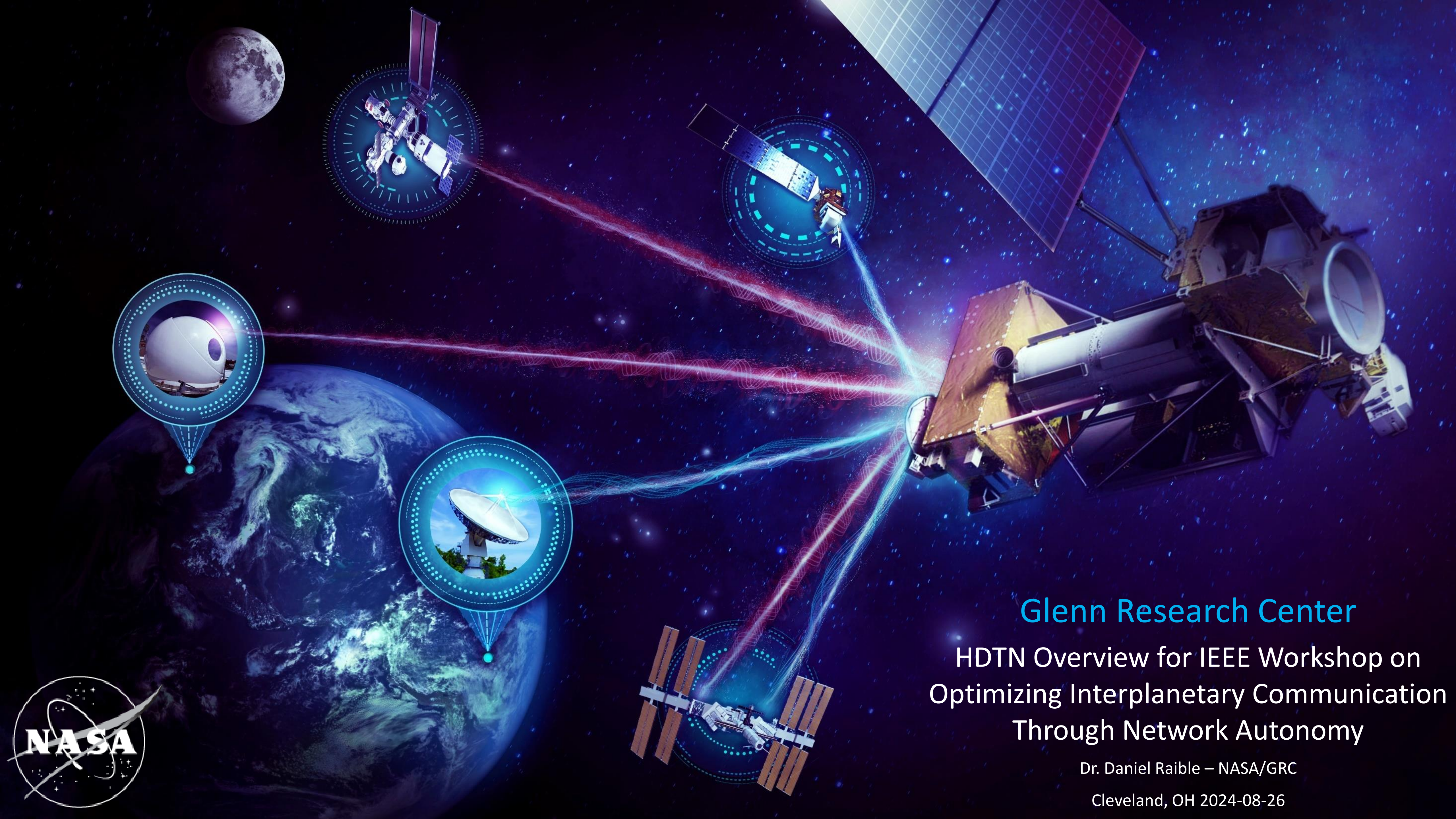


Glenn Research Center

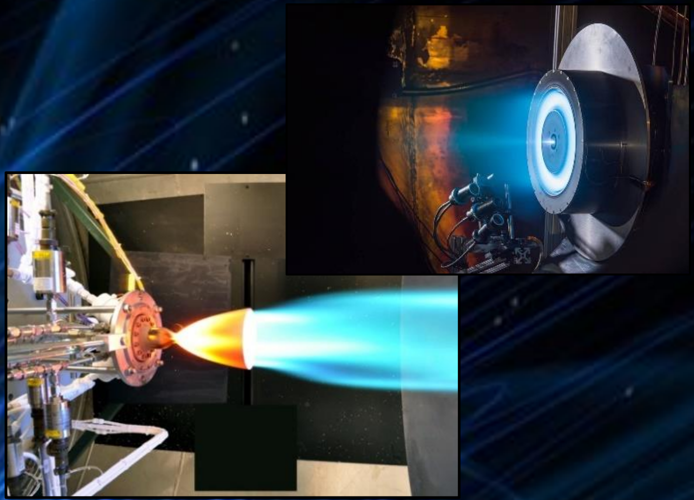
HDTN Overview for IEEE Workshop on Optimizing Interplanetary Communication Through Network Autonomy

Dr. Daniel Raible – NASA/GRC

Cleveland, OH 2024-08-26

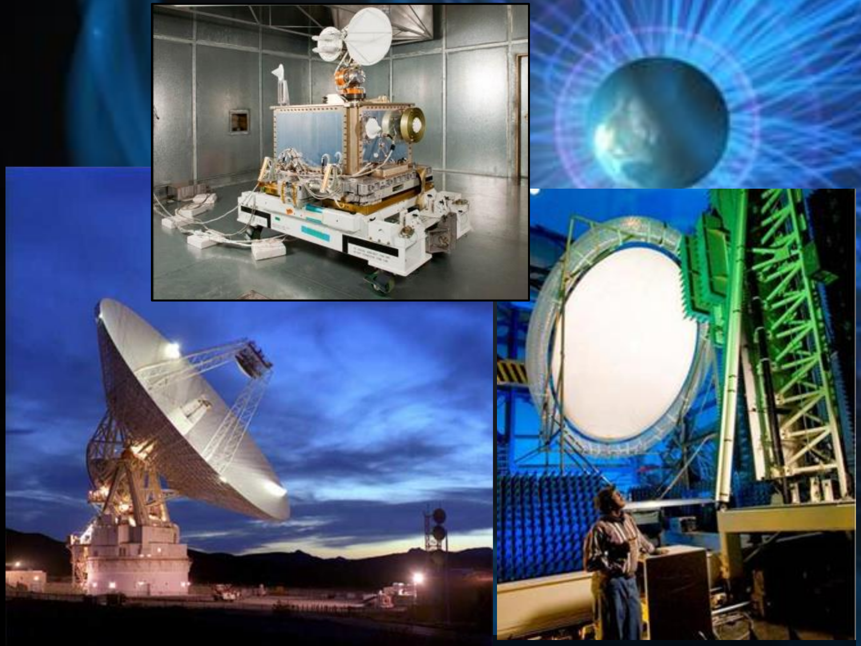
NASA Glenn Core Competencies

Aircraft Propulsion

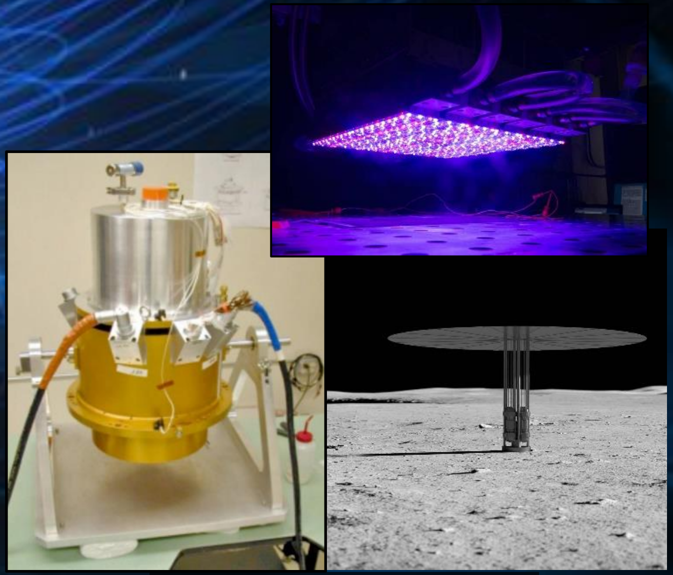


Spacecraft Propulsion and
Cryogenic Fluids Management

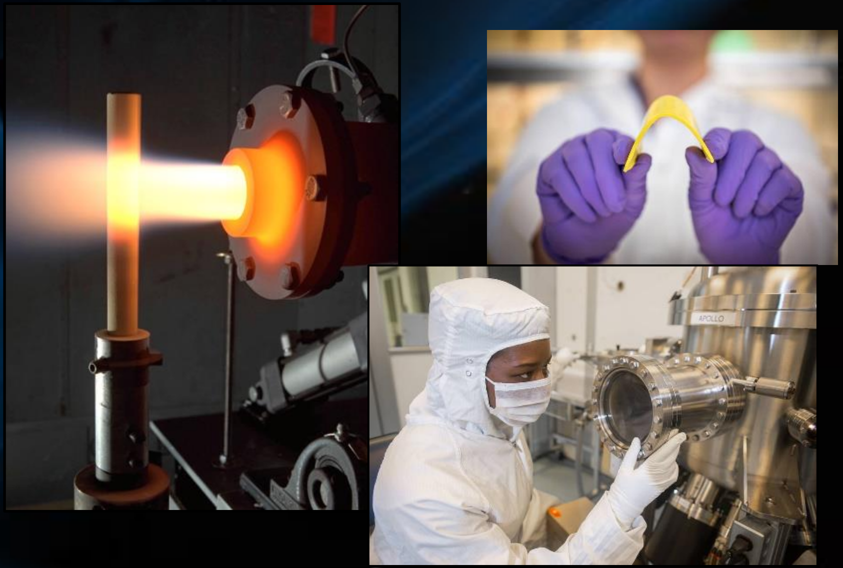
Physical Sciences and
Biomedical Technologies in Space



Communications Technology and Development



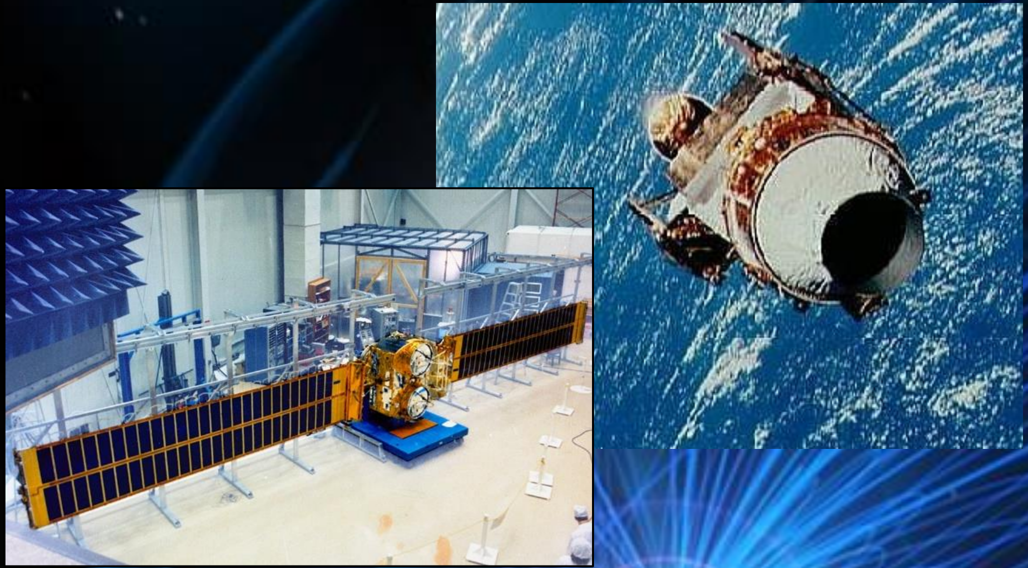
Power, Energy Storage
and Conversion



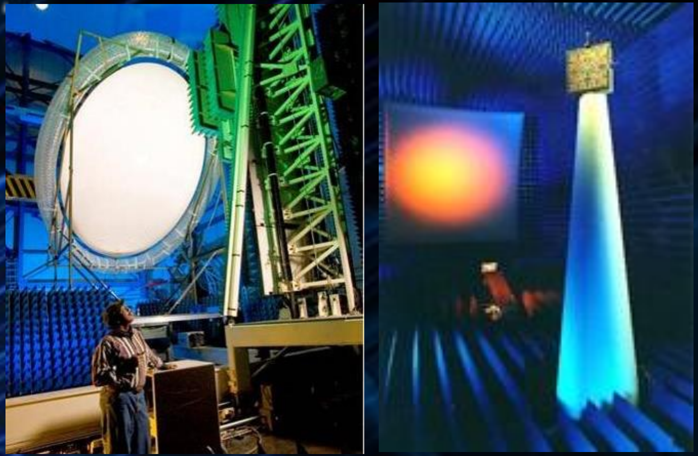
Materials and Structures
for Extreme Environments

GRC Communications Highlights

https://www.nasa.gov/centers/glenn/technology



Hermes and Advanced Communication Technology Satellite (ACTS) introducing Ku and Ka-band to the world

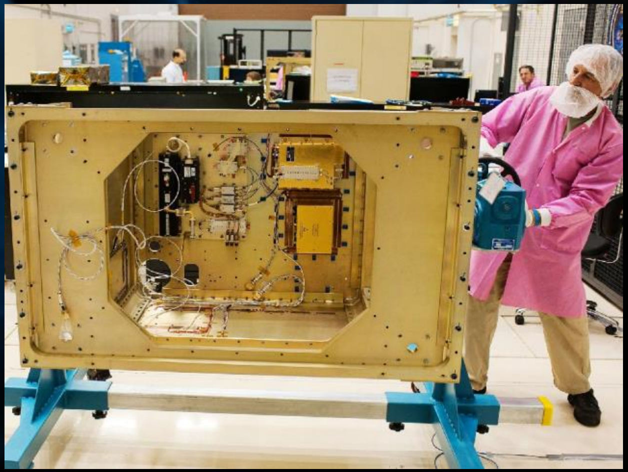


Test ranges to characterize antennas

Critical component experiments onboard the International Space Station (ISS) to perform evaluations in the space environment

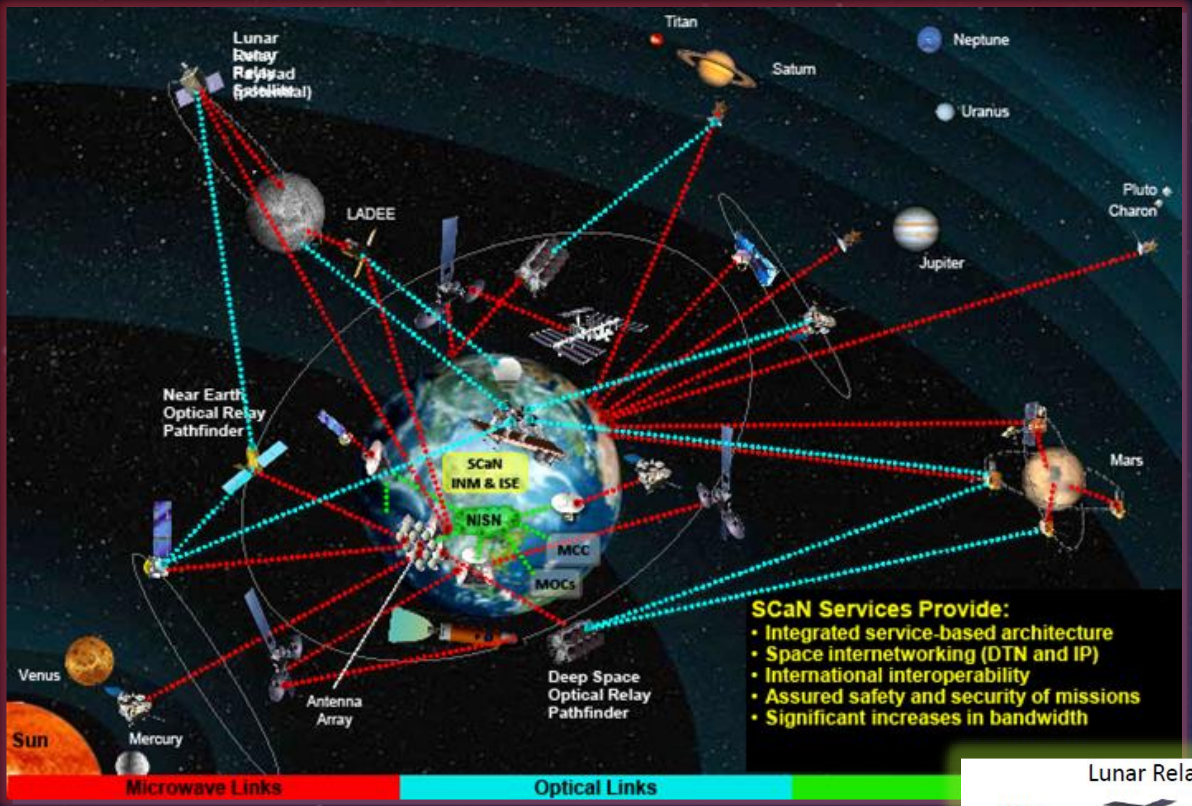
Laboratory facilities to develop RF & optical communication technologies and emulate network scenarios from deep space to ground

RF atmospheric propagation research



SCaN Testbed onboard the ISS to conduct software defined radio (SDR) experiments

Problem Formulation

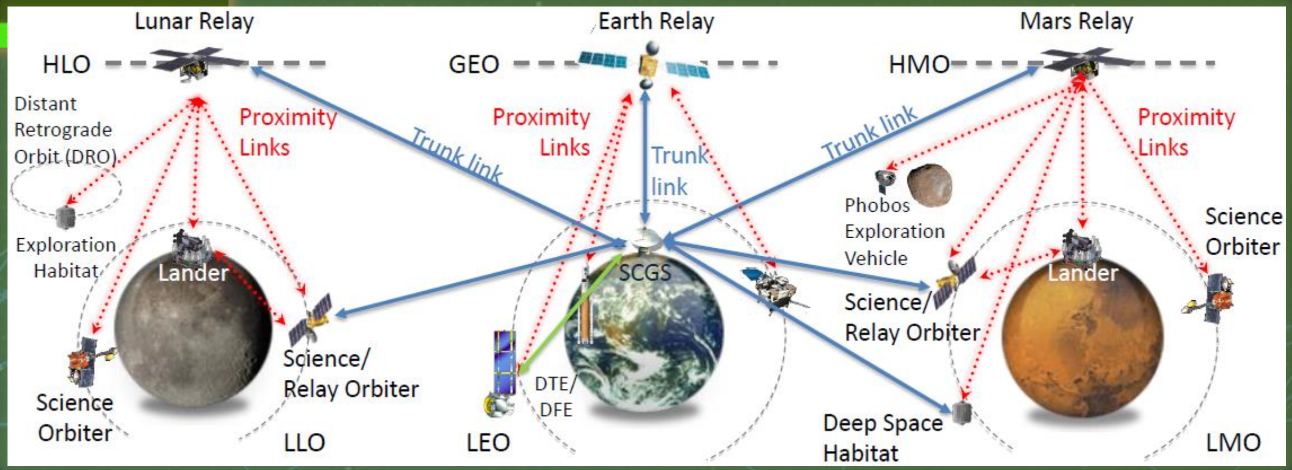


Space Naturally Exhibits Several Communications Challenges

- Disconnection (*an end-to-end path is not always available*)
- Disruption (*free-space links are often interrupted*)
- Delay (*long distances negate acknowledgment-based protocols*)
- Security (*imparts requirements on transceivers*)

Goals for Planetary Networks

- Reduce mission burden with short mesh links for increased connectivity, enables proximity telerobotics
- Common architecture reduces development costs
- Reuse of hardware and software across different environments



Customer Needs

SCaN Architectures

Migrating to Flexibility, Scalability and Affordability

High-Rate Delay Tolerant Networking

Realizing a Solar System Internet through the Bundle Protocol (BP)

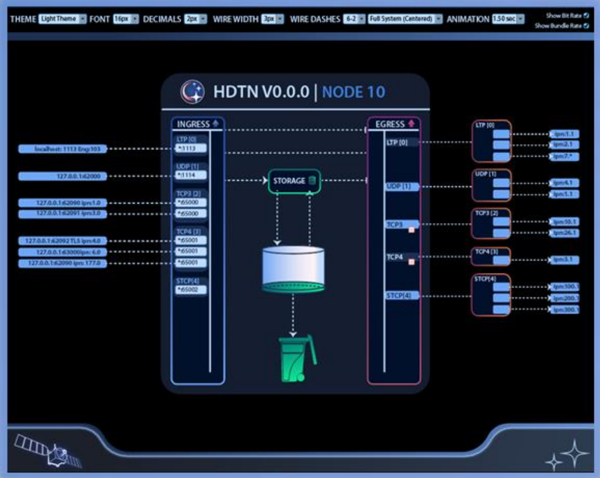
A Kármán Line View:

Improve network data throughput to meet future user needs,

by enhancing communications capability to increase mission science return

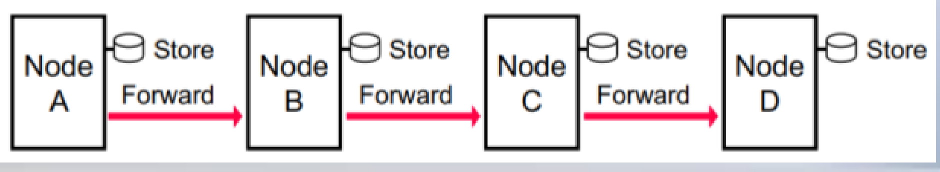
We get your data home

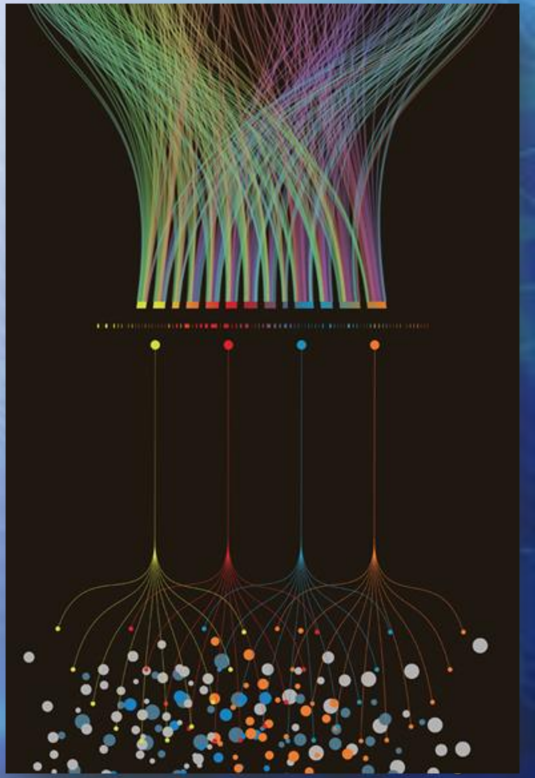
GUI's:



HDTN is a performance optimized implementation of the BP standards, which targets applications involving high-rate RF and optical links

- Open-sourced availability (GitHub, w/docs & YouTube tutorials)
- Offers a wide range of mission services:
  - Data aggregation, storage, scheduling, routing, reliability, security, 4K UHD video streaming, operator GUI's, logging, link status, and web interfaces
  - Supports Linux, Windows, Intel, AMD, ARM & cloud platforms
  - Rates exceeding Gbps are proven
- NASA 7150.2D class-B software engineering compliant in 2024
- Large-scale demonstration on ISS with LCRD & ILLUMA-T
- Targeting Near Space Network (NSN) and commercial infusion





FY24: A Year of Software Releases

Prototyping:

- Chat
- Vox
- Email
- Clock synchronization
- Biometric telemetry
- Videoconferencing
- Common DTN test suite
- Asynchronous Network Management System
- Neighbor discovery
- Dynamic addressing
- Traffic shaping
- DTN common web interface
- Clustering/ network partitioning
- LTP optimizations
- Contact plan visualization
- BIBE implementation
- Enhanced API's

Upcoming: v2.0

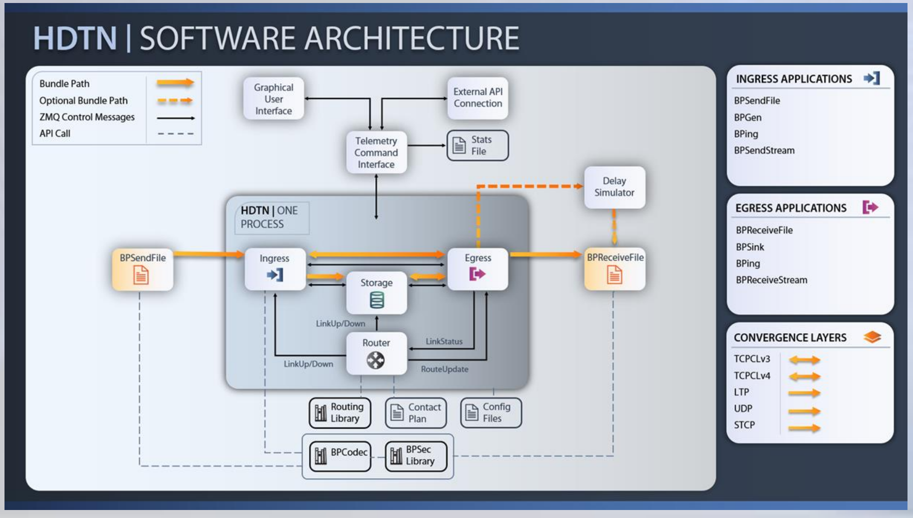
- 7150.2D class-B compliance

v1.3

- 4K UHD RTP multimedia streaming
- Edit config files via web interface
- Tested with ISS/LCRD/PC-12

v1.2

- LTP ping disable for unavailable contacts
- C++ console interface for API
- BP Encap convergence layer
- Enforce bundle priority
- MacOS support
- Tested with ISS/LCRD



v1.1

- BPSec
- Combined scheduler and routing module
- Initial API calls
  - Updating contact plans
  - Changing transmission rates
- SLIP over UART
- 7150.2D class-D
- Variable rate LTP
- Re-routing around failed nodes
- HDTN FPrime support

v1.0

- LTP, STCP, UDP, TCPCL v3 and v4
- BP v6 and v7
- Custody transfer
- Web interface w/ system view
- Logging and statistics
- Containerization
- Test scripts
- CGR & CMR
- Dynamic contact plan updates
- HDTNSim
- Linux and Windows support
- Tested at JSC SDIL

2024 DTN Engineering Network (DEN) Enhancements

Supports simultaneous and isolated network testing

External Collaborations

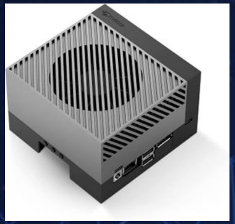
- Agency
- Academia

Unit Testing

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

Interoperability

- Platforms
- Processors
- Applications



Network Emulation

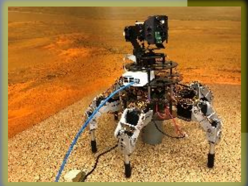
- 100's of nodes
- TB's of storage
- Up to >Gbps rates
- Minutes of link delay
- Bundle reordering
- Bundle duplication
- Bundle loss
- Dynamic topologies
- Link scheduling

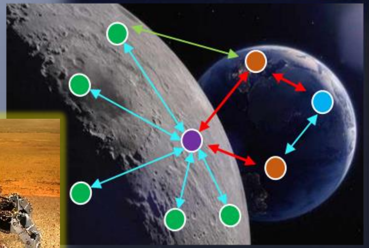
Intranetwork Connections

- Cloud to LCRD
- Flight research
- 3GPP

Scenario Testing

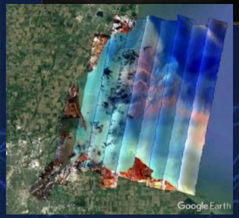
- LunaNet
- Mars Network
- Endurance testing





Hardware in the Loop (HIL)

- Instrumentation interfacing
- Mission integration support



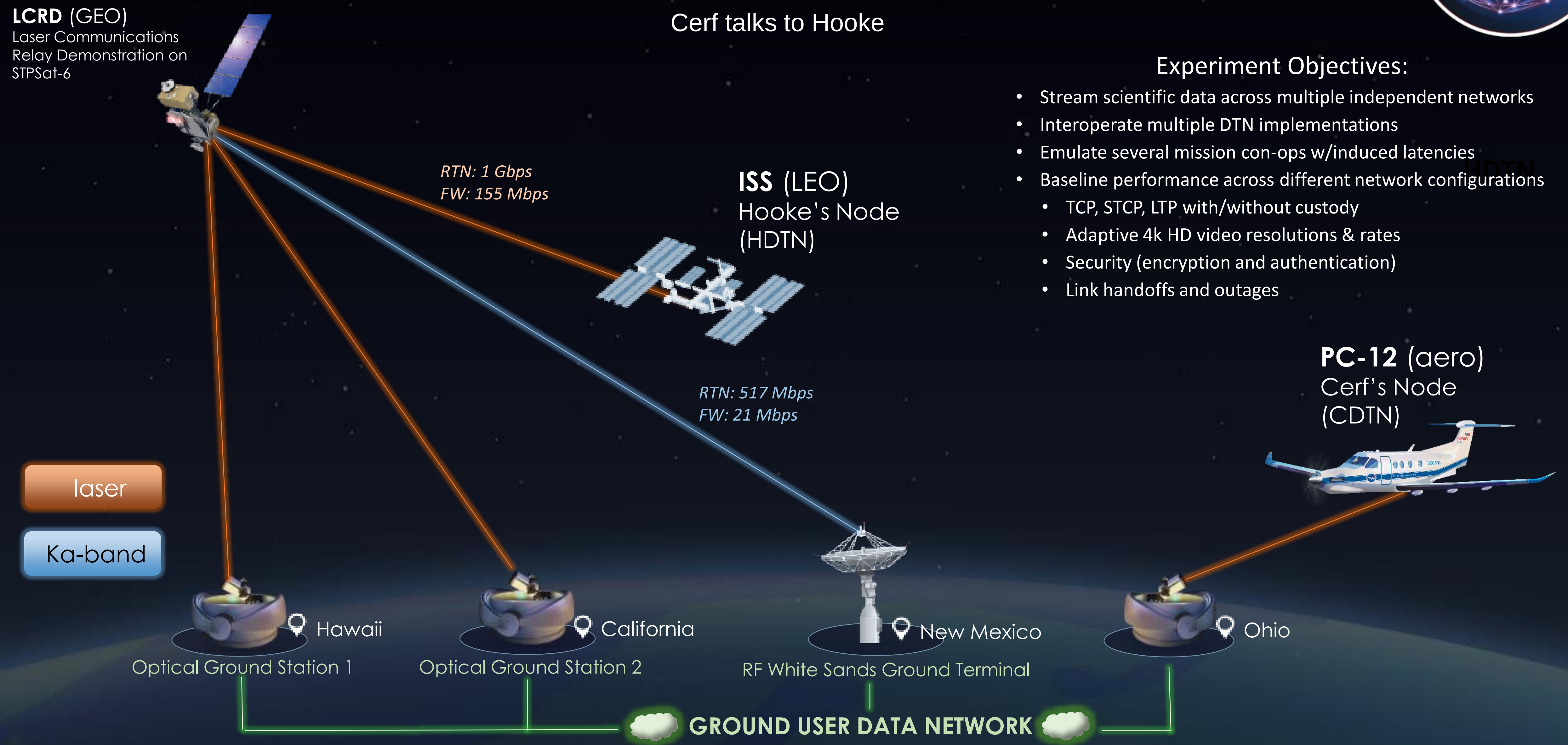
2024 Demos: Internetworked ISS Experiments

Enhancing High-Rate RF & Optical Networks

Cerf talks to Hooke

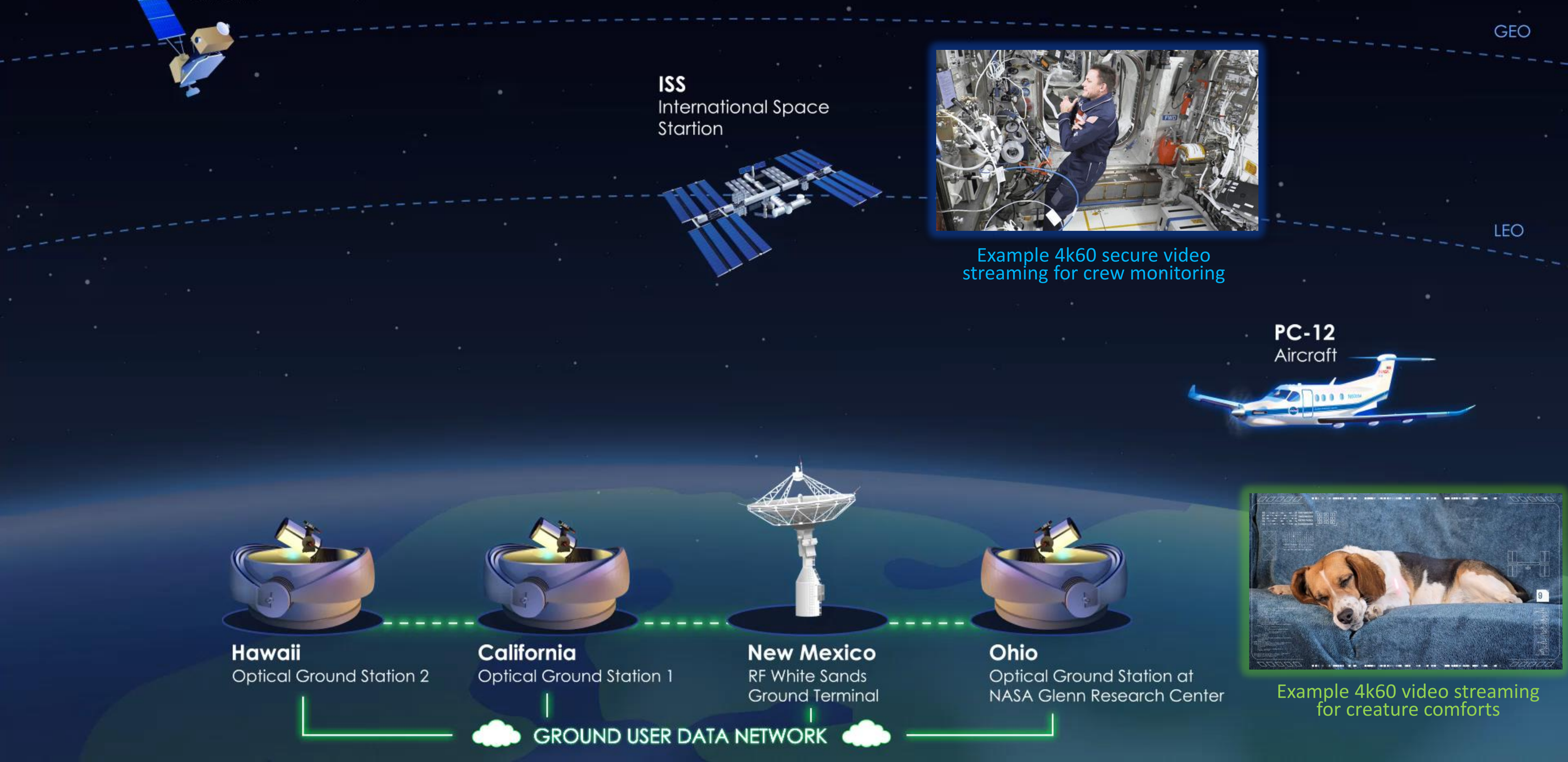
Experiment Objectives:

- 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

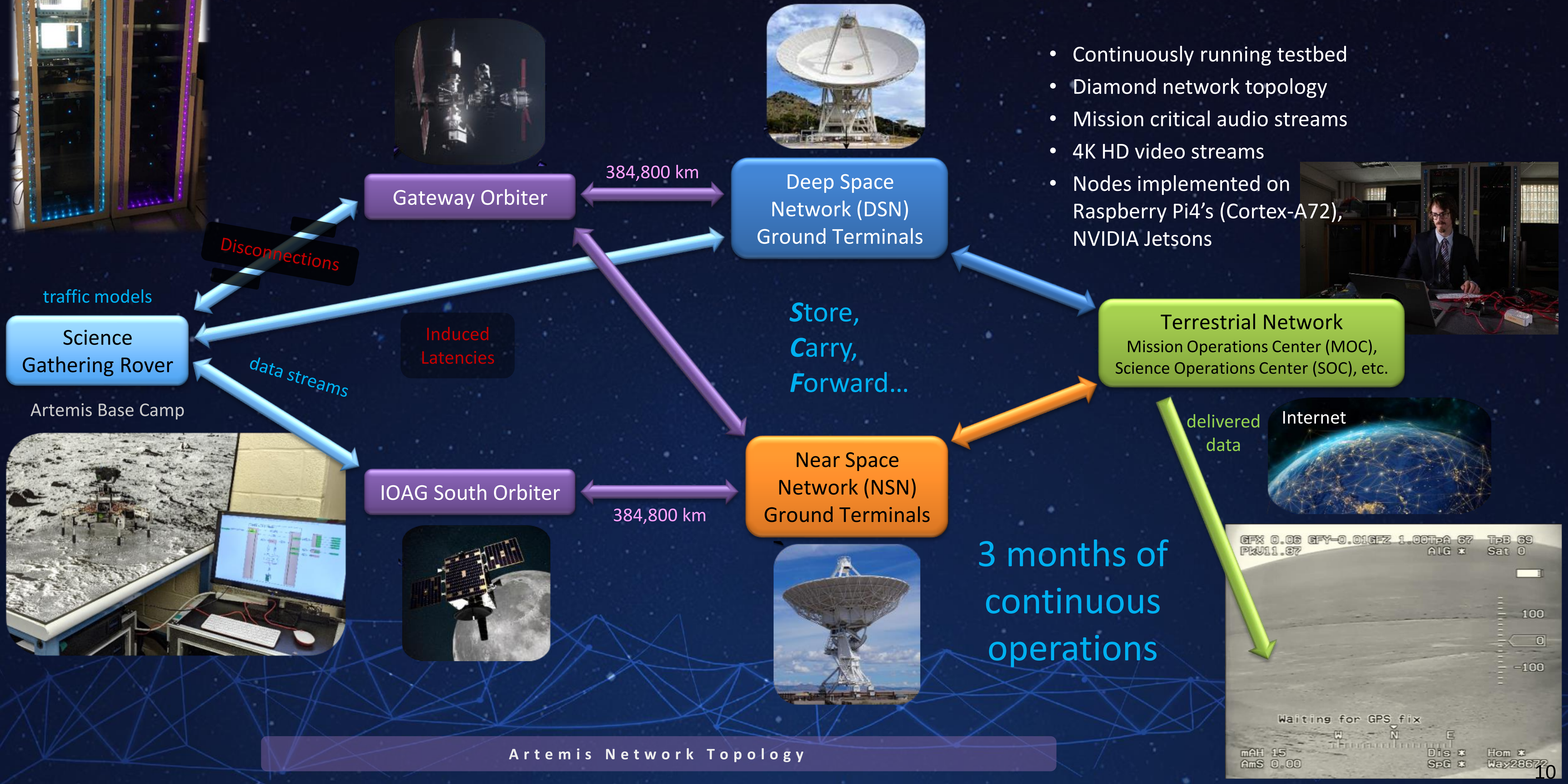
Large scale demonstration of HDTN capabilities, including file transfers, 4K UHD video streaming, storage, scheduling, routing, reliability, operator GUI’s, logging, link status, security and web interfaces



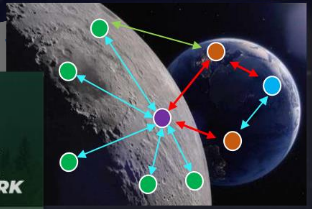
Long-Duration Testing: Hardware Emulation of LunaNet Operations

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



HDTN Technology Readiness Level (TRL) Path to Artemis and Beyond



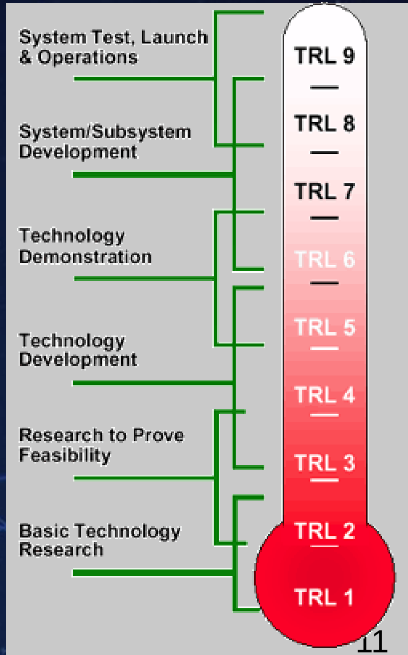
Technology Development and Testing: 2015 – 2022
Implementation and documentation of reference design
Establish space networking emulation laboratory at GRC for verification
Integrated testing at JSC Software Development and Integrated Laboratory (SDIL)
Field testing with GRC aircraft laser communications
Public release of products on GitHub
TRL 4-6

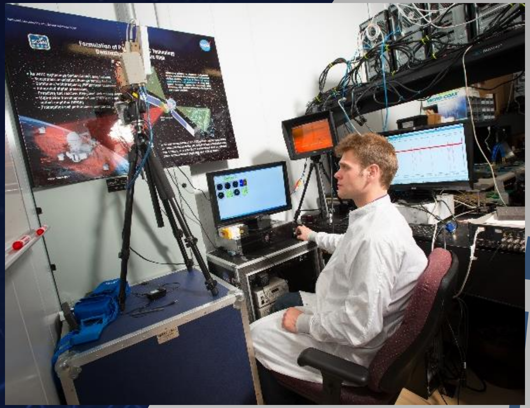
Infusion into Artemis LunaNet operations: 2025 ->
Supporting human and robotic missions
TRL 9

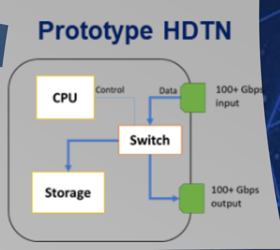
ARTEMIS

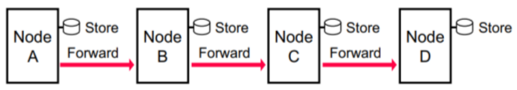
Flight Technology Demonstrations: 2023 - 2024
Laser Communications Relay Demonstration (LCRD) and
International Space Station (ISS)
experiments conducted in relevant environments
Compliance with NPR-7150.2D engineering requirements
TRL 7-8

GitHub







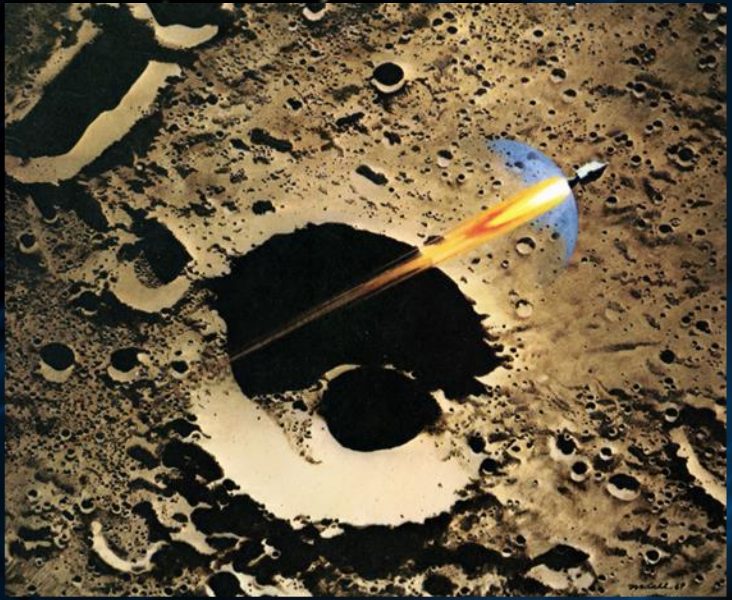


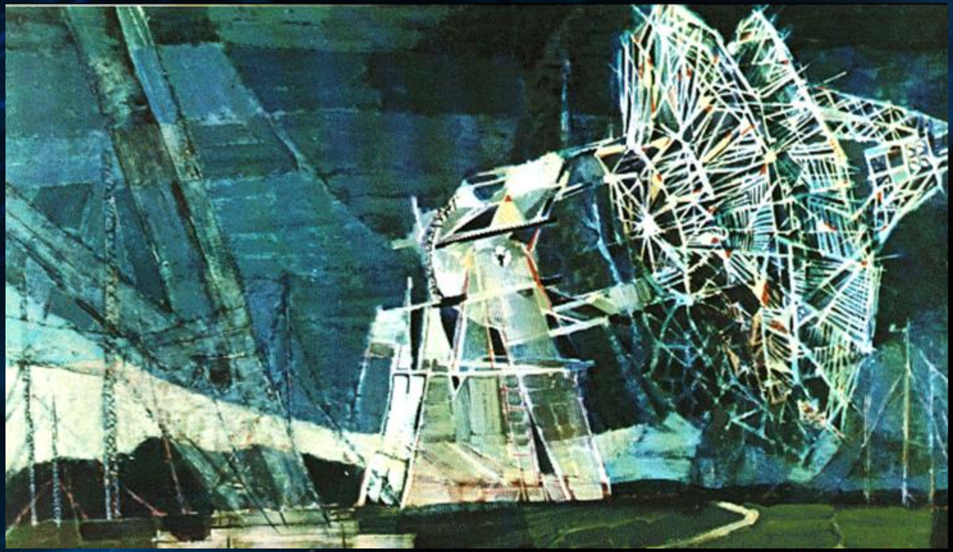
Research and Formulation: 2009 – 2014
Problems associated with high rate space networking analyzed
Concept of operations established, feasibility proven with separate control & data planes
Critical components identified including scheduling, routing, storage, security, streaming
Contribute to international open standards communities
Performance-optimized architecture proposed, prototyped and demonstrated in laboratory
TRL 2-3

High-Rate Delay Tolerant Networking (HDTN)

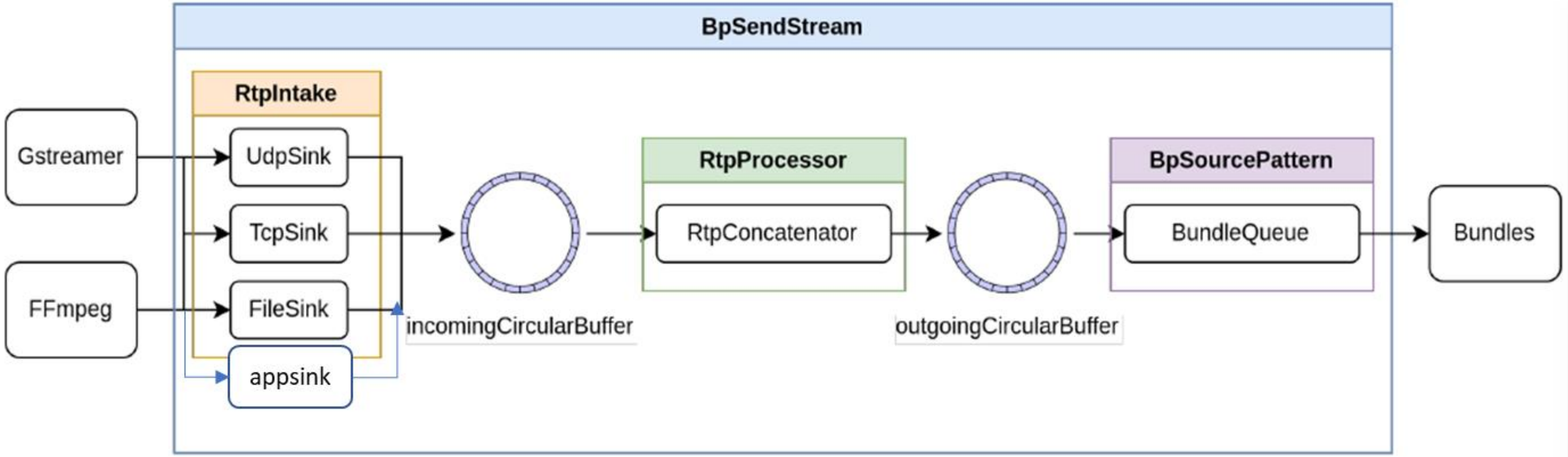
We get your data home

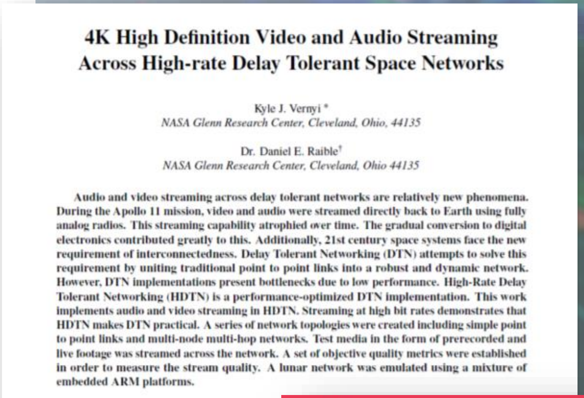
HDTN
High-Rate Delay Tolerant Networking





Implementing BP based Real-time Transport Protocol (RTP)



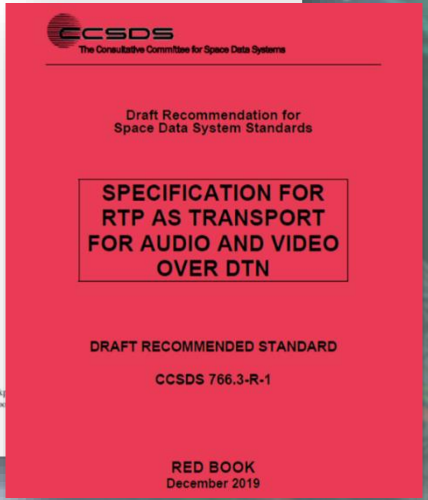

4K High Definition Video and Audio Streaming Across High-rate Delay Tolerant Space Networks

Kyle J. Vernyi *
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.

2024
SciTech

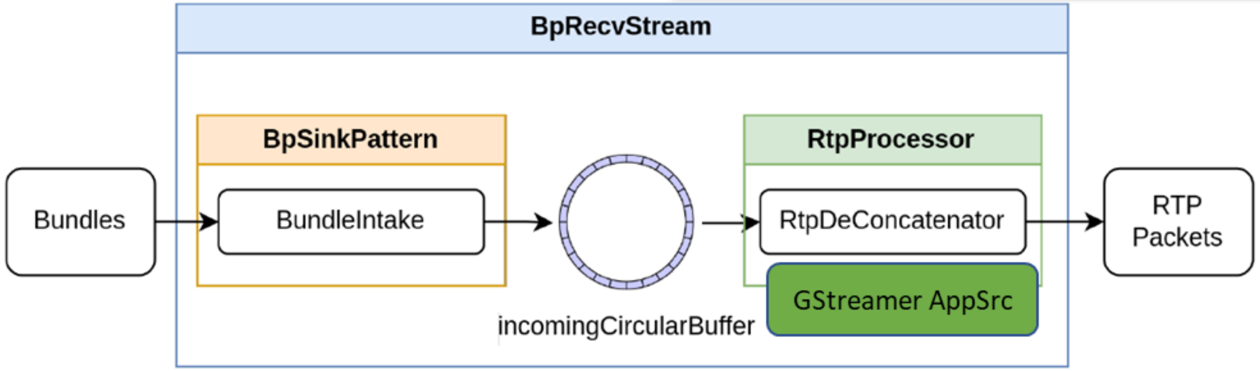


ISS *"WaterBubble"* test example:

- 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

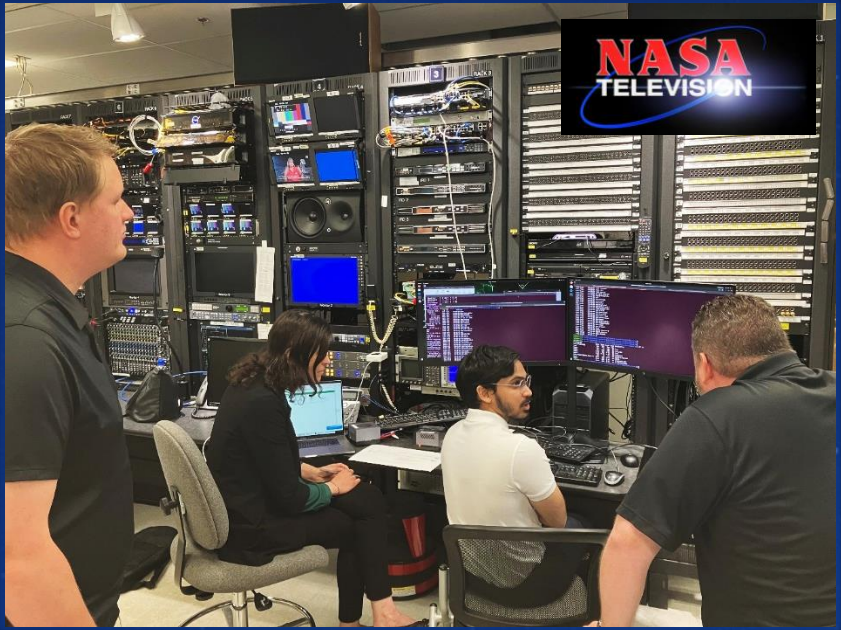


Performance Metrics:

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

Streaming Results Across Various Camera and Encoder Configurations

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

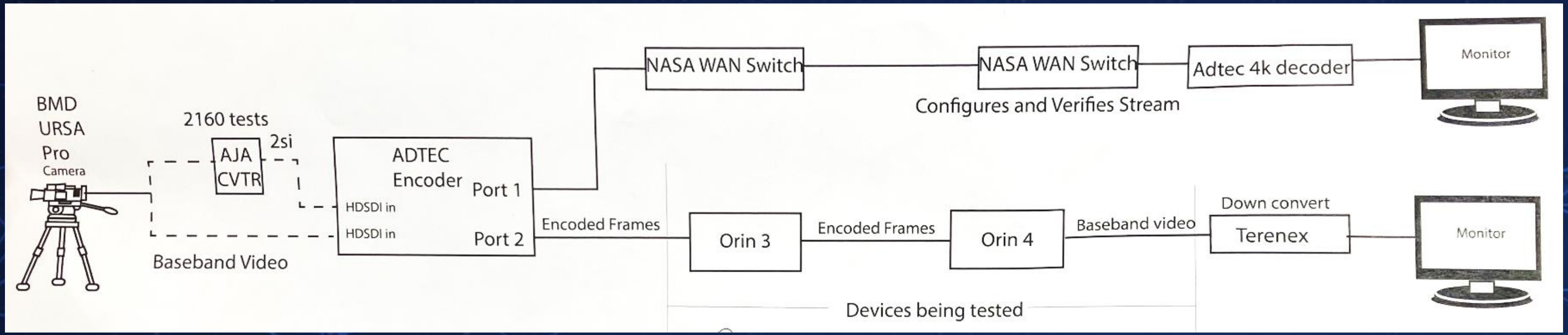


Hardware encoder test points:

- 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

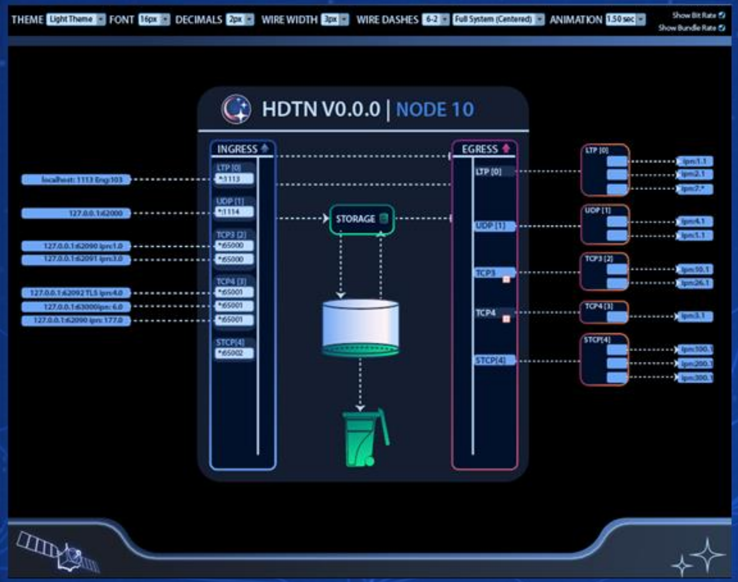
NVIDIA Jetson Orin's used for DTN nodes

Sony 4K60 networked remote box camera

Blocking Example With Too Few RTP Packets per Bundle and Disruptions

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