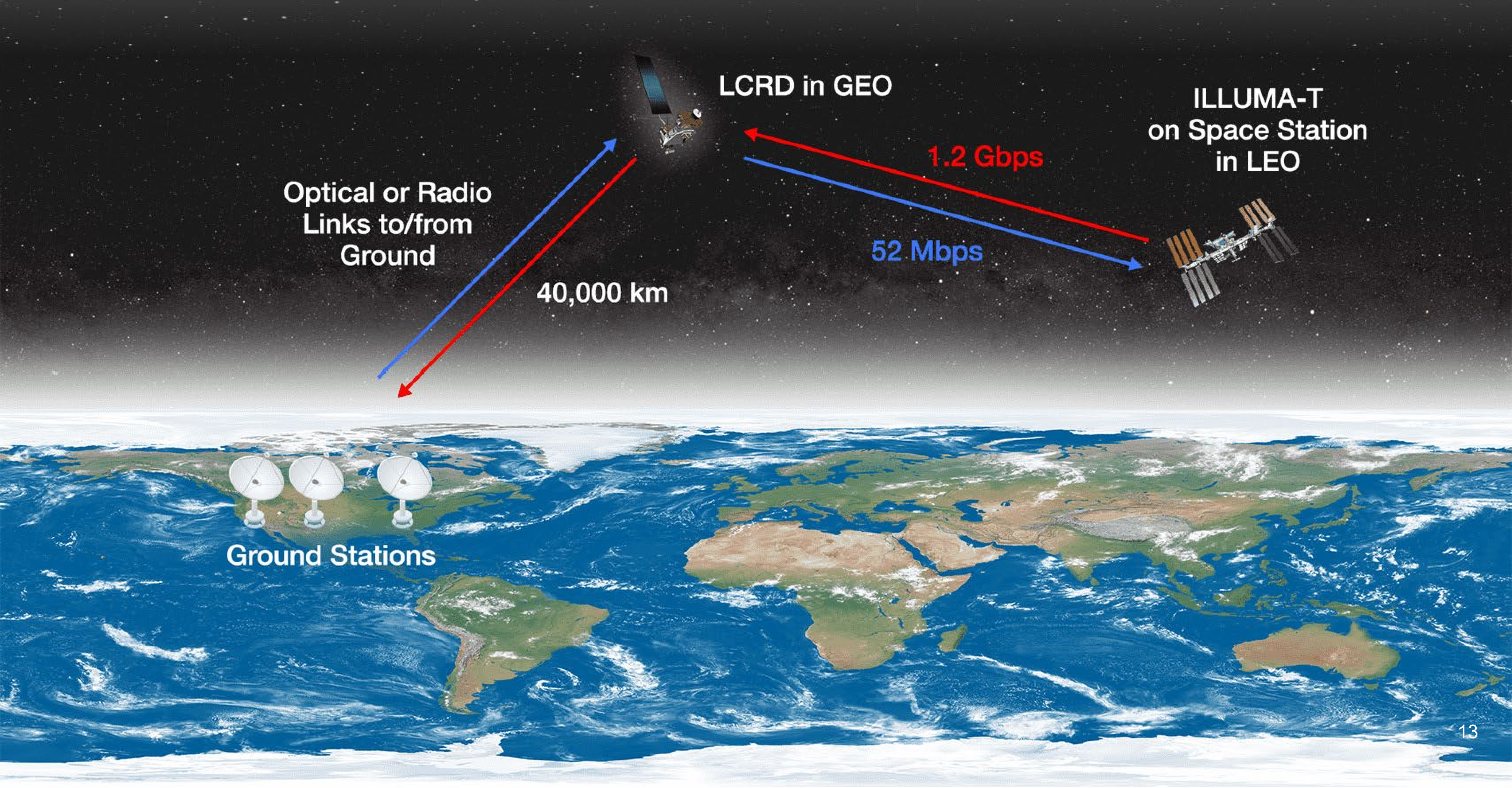

Alaska Satellite Facility, AK
North Pole Satellite Station, AK
Fairbanks Command and Data Acquisition Station, AK
NASA Wallops Ground Station, VA
Blossom Point, MD
Svalbard Satellite Ground Station, Norway
Esrange Satellite Station, Sweden
Singapore Satellite Ground Station
Guam Remote Ground Terminal
Goldstone Deep Space Communications Complex, CA
Remote Ground Relay Terminal, Australia
South Point Satellite Station, HI
Canberra Deep Space Communications Complex, Australia
10
11
9
6
12
13
7
8
White Sands Ground Station, NM
White Sands Complex, NM
Launch Communications Segment, FL
Santiago Satellite Station, Chile
Madrid Deep Space Communications Complex, Spain
Troll Satellite Ground Station, Antarctica
Hartebeesthoek Ground Station, South Africa
McMurdo Ground Station, Antarctica
Dongara Satellite Station, Australia
NSN NEAR SPACE NETWORK
TDRS
DSN DEEP SPACE NETWORK

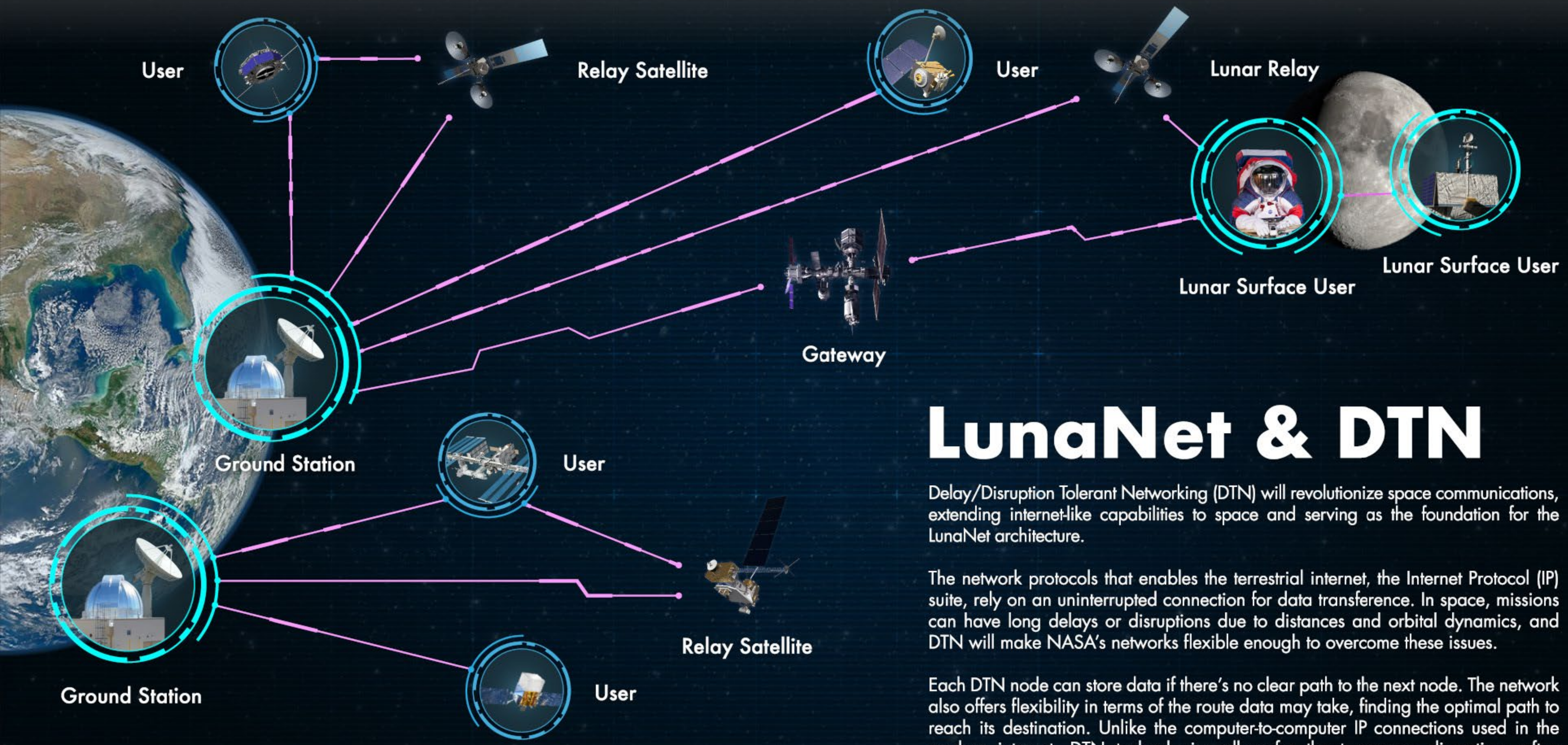
Laser Communications Relay Demonstration (LCRD)

- 1.2Gbps, 4s RTT
- Two optical ground stations
- One Ka-band ground station



- Launched and operational
- DTN experiment campaign underway


LCRD in GEO
ILLUMA-T
on Space Station
in LEO
1.2 Gbps
52 Mbps
Optical or Radio
Links to/from
Ground
40,000 km
Ground Stations



**Conceptual visualization. Not meant to show actual present or future network architecture. Not to scale.*

LunaNet & DTN

Delay/Disruption Tolerant Networking (DTN) will revolutionize space communications, extending internet-like capabilities to space and serving as the foundation for the LunaNet architecture.

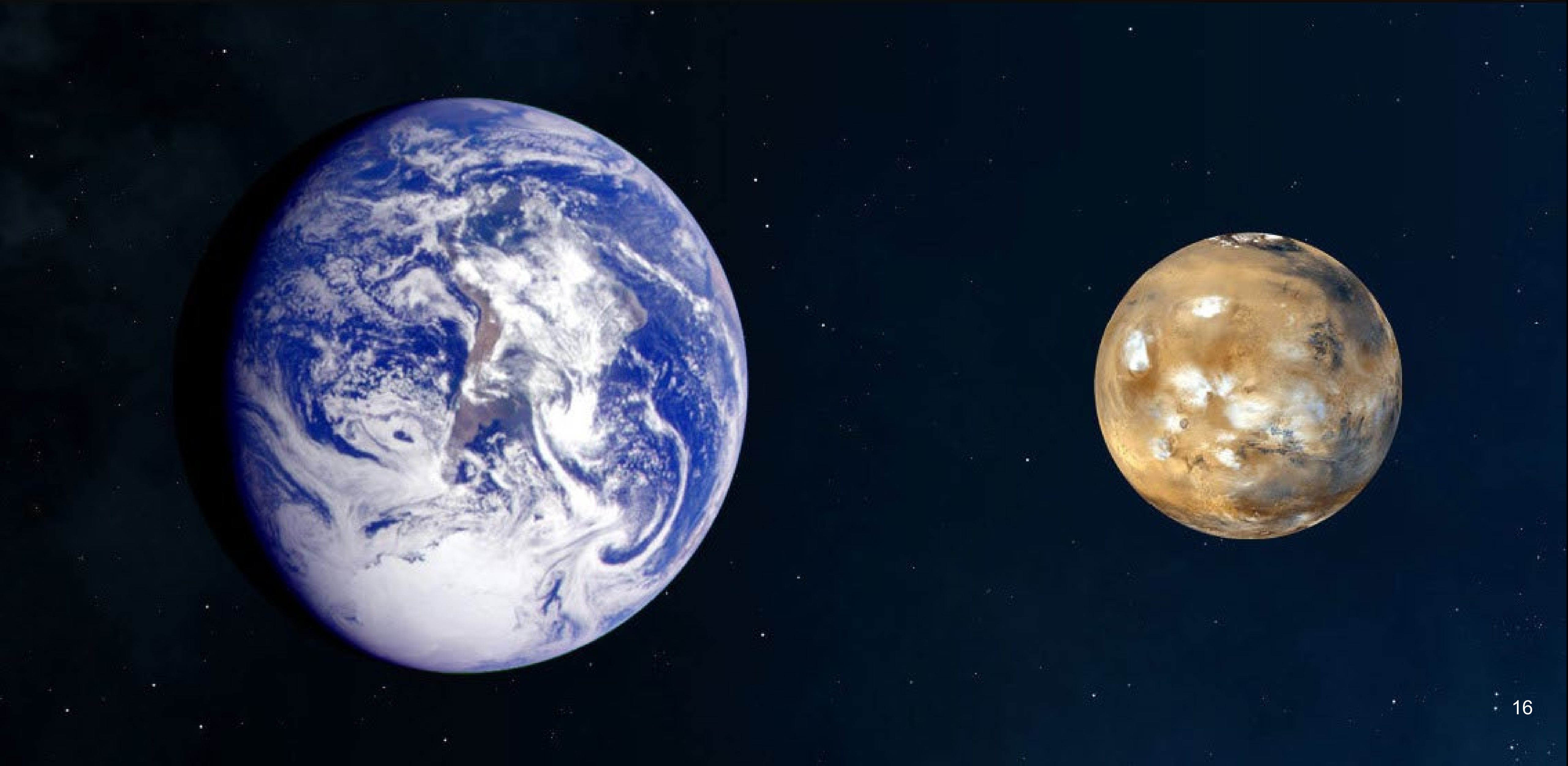
The network protocols that enables the terrestrial internet, the Internet Protocol (IP) suite, rely on an uninterrupted connection for data transference. In space, missions can have long delays or disruptions due to distances and orbital dynamics, and DTN will make NASA's networks flexible enough to overcome these issues.

Each DTN node can store data if there's no clear path to the next node. The network also offers flexibility in terms of the route data may take, finding the optimal path to reach its destination. Unlike the computer-to-computer IP connections used in the modern internet, DTN technologies allow for the temporary disruptions often experienced by spacecraft far from Earth.

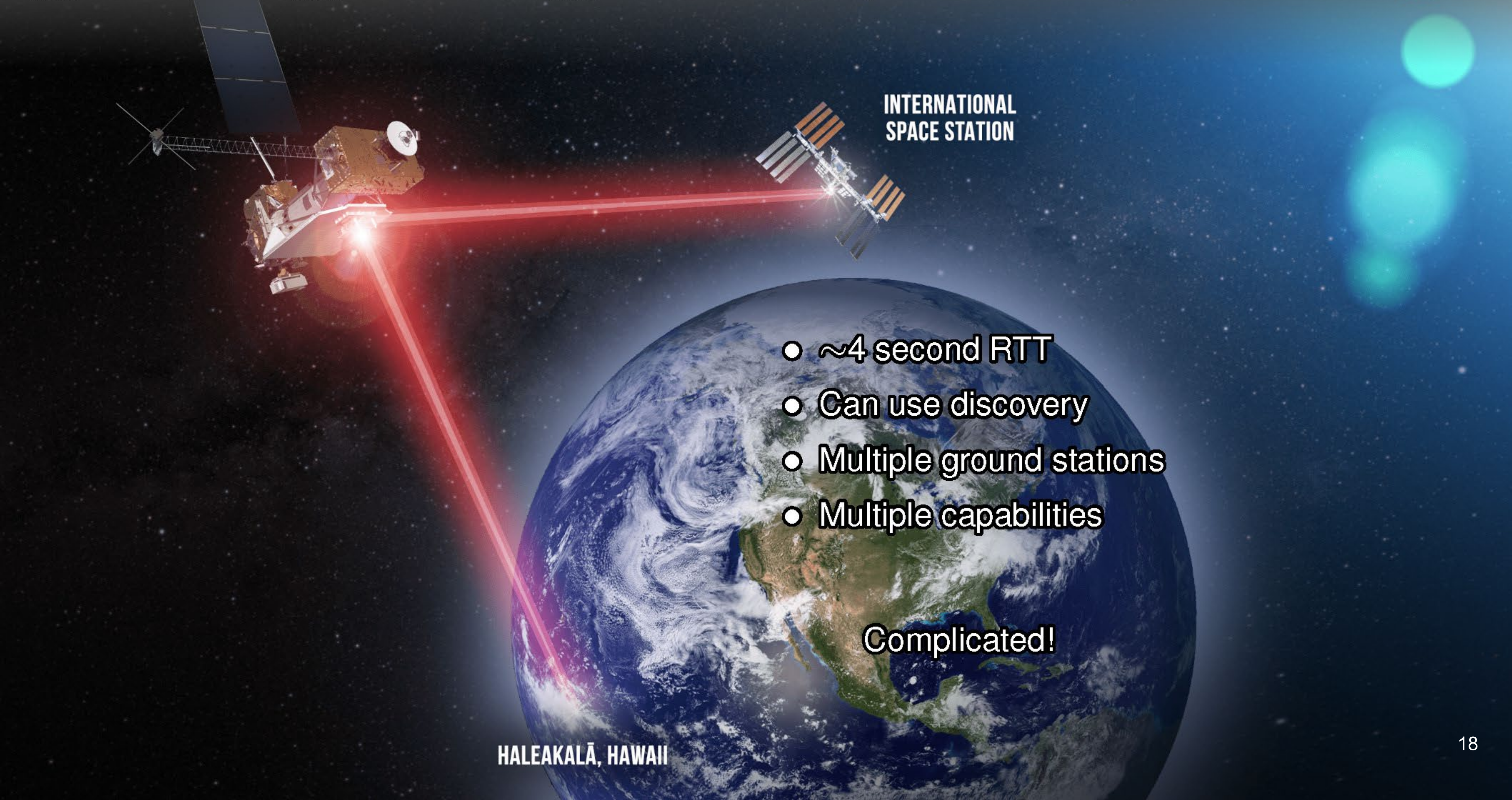
Towards the Solar System Internet

- Higher latencies
- Higher variance of latencies
- Disruption
- Mobility
- Density
- Limited ground stations
- Limited relays

Store, Carry, and Forward




22 minutes
⇐ 13 minutes ⇒
3.1 minutes



- ~4 second RTT
- Can use discovery
- Multiple ground stations
- Multiple capabilities

Complicated!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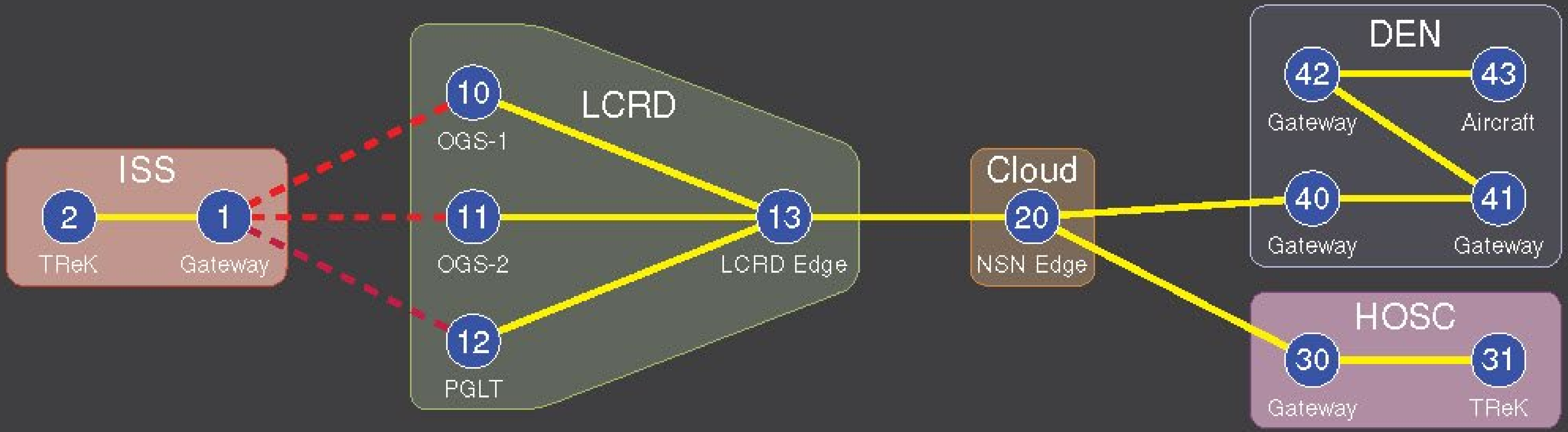
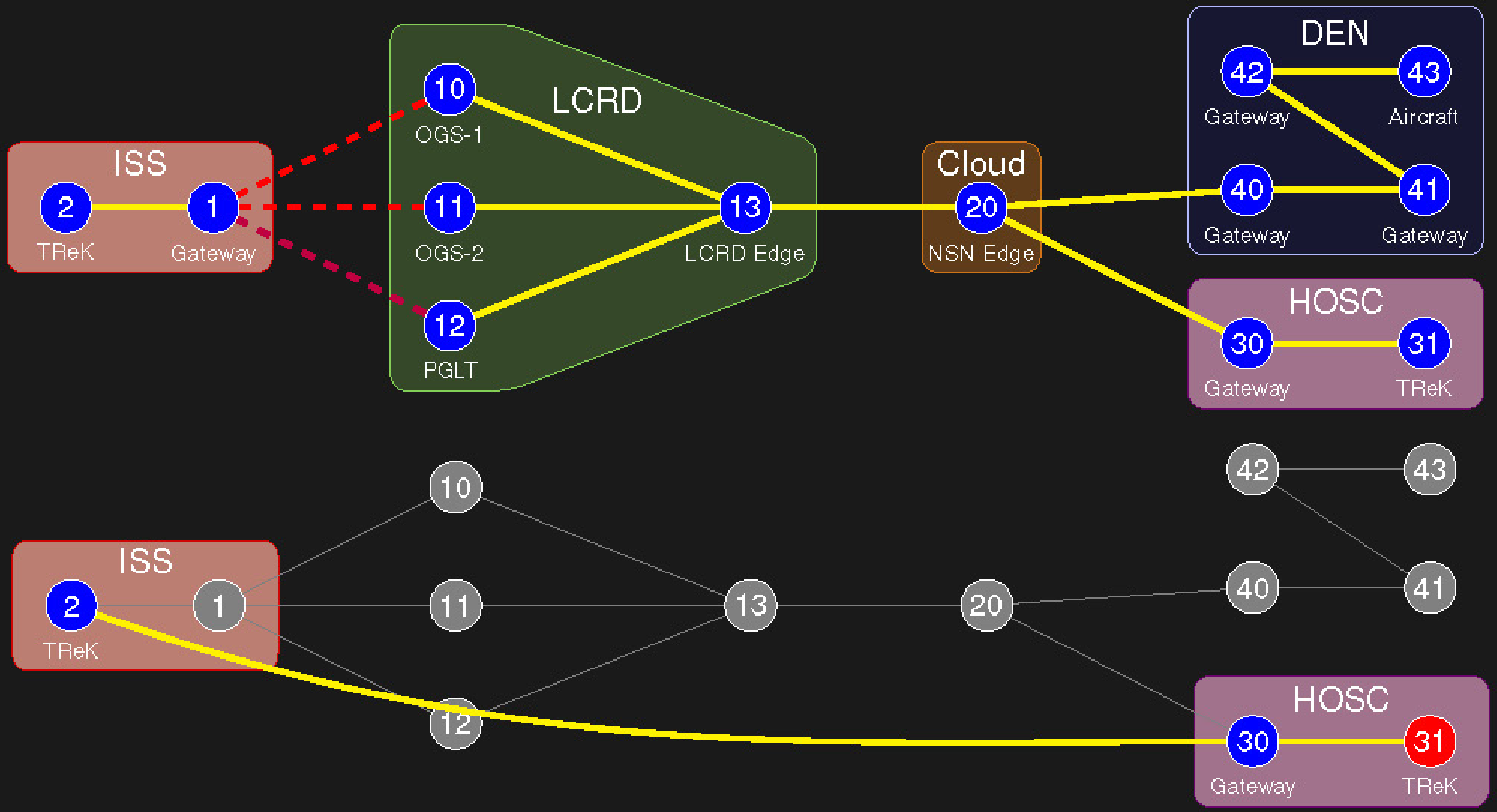
N608NA
Newport

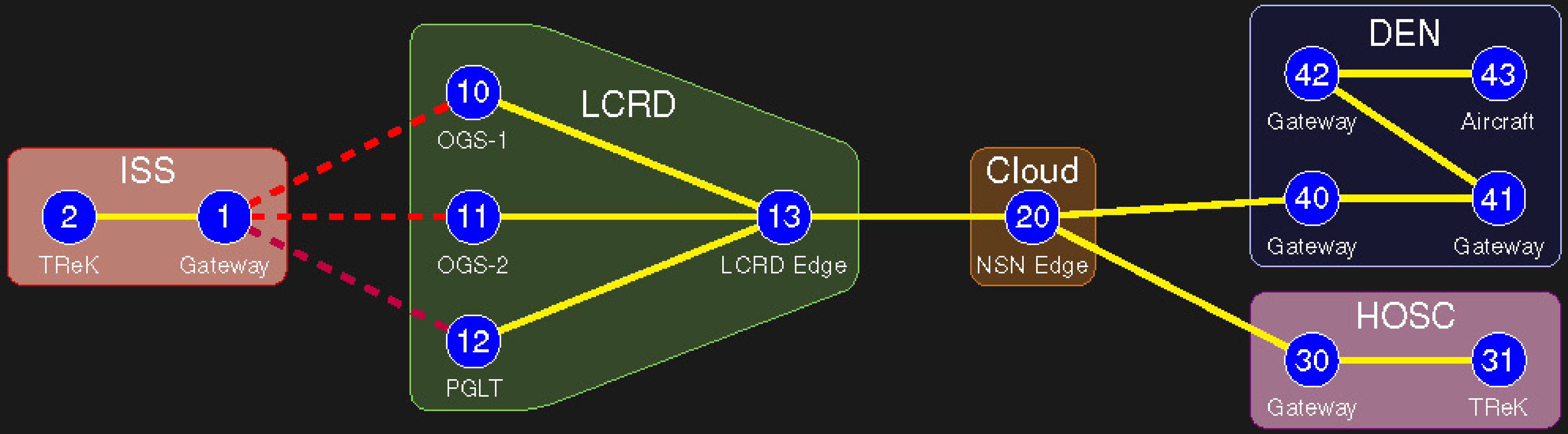
An Omniscient View

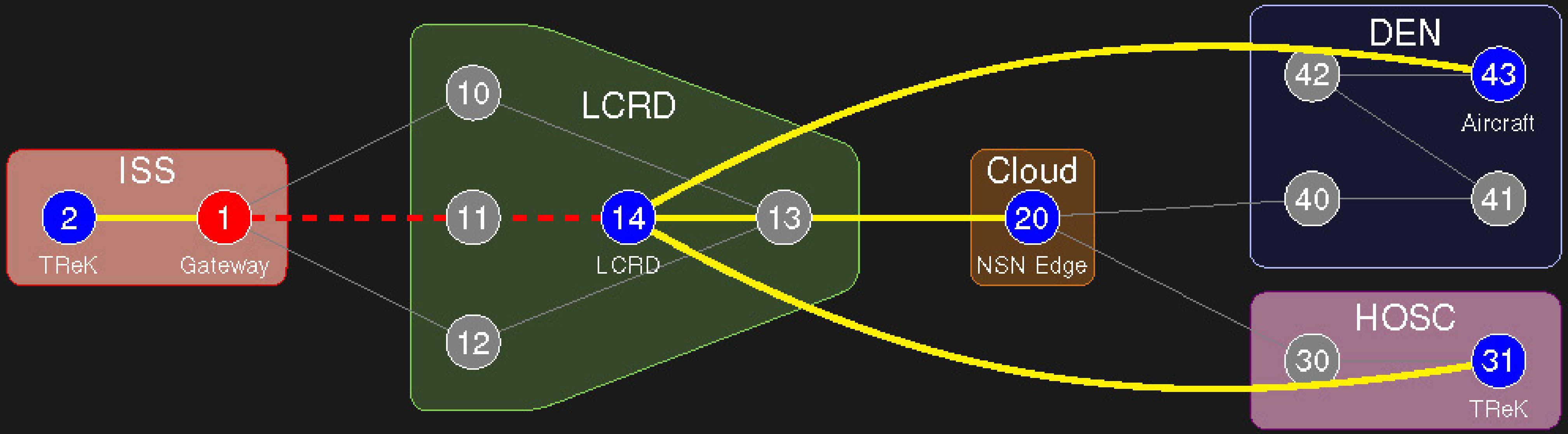


HOSC TReK Node

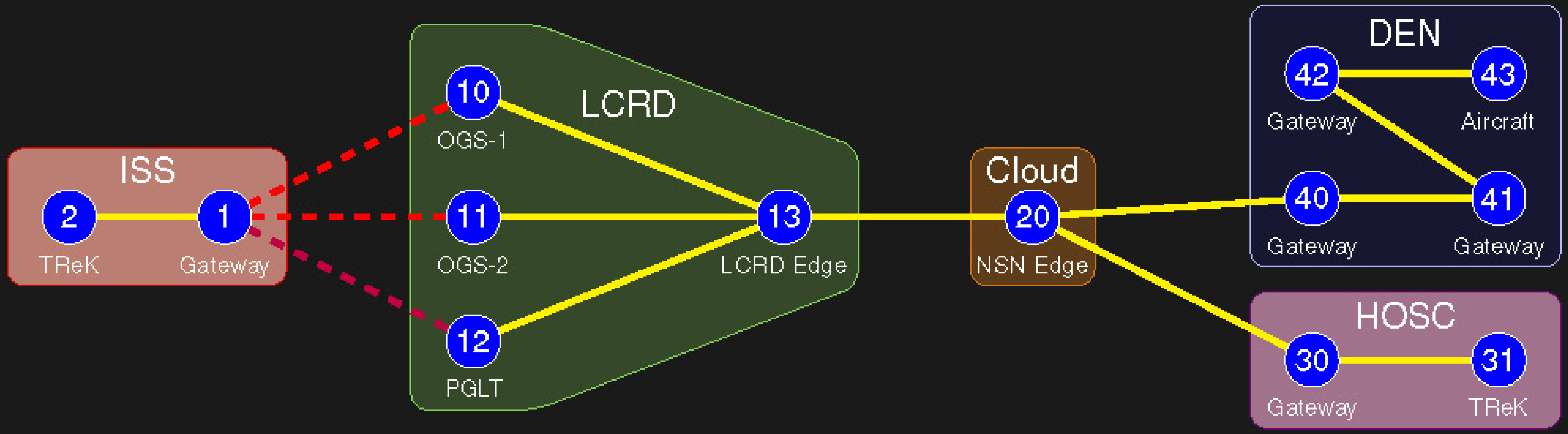


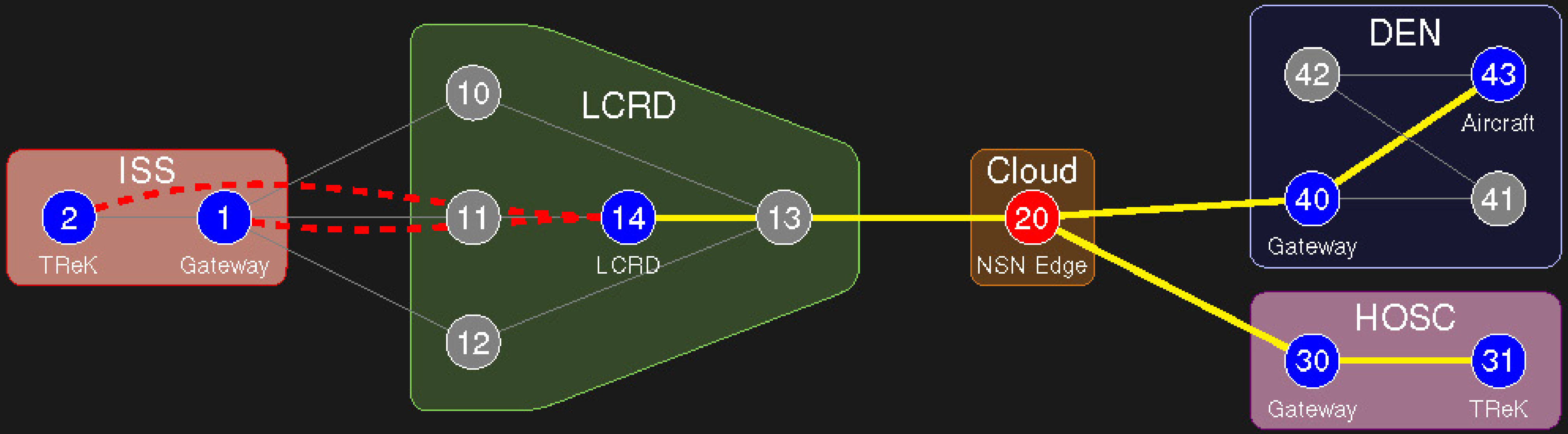
ISS Gateway Node





Cloud Node

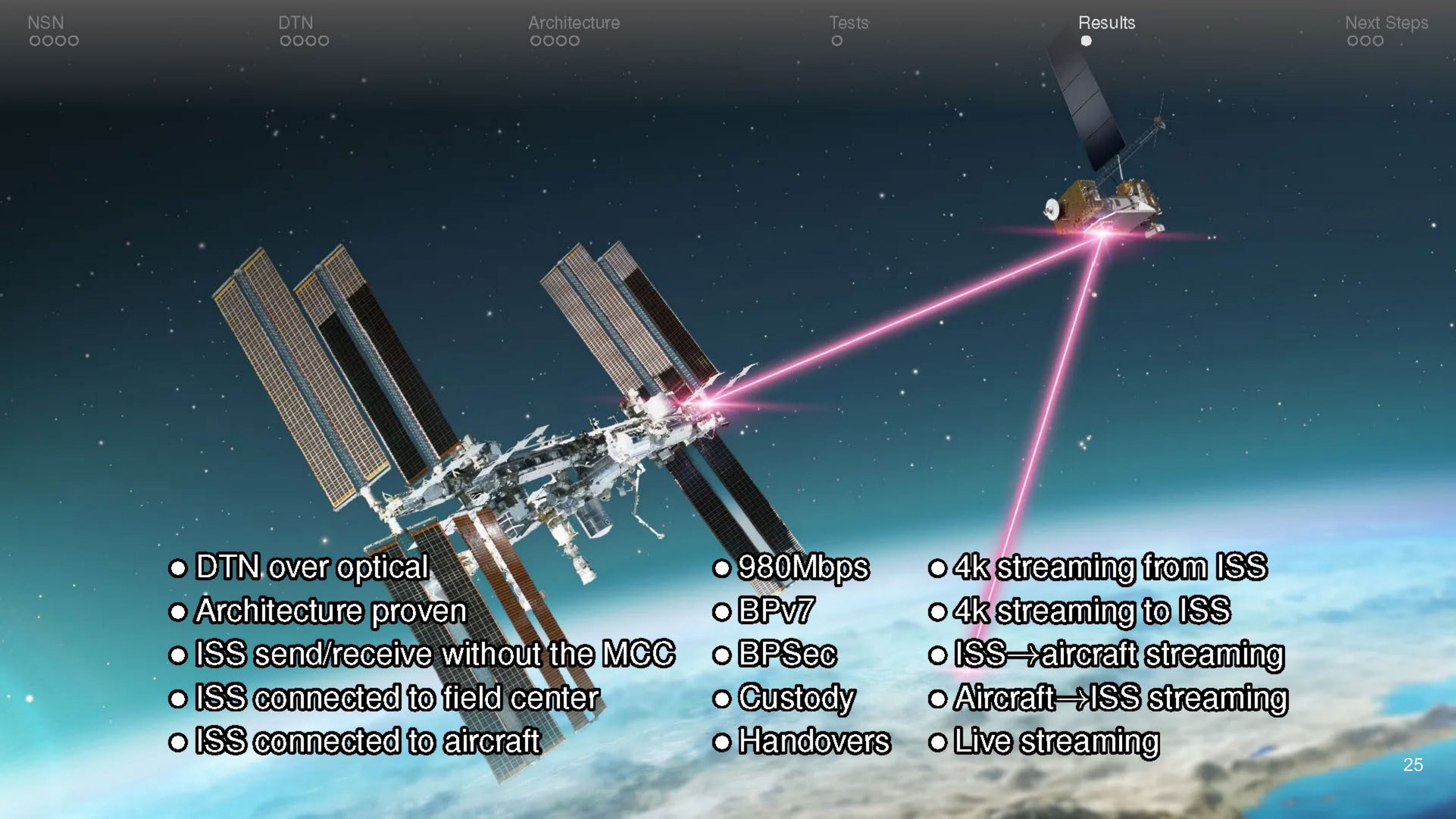

ISS
2
TReK
1
Gateway
LCRD
10
OGS-1
11
OGS-2
12
PGLT
13
LCRD Edge
Cloud
20
NSN Edge
DEN
42
Gateway
43
Aircraft
40
Gateway
41
Gateway
HOSC
30
Gateway
31
TReK


ISS
2
TReK
1
Gateway
LCRD
10
11
12
14
LCRD
13
Cloud
20
NSN Edge
DEN
42
43
Aircraft
40
Gateway
41
HOSC
30
Gateway
31
TReK

1: BP
- v6, with custody
- v7, with and without BPSec

2: Files
- Small (up to a few MB)
- Large (up to a few GB)

3: Streaming
- To the ISS
- From the ISS



- DTN over optical
- Architecture proven
- ISS send/receive without the MCC
- ISS connected to field center
- ISS connected to aircraft

- 980Mbps
- BPv7
- BPSec
- Custody
- Handovers

- 4k streaming from ISS
- 4k streaming to ISS
- ISS→aircraft streaming
- Aircraft→ISS streaming
- Live streaming

Observations

- Space Network Service Provider
  - DTN *can* contain complexity
  - DTN *can* join networks across project and programmatic boundaries
- Infrastructure
  - DTN embiggens the case for laser communications
  - DTN improved data return per pass
- Next steps for NASA
  - Cultivate our new-found critical mass of DTN operators
  - DTN infusion into NASA networks and missions
  - Strengthen DTN relationship with aero

Next Steps

- BPv7 custody
- Multi/broad/any cast
- Next generation LTP
- Capturing lessons learned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Welcome!
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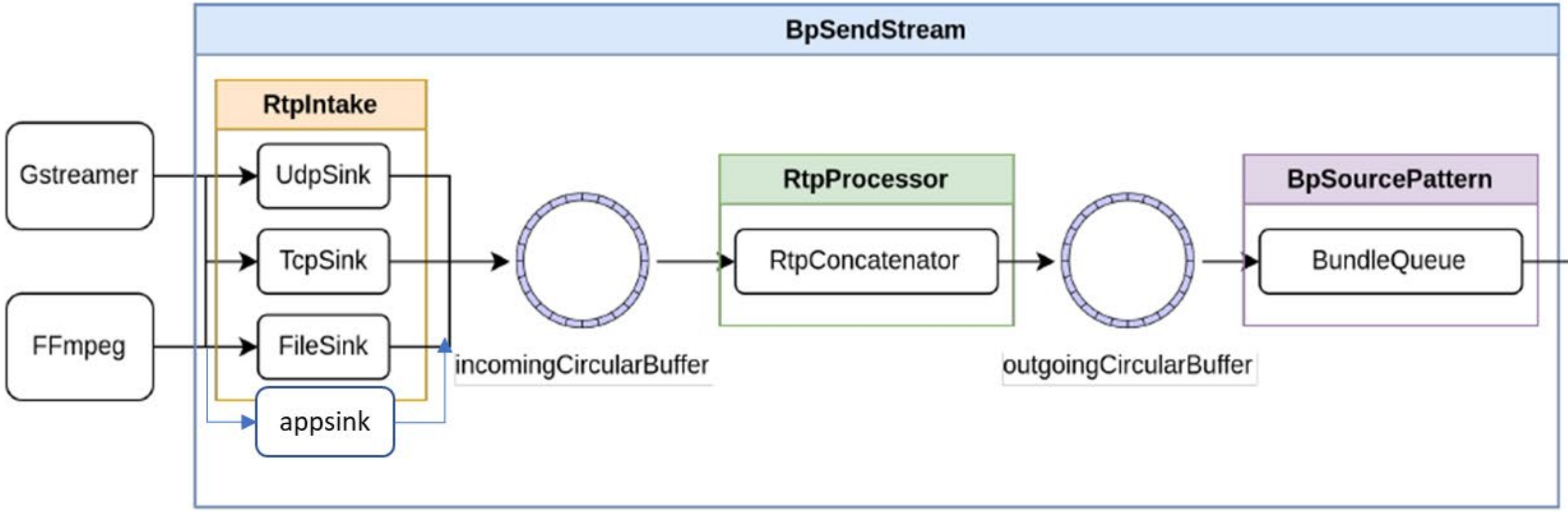
NASA
DOUG WHEELOCK

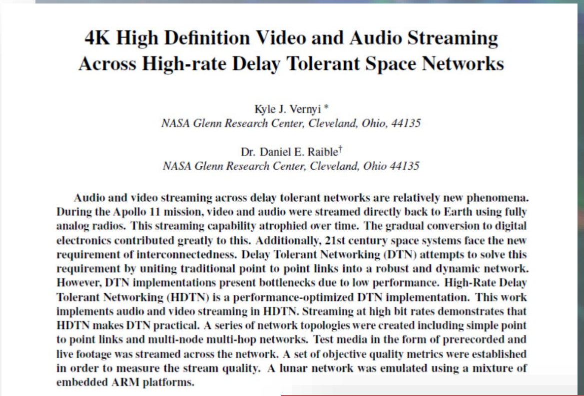
High-Rate Delay Tolerant Networking (HDTN)

Media Streaming Test Results

2024-08-13

Implementing BP based Real-time Transport Protocol (RTP)





4K High Definition Video and Audio Streaming Across High-rate Delay Tolerant Space Networks

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NASA Glenn Research Center, Cleveland, Ohio, 44135

Dr. Daniel E. Raible†
NASA Glenn Research Center, Cleveland, Ohio 44135

Audio and video streaming across delay tolerant networks are relatively new phenomena. During the Apollo 11 mission, video and audio were streamed directly back to Earth using fully analog radios. This streaming capability atrophied over time. The gradual conversion to digital electronics contributed greatly to this. Additionally, 21st century space systems face the new requirement of interconnectedness. Delay Tolerant Networking (DTN) attempts to solve this requirement by uniting traditional point to point links into a robust and dynamic network. However, DTN implementations present bottlenecks due to low performance. High-Rate Delay Tolerant Networking (HDTN) is a performance-optimized DTN implementation. This work implements audio and video streaming in HDTN. Streaming at high bit rates demonstrates that HDTN makes DTN practical. A series of network topologies were created including simple point to point links and multi-node multi-hop networks. Test media in the form of prerecorded and live footage was streamed across the network. A set of objective quality metrics were established in order to measure the stream quality. A lunar network was emulated using a mixture of embedded ARM platforms.

*Software Engineer, NASA Glenn Research Center, 21000 Brook
†Electronics Engineer, NASA Glenn Research Center, 21000 Bro

2024
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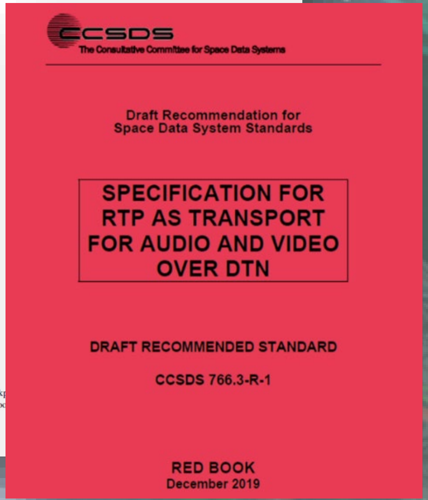
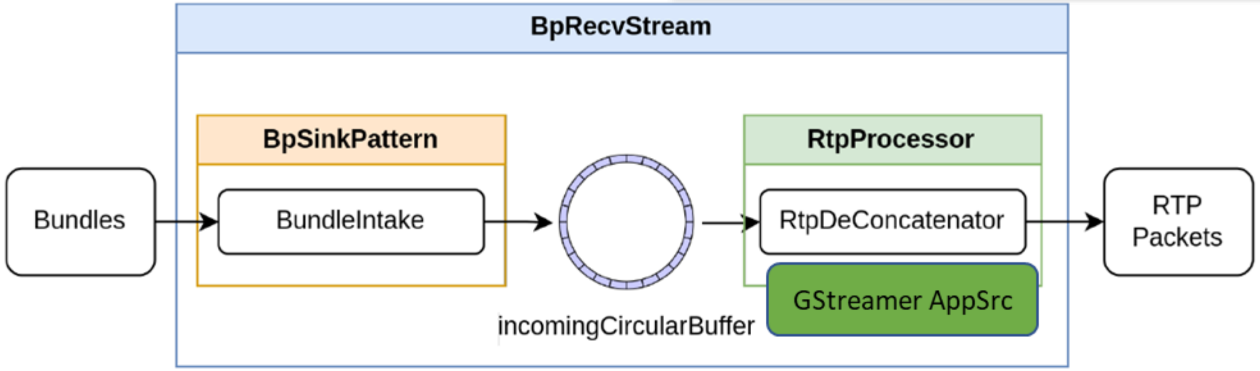


ISS *"WaterBubble"* test example:

- Demanding 4K60
- 10bit 4:2:2 color
- ~33Mbps, depending on encoding
- 1, 20, 30 & 45 RTP packets per bundle
- Induced disconnections and 10s delays

Implemented on network of Raspberry Pi-4's

Thanks to Joshua Deaton for steering us toward the draft standards

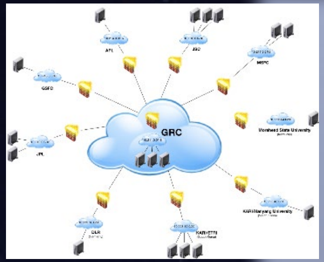


Performance Metrics:

Media Type	Metric Name	Units	Range	Notes
Video	Peak SNR (PSNR)	dB	-	Not a good indicator of video quality but is industry standard.
Video	Structural Similarity (SSIM)	-	[-1, 1]	Considers image degradation as perceived change in structural information. Moving towards human perception.
Video	VMAF	-	[0, 100]	ML model trained by Netflix. Attempts to model human perception of the media.
Audio	PSNR	dB	-	Standard measurement

2024 DTN Engineering Network (DEN) Enhancements

Supports simultaneous and isolated network testing



External Collaborations

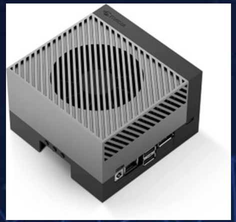
- Agency
- Academia

Unit Testing

- Bare metal & VM's
- Containerization
- 7150 V&V framework

Interoperability

- Platforms
- Processors
- Applications

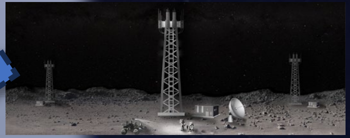


Network Emulation

- 100's of nodes
- TB's of storage
- Up to >Gbps rates
- Minutes of link delay
- Bundle reordering
- Bundle duplication
- Bundle loss
- Dynamic topologies
- Link scheduling

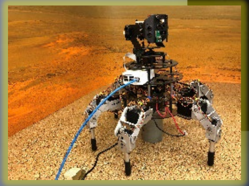
Intranetwork Connections

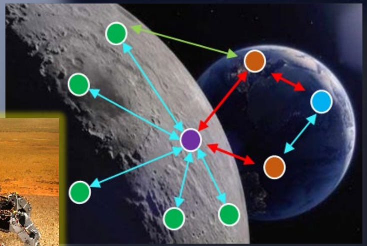
- Cloud to LCRD
- Flight research
- 3GPP



Scenario Testing

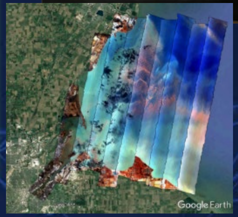
- LunaNet
- Mars Network
- Endurance testing





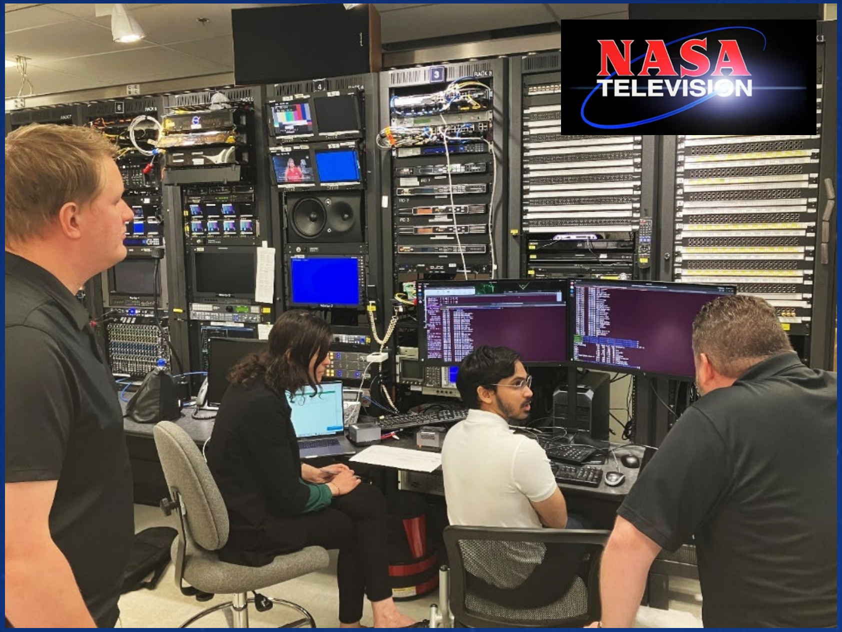
Hardware in the Loop (HIL)

- Instrumentation interfacing
- Mission integration support



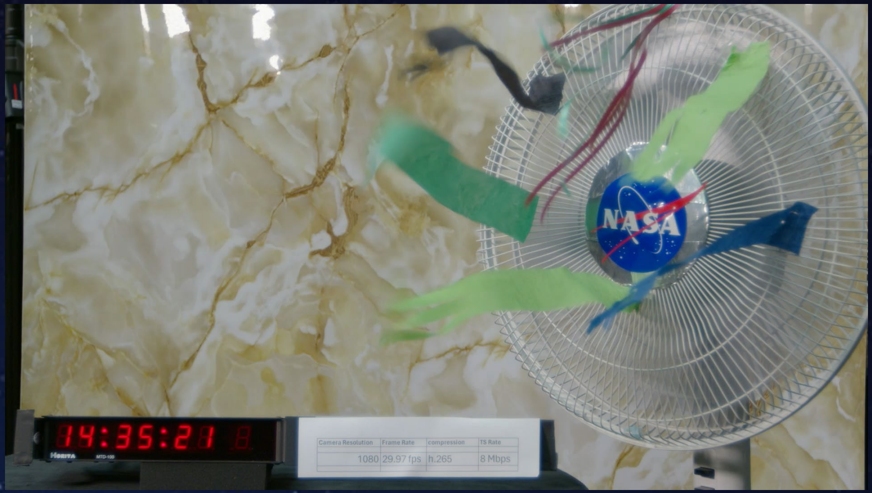
Streaming Results Across Various Camera and Encoder Configurations

Visual review of the received streams revealed no discernable degradation of the video



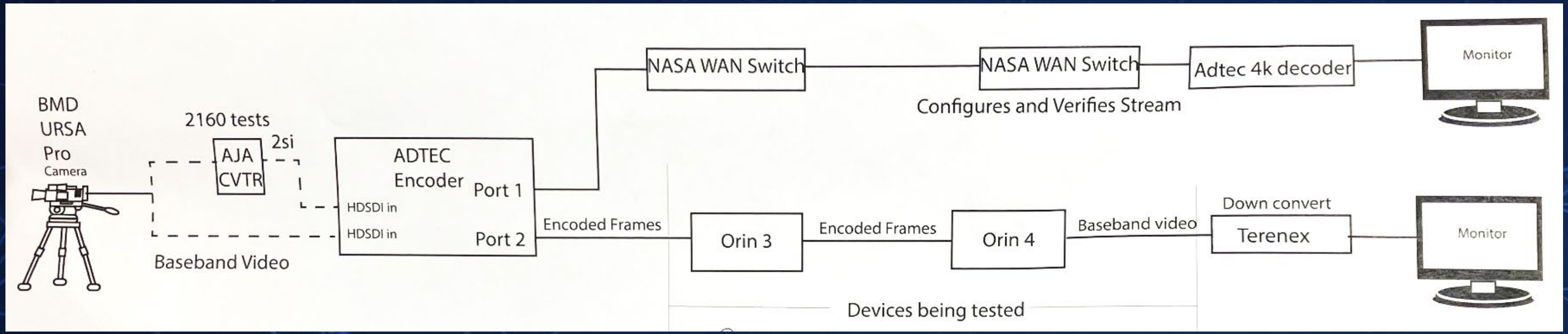
Hardware encoder test points:

- 720P30 h.264 @ 2 Mbps
- 720P60 h.264 @ 4 Mbps
- 1080P30 h.265 @ 4 Mbps, 6 Mbps and 8 Mbps
- 1080P60 h.265 @ 6 Mbps and 8 Mbps
- 2160P30 h.265 @ 6 Mbps and 8 Mbps
- 2160P60 h.265 @ 6 Mbps and 8 Mbps



Measured SSIM values were consistently exceeding 0.92 in all configurations

Video quality	SSIM value
Excellent	0,93 or more
Good	0,88-0,93
Fair	0,84-0,88
Poor	0,78-0,84
Bad	0,78 or less

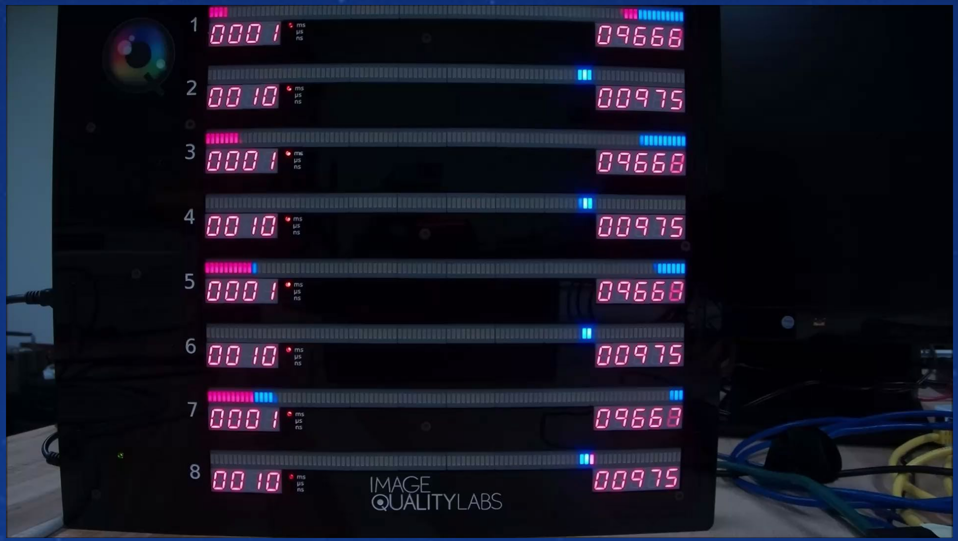


Huge thanks to Hugh Aylward, Jim Firak and Mike Burroughs for offering their assistance in configuring all the equipment and keeping us organized

HDTN Streaming Results Using Delay and Disruption (reordering and duplication)

Camera Settings: 1080P60 H.265 @ 8 Mbps

Netropy Path	Reordering Probability	Reordering Timeout	Duplication Probability
Path 1	10%	750 ms	0%
Path 2	10%	750 ms	10%
Path 3	50%	1500 ms	0%
Path 4	10%	100 ms	0%

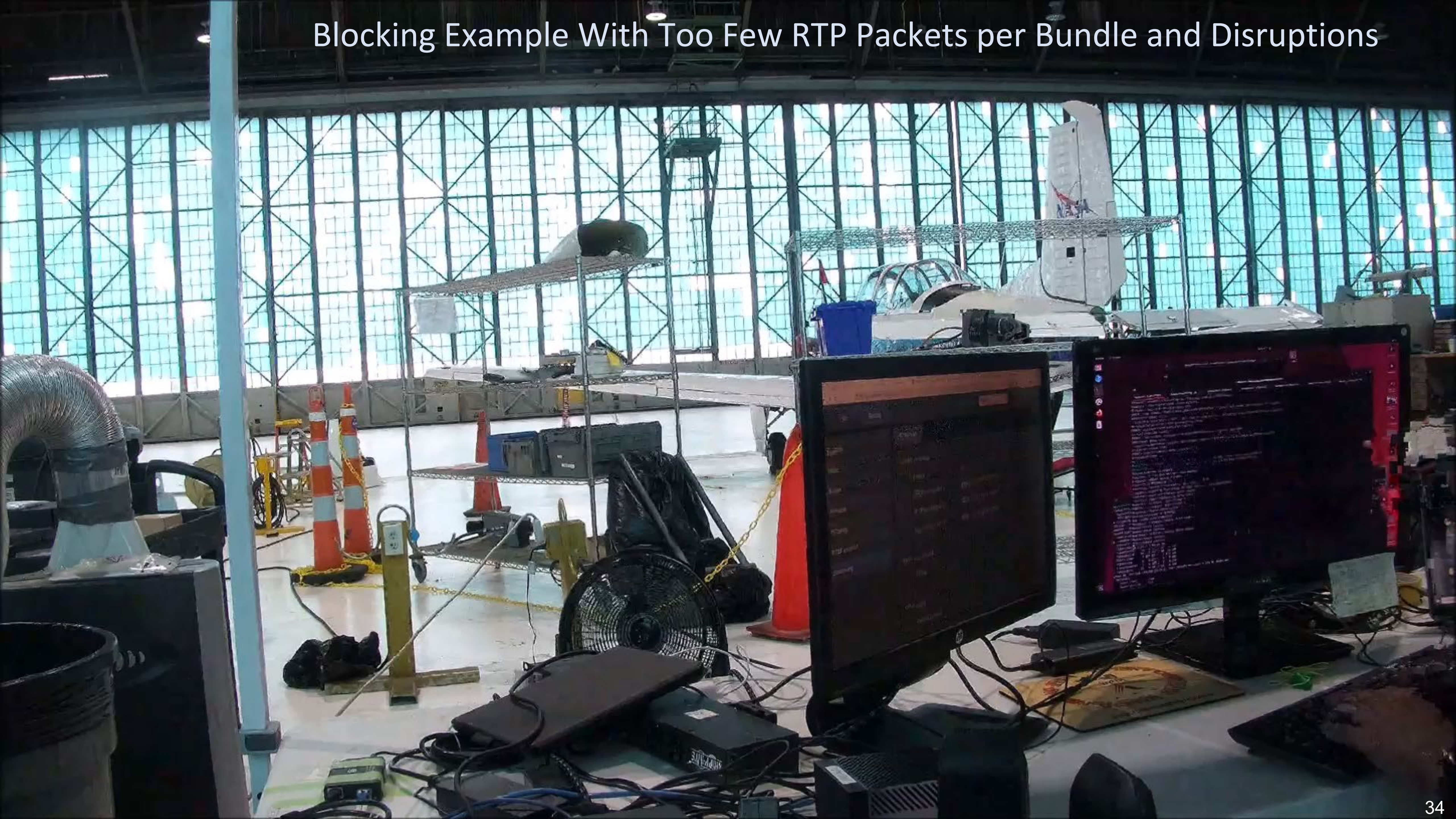


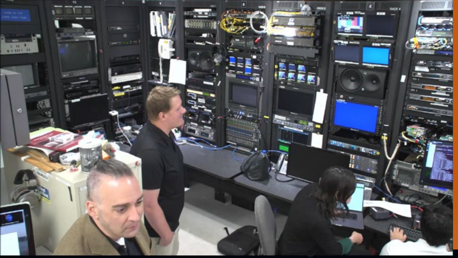
Scenarios	Configuration	Average Peak Signal-to-Noise Ratio (dB) Between Baseline and Received	Structual Similarity Index (SSIM) Between Baseline and Received
1	No DTN (just RTP over UDP)	11.264069	0.661995
2		11.674342	0.686143
3		9.786832	0.514632
4		10.2071	0.595434
1	HDTN with 1 RTP packet per bundle	10.935887	0.6765
2		9.388365	0.540245
3		9.012866	0.497818
4		10.669843	0.656239
1	HDTN with 5 RTP packets per bundle	27.847981	0.921007
2		24.573204	0.904236
3		28.190421	0.925601
4		26.974887	0.906726
1	HDTN with 20 RTP packets per bundle	28.913023	0.93251
2		28.783082	0.934622
3		29.327898	0.948557
4		30.874348	0.983011

NVIDIA Jetson Orin's used for DTN nodes

Sony 4K60 networked remote box camera

Blocking Example With Too Few RTP Packets per Bundle and Disruptions





2024 Demos: Internetworked ISS Experiments

Enhancing High-Rate RF & Optical Networks

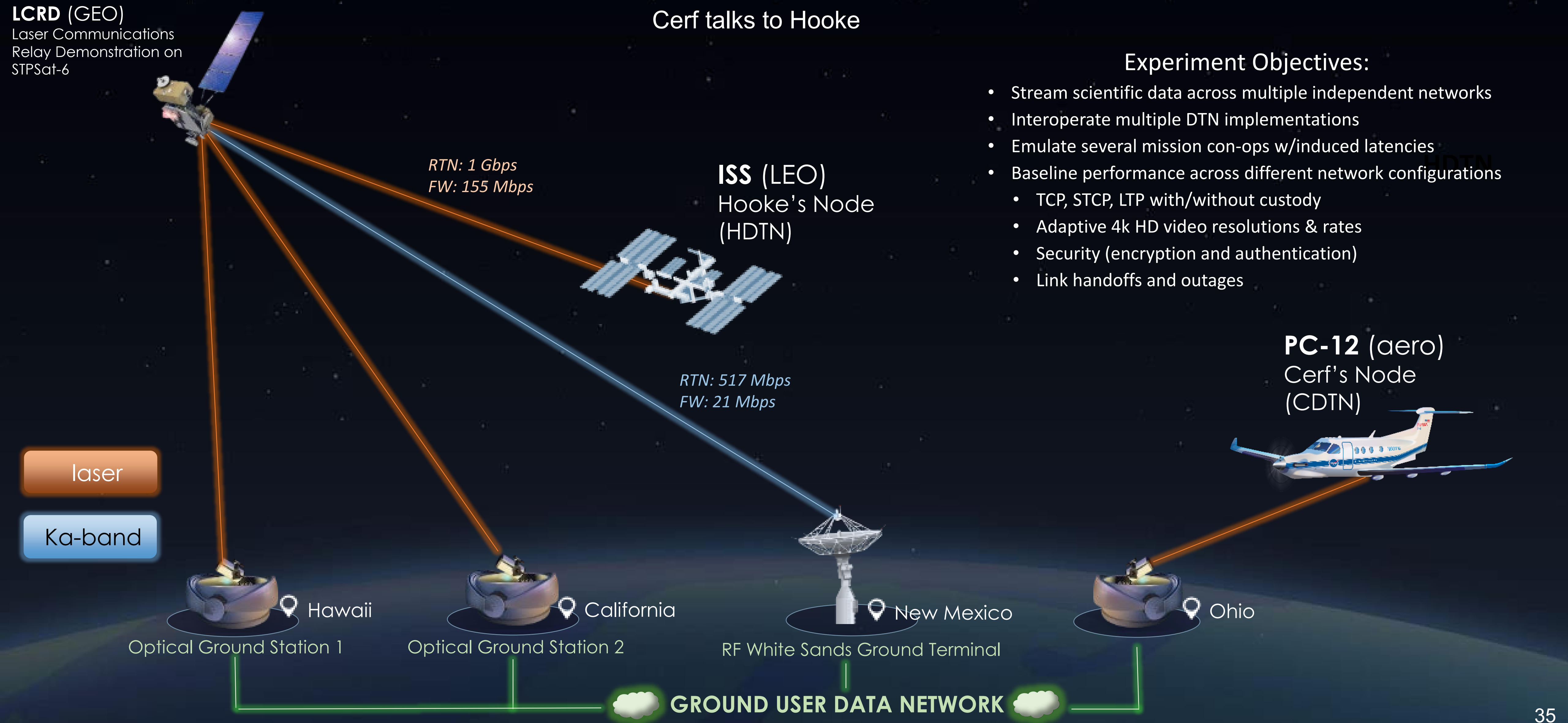
HDTN

We get your data home

Cerf talks to Hooke

Experiment Objectives:

- Stream scientific data across multiple independent networks
- Interoperate multiple DTN implementations
- Emulate several mission con-ops w/induced latencies
- Baseline performance across different network configurations
  - TCP, STCP, LTP with/without custody
  - Adaptive 4k HD video resolutions & rates
  - Security (encryption and authentication)
  - Link handoffs and outages



2024 HDTN Internetworking Demonstrations

Large scale demonstration of HDTN capabilities, including file transfers, 4K UHD video streaming, storage, scheduling, routing, reliability, operator GUI's, logging, link status, security and web interfaces

LCRD
Laser Communications Relay Demonstration on STPSat-6

GEO

ISS
International Space Startion

Example 4k60 secure video streaming for crew monitoring

LEO

PC-12
Aircraft

Hawaii
Optical Ground Station 2

California
Optical Ground Station 1

New Mexico
RF White Sands Ground Terminal

Ohio
Optical Ground Station at NASA Glenn Research Center

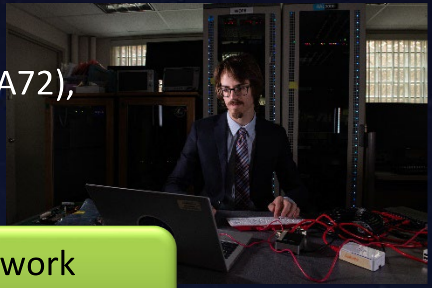
GROUND USER DATA NETWORK

Example 4k60 video streaming for creature comforts

Long-Duration Testing: Hardware Emulation of LunaNet Operations

Buffering data until a transmit opportunity arises, where an end-to-end path may not be available

- Continuously running testbed
- Diamond network topology
- Mission critical audio streams
- 4K HD video streams
- Nodes implemented on Raspberry Pi4's (Cortex-A72), NVIDIA Jetsons



384,800 km

Gateway Orbiter

Deep Space Network (DSN) Ground Terminals

Disconnections

traffic models

Science Gathering Rover

Induced Latencies

data streams

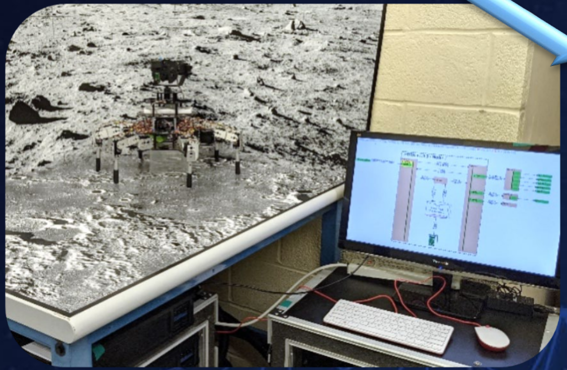
Store, Carry, Forward…

Terrestrial Network
Mission Operations Center (MOC), Science Operations Center (SOC), etc.

Artemis Base Camp

delivered data

Internet



IOAG South Orbiter

384,800 km

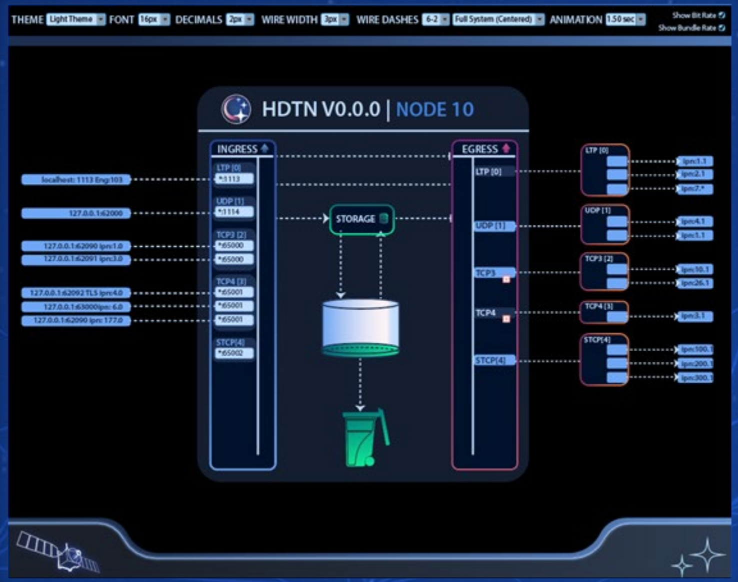
Near Space Network (NSN) Ground Terminals

3 months of continuous operations

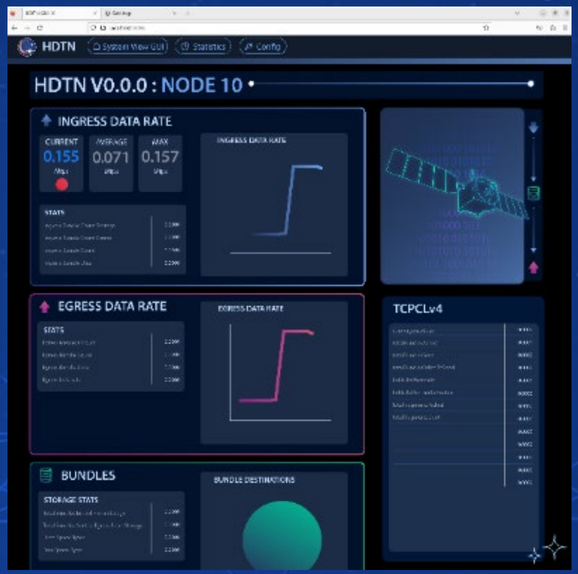
Artemis Network Topology

Next Steps

- Continue gathering and post-processing data, further look at VMAF
- Upgrade LunaNet scenario to multi-source/destination BP video streaming services w/ microphones
- Development of DTN videoconferencing application
- Investigate further DTN performance optimizations (such as LTP tuning)
- Examine variations of parameter:
  - Video lengths, RTP per bundle numbers, bundle sizes, etc.
  - Constant Bit Rate (CBR) to Variable Bit Rate (VBR) comparisons
- Demonstrate multi-source and multi-destination BP streaming services
- Further field testing on aerospace networks…
- Publish combined results of LunaNet duration testing and ISS/LCRD performance results



Thanks to Tad Kollar, Prash Choksi, Nadia Kortas and Shaun McKeehan for supporting on the HDTN side



Conclusions

- Highly successful series of experiments and demonstrations
- Some mindsets and operational cultures need to evolve for users to appreciate and achieve full benefits from DTN,
- More DTN-based applications needed
- Opportunity for continued experiments using LCRD with ground stations
- Let's keep learning and growing from experience!

Special thank you to the *many* individuals who made these activities so successful


Questions?