DTN Network Reference Implementation

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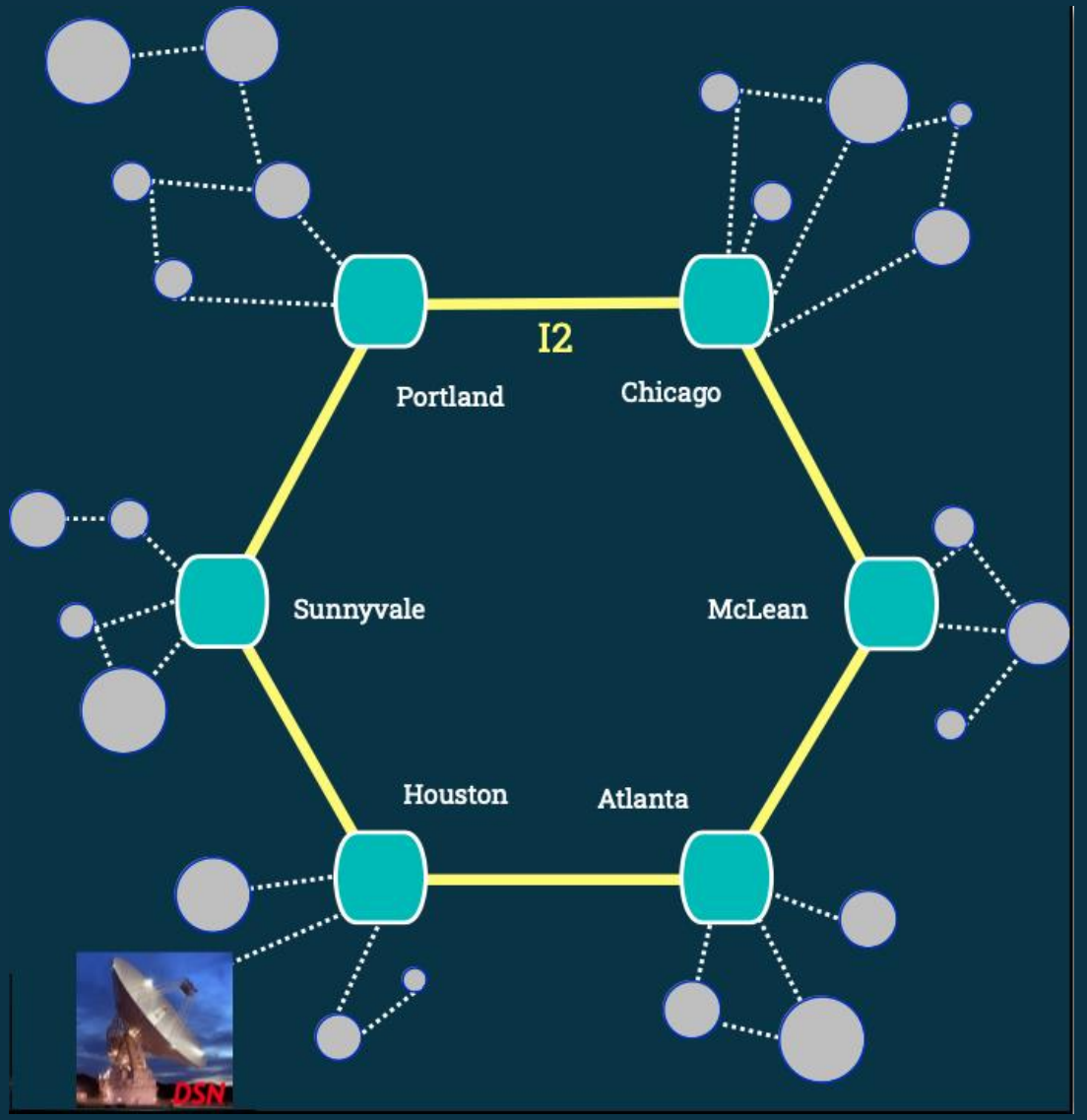
Phase 1 Infrastructure

6 High-Performance Nodes – Operating Over Internet2

The initial deployment of **BundleBone** consists of six computers strategically distributed and running over **Internet2**. This high-bandwidth, research-centric network provides the ideal substrate for large-scale DTN testing and orchestration.

These nodes form the core reference implementation, designed to facilitate cross-institutional protocol validation and telemetry gathering.

Users will include universities, commercial entities who want to develop and certify their DTN implementations, national space agencies and public application developers for terrestrial use of DTN.



ION DTN Reference Network Implementation

Task: Demonstrate full multi-node DTN network in LunaNet-relevant operations with 50 Mbps goodput with DTN Protocols now implemented in the Deep Space Network

Implementation focus on the **BPv7** standard, demonstration of reliable long-haul data transmission, custody transfer, network management and security provisions for encryption, and integrity checking. Provides platform for Asynchronous Messaging Services (AMS) evaluation. Objective: FULL END-to-END DTN Network Operation demonstrations and evaluations (Green text below = already implemented; white TBD)

Telemetry and Data File generation		ION Configuration Tool and DTN Node Registry		BSSP / VIDEO
Bundle Protocol (BP	CFDP	Network Test Tools	Bundle Protocol (Security (Native)	DTPC
Licklider Transmission Protocol (LTP)		BPSec Library	DTN Asynchronous Management Protocol	DTKA

DTN Network Reference Implementation Test Conditions

Noise Injection

The ability to emulate noise and signal degradation typical of long-range radio and optical links.

Intermittency

Simulating intermittent connectivity caused by orbital mechanics, planet rotation, or obstacles.

Variable Delay

Injecting multi-second delays to accurately simulate one-way light time for Earth-to-Lunar distances.

Phases: Following Prototyping of ION DTN Network in the dtn-lab, Phased work on the I2 BundleBone VM Servers completed:

Phase 0 — Development

Initial installation of Ubuntu 24.04LTS, addition of required additional software, installation of ION 4.2.0b, and then Pre-formal-validation development testing. Development of telemetry and CFDP file generation/display for external rp61/rp62 experimenter nodes. Informs Phase 1 baseline expectations.

Pass criteria: 9 ION node network fielded, with 7 nodes on Internet2 operating with 2 external nodes

Phase 1 — Reference Characterization – Linear Topology

Formal testing with 15 minute, 60 minute and 8 hour runs, with ~3 Mbps link rates, and representative spacecraft telemetry and CFDP science and command data files. Informs Phase 2 Tuning and Optimization

Pass criteria: 100% delivery in a Linear topology; demonstrated ION BP/LTP/CFDP and IPv6 stability

Phase 2 — Optimization Qualification – Linear Topology

Optimization is qualified in independently reversible Cases, with no loss injected. `TN01` changes Linux UDP buffers only; `TN02` adds improved LTP configuration to decrease ipv6 fragmentation; `TN03` adds the enhanced-watch plus UDP-multisend ION build. Add random loss in steps up to 5% and verify 100% data delivery. Essentially tuning LTP operations. Each Case is first compared at the proven 3 Mb/s contact allocation before the accepted combined configuration is rate-ramped toward 10 Mb/s.

Pass criteria: 100% delivery and efficiency improvement over the Linear P1 reference

Phases: continued

Phase 3 — Relay Resilience and Scenario Qualification

Reconfigure from Linear to Relay Topology, and conduct baseline (lossless links) and controlled loss-recovery Cases and full lunar relay scenarios with disruptions, contact-window scheduling, and CGR routing validation.
Pass criteria: Successful store-and-forward delivery through contact windows, full CGR routing validation

Phase 3a — Relay Resilience and Scenario Qualification – Medium LCRNS S-band Rates

Long-term steady state test of LCRNS-like uncrewed data rates; 2-5 Mb/s relay orbiter to Moon surface, 10-15 Mb/s relay orbiter to GS/DSN.
Pass criteria: Successful store-and-forward delivery through contact windows, full CGR routing validation;
Link loss tests completed. 2x expected 10^5 frame loss on GS to Orbiter links with 100% of data recovered
Random SDR corruption (only seen 3 times in hundreds of hours of tests) corrected and tested (ION 4.2.1 -a1)

Phase 3b — Relay Resilience and Scenario Qualification – Higher SCaN Demand LCRNS Rates

Long-term steady state test of Higher Ka-band LCRNS rates; 25-50 Mb/s relay orbiter to Moon surface, 10-15 Mb/s relay orbiter to GS/DSN.
Complete : Successful store-and-forward delivery through contact windows, full CGR routing validation;
Link loss tests completed. 2x expected 10^5 frame loss on GS to Orbiter links with 100% of data recovered

Phase 4 — Addition of BPSec and Demonstration of Secure ION Space Networking

Near-Complete – 100% success for what is implemented in ION today for the DSN; awaiting completion of BSL by APL.

Work to get to this point:

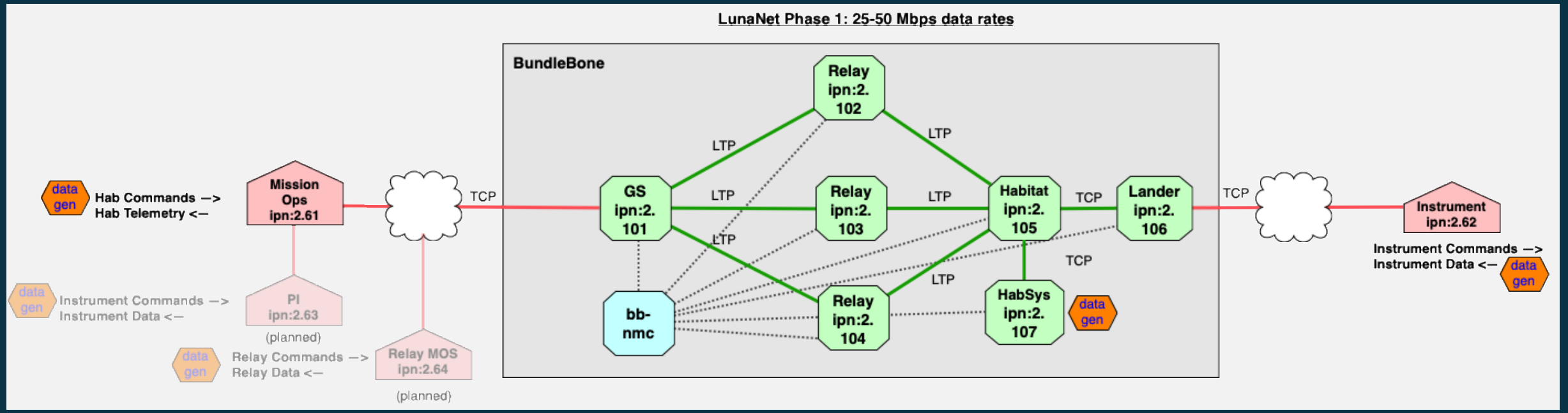
Configuration-managed data and test documentation -- document counts

Material	dtn-lab*	BundleBone	Total
Operational scripts/supporting code	170	191	361
Automated test source files	44	63	107
Plans and architecture/design documents	22	38	60
Test reports	9	221	230
Other documentation	48	105	153
All documents	79	364	443

The projects comprise roughly 470 software files and 440 documents, including 60 planning/design documents and 230 test reports.

(*dtn-lab is the author's 12-computer consulting lab network on regular internet, IPv4)

Current DTN Network Reference Implementation running on BundleBone 10/6/2026



- IPv6
- 3-part EIDs; IPNSIG IANA Allocator 2
- Running nearly 24x7 basically since July
- Scenario derived from NASA specs (LNIS, LCRNS data from GSFC)
- Instrument/Lander nodes ←→Habitat node – 15 Mbps
- Orbiter←→GS & Habitat 25-50 Mbps
- GS←→MOS 50 Mbps

BundleBone DTN Reference Network Operations and Observer System — Current Architecture

Five capability categories • independent execution and observation • reviewed 2026-09-28 / Rev2

Reviewed inputs and provenance

Inventory • ION build/configuration • relay and endpoint contact allocations • source/receiver schedules • frozen software hashes

Test / Operations Control - optional coordination, not a runtime dependency

Scripts to plan → prepare / apply network → start → reconcile → finish → collect-accounting / assess
Accepted endpoint work continues through controller / SSH for netem outages. Successful test Finish requires reconciled receipts and closures.

BB Network Operations

Stage / activate configs; verify contacts and readiness
Explicit ION start / stop / reset; inventory and ownership and fresh health and queue queries with SSH (until DTN-AMP is installed) for eight BB VMs; external user IPNs when explicitly selected.

Data Simulation and Application Accounting

independently usable scripts → Independent Instrument / HabSys generators; MOS receivers and command senders
Sims independent of ION node network operations
Authoritative local receipts + pre-traffic file provenance + size/hash verification
Optional displays: four mission windows and port 8767 receipt view - neither controls traffic

DTN Reference Network mission-data path - (simplified logical flow, not the physical topology)

Instrument – ipn:2.62
HabSys – ipn:2.107

ION forwarding core — ipn:2.101 through ipn:2.106
• BP • LTP/TCPCL • SDR/ZCO • scheduled contacts

MOS - ipn:2.61
Receive data / send command files

Node Observation - optional, independent of simulations

Basic: four-pane BB Wall; BPstats/ snapshots; collectors and dashboards
Extended plots: Mission data Receipt Accounting, SDR/node memory use, RT Link status, CGR timeline
Timestamped JSON for host status → bb-nmc collects node state data
DTN-AMP manager / agents: future capability, not required by the current workflow.

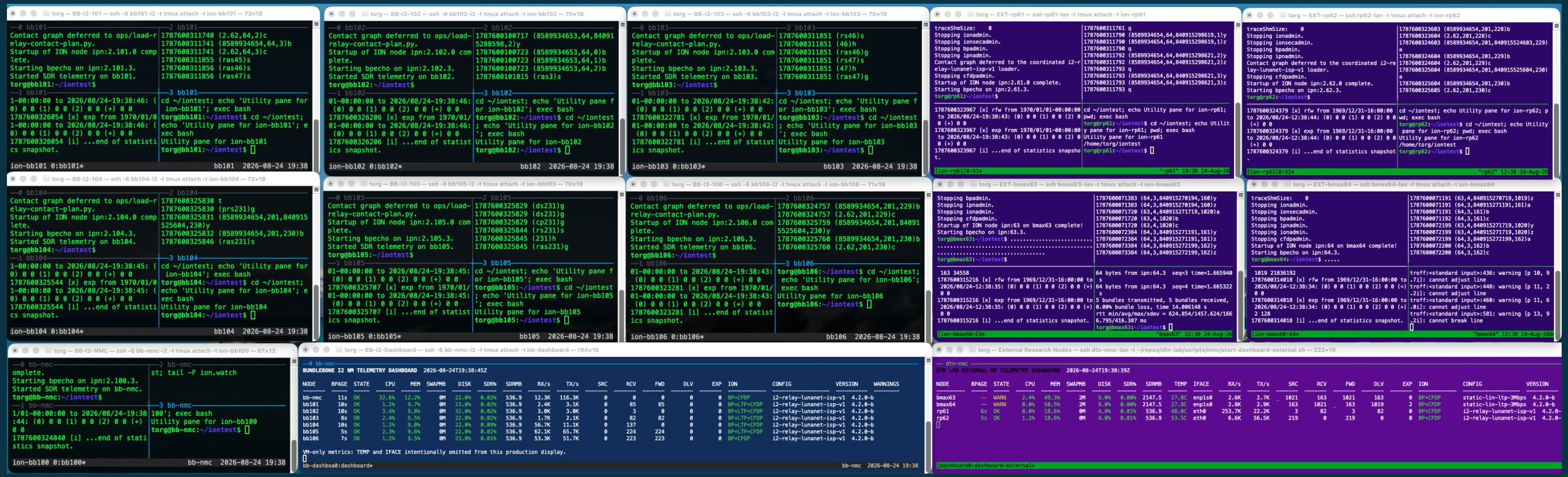
Forensics / Diagnostics - explicitly selected

CPU attribution • packet / trace / core capture
Bounded collection, overhead and coverage recorded
Existing tools; full profile interface still evolving
Impairment is an authorized network change, not observation.

Network Monitoring Displays for BundleBone Operator Use

Network Monitoring and Control Display

All ION nodes monitored and available for direct SSH access for manual tests or troubleshooting



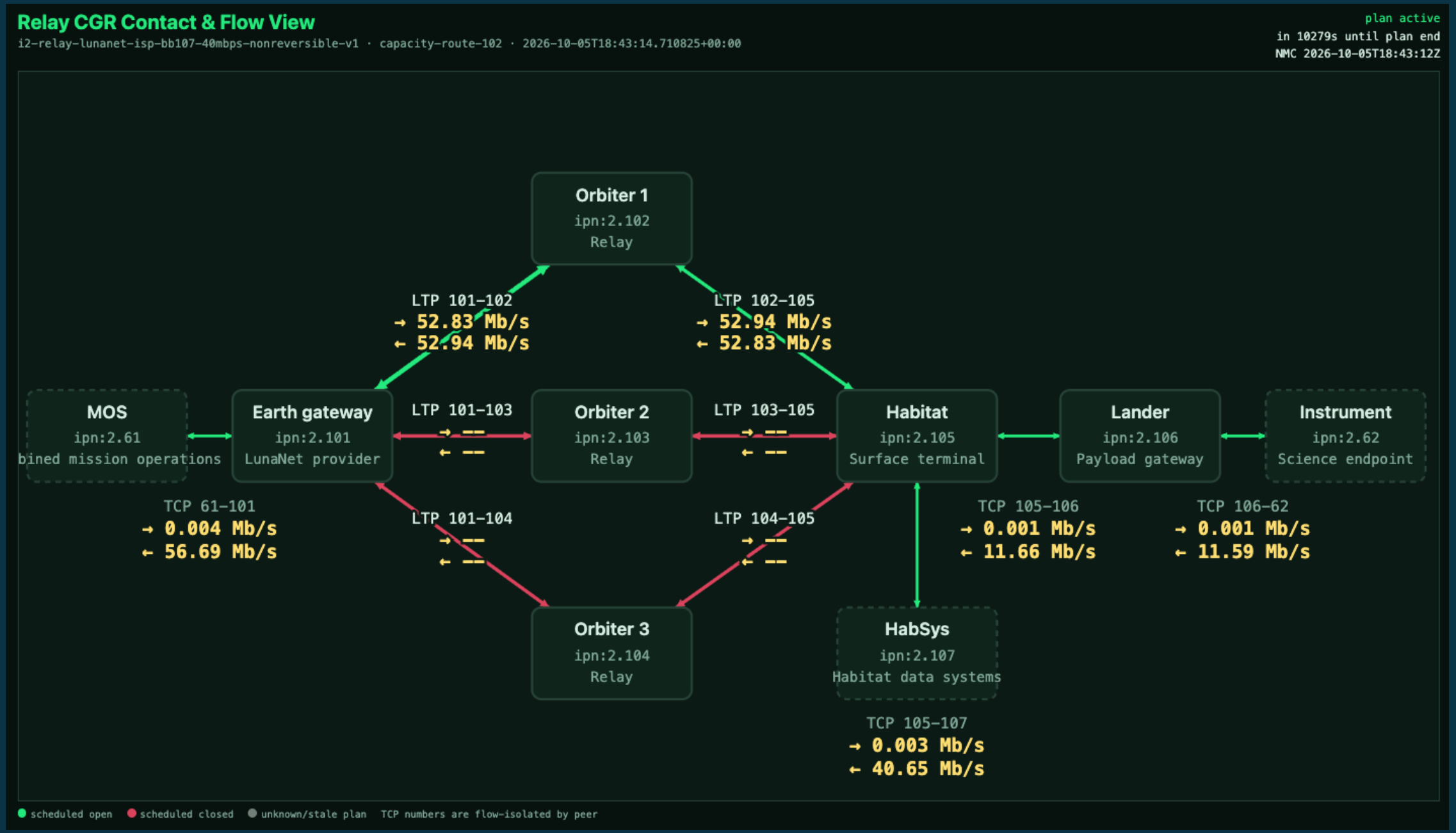
11 nodes monitored via periodic host state telemetry with bpstats and SDR watch statistics

(note- BMAX63 and BMAX64 are currently still part of the ipv4 prototype local LAN dtn-lab setup)

Additional Web-based Monitoring Displays

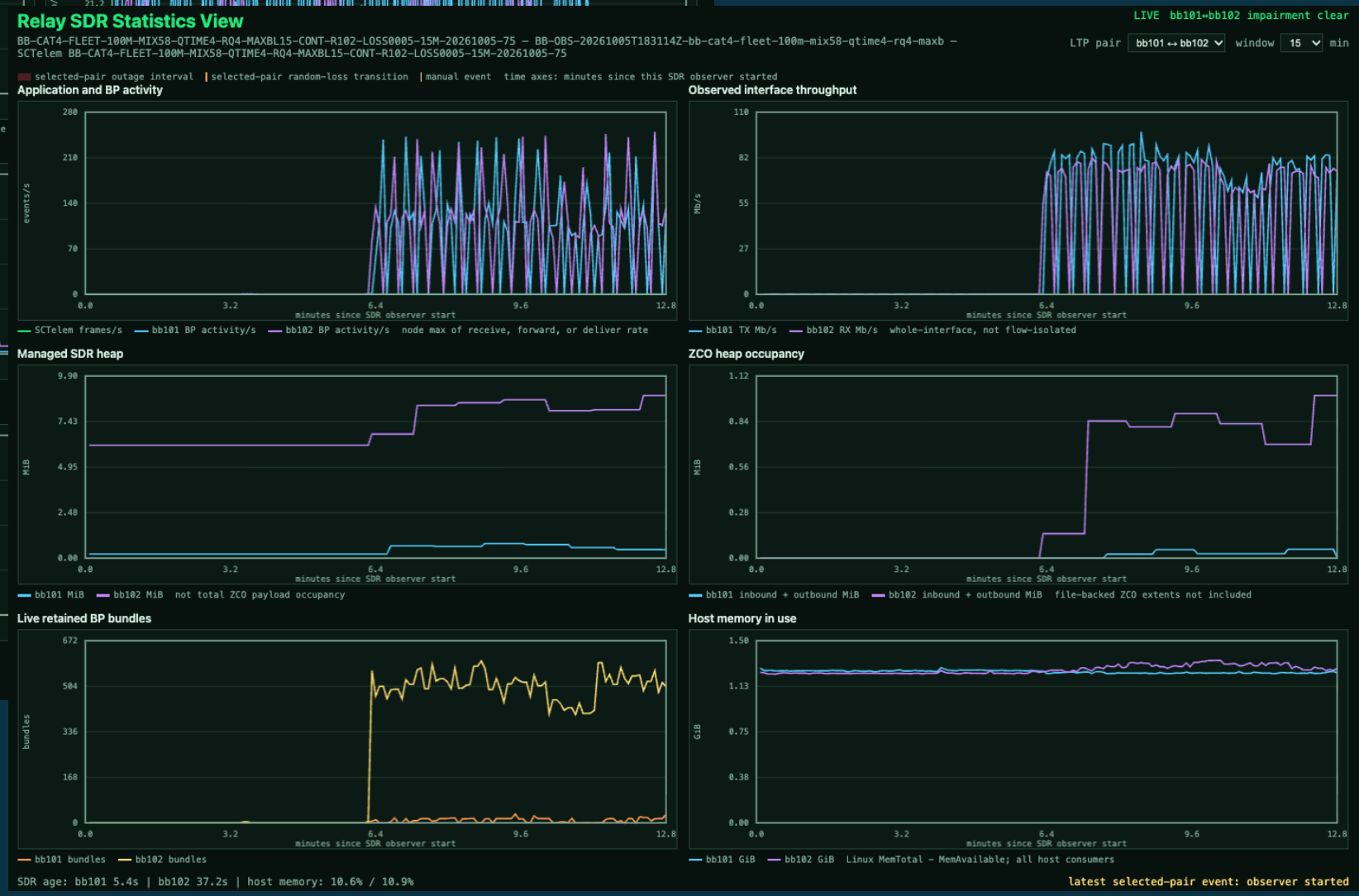


Additional Web-based Monitoring Displays, cont.

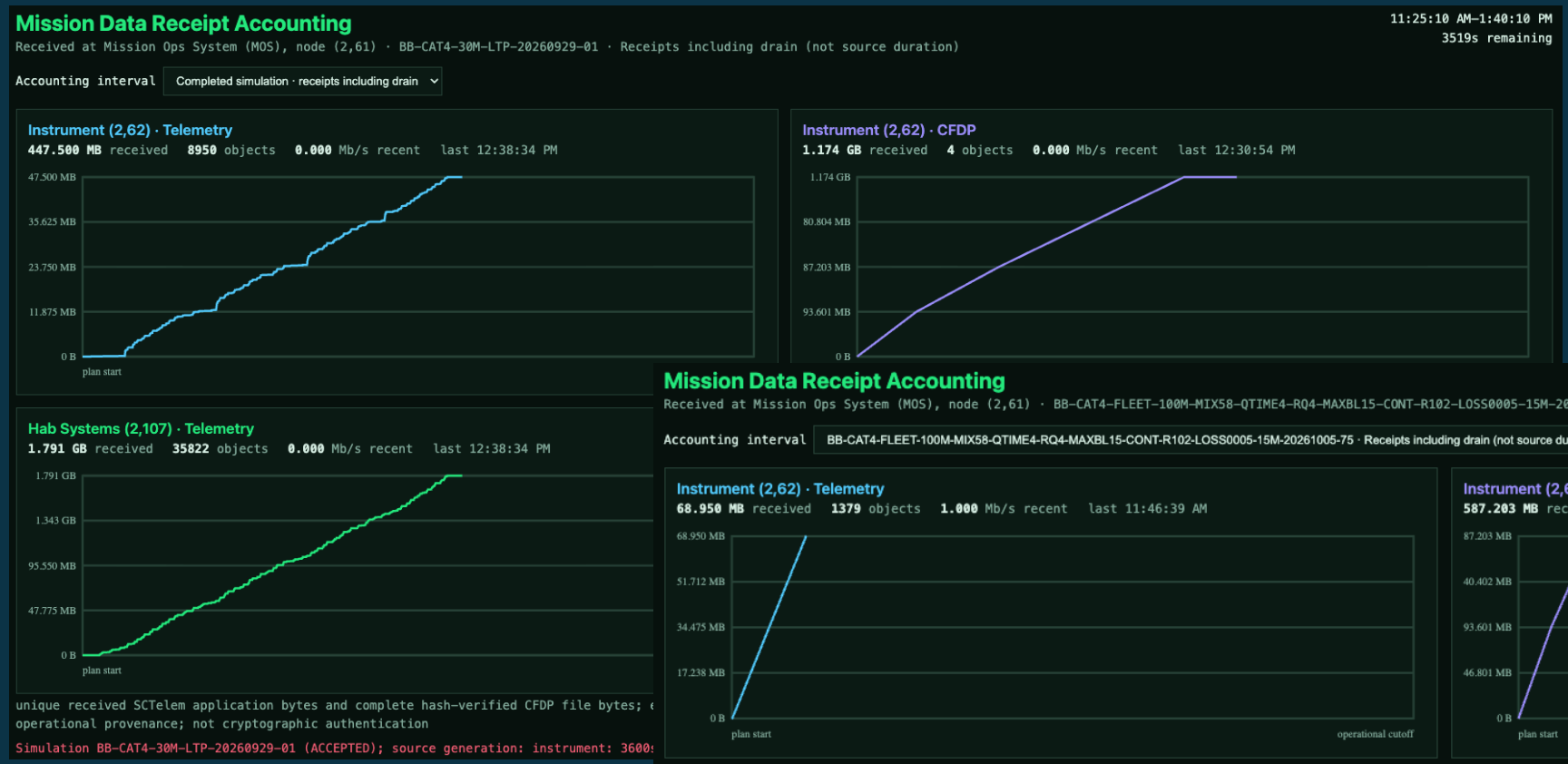


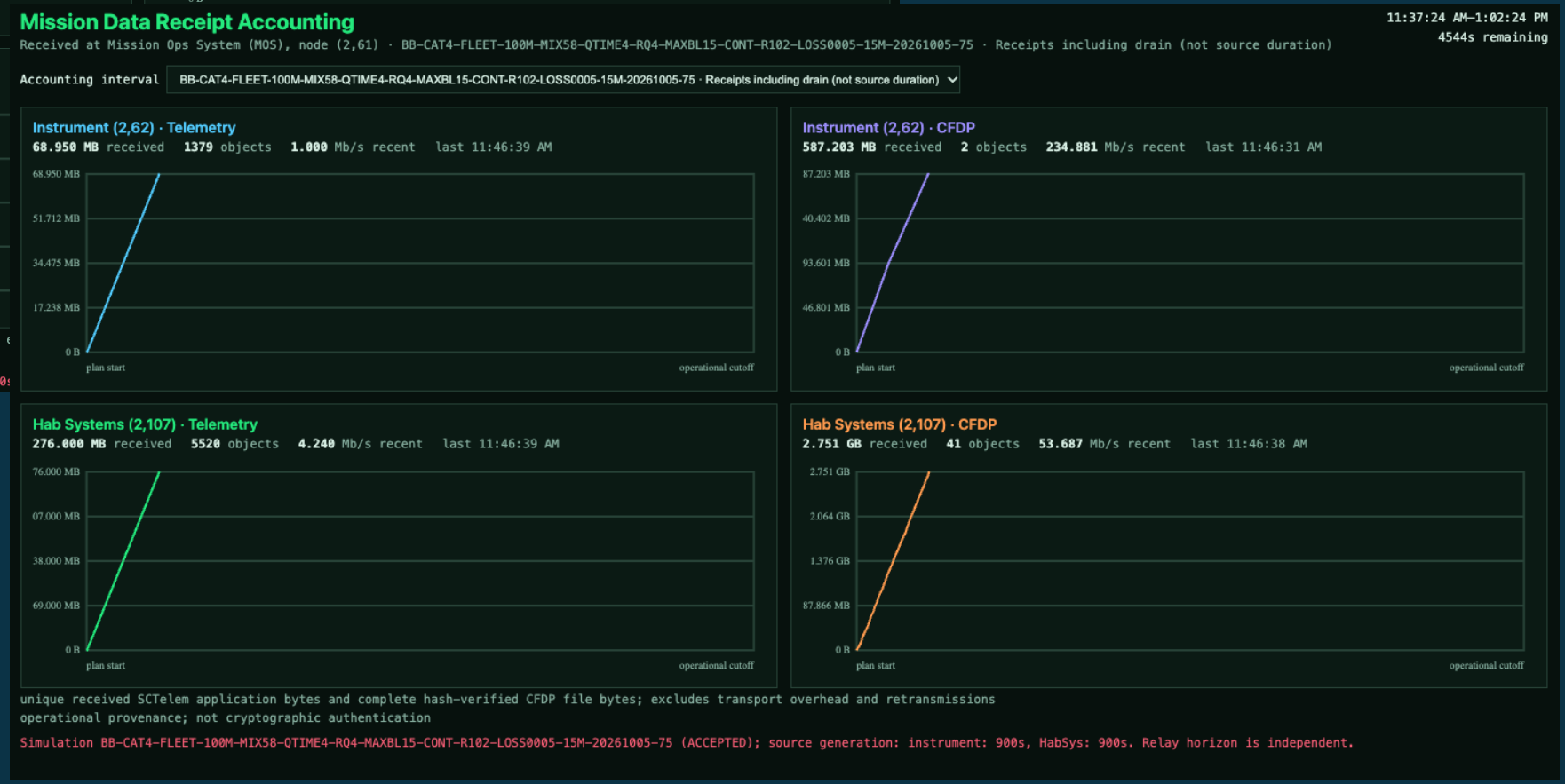
Additional Web-based Monitoring Displays, cont.



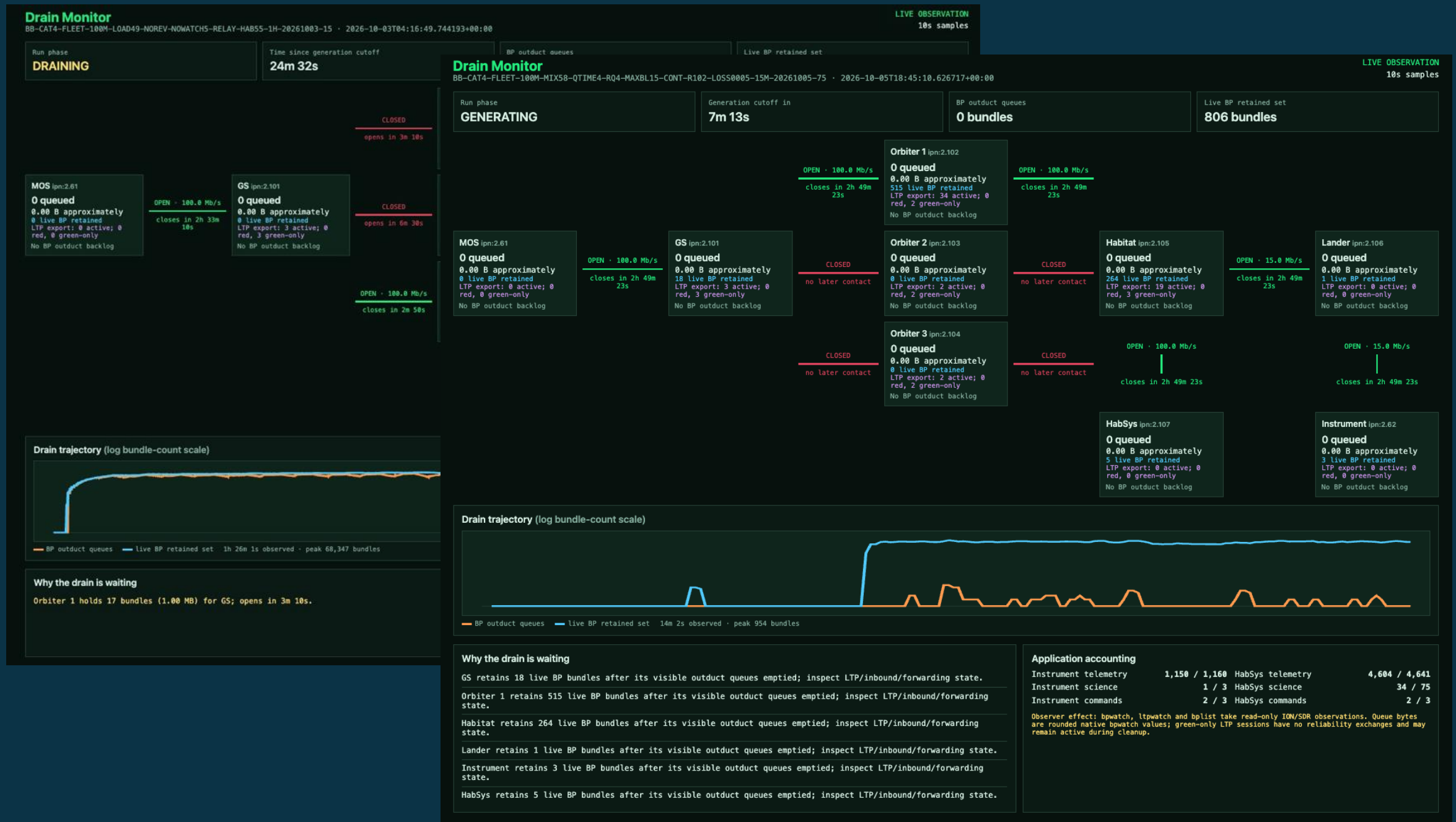


Additional Web-based Monitoring Displays, cont.





Additional Web-based Monitoring Displays, cont.



Additional Web-based Monitoring Displays, cont.

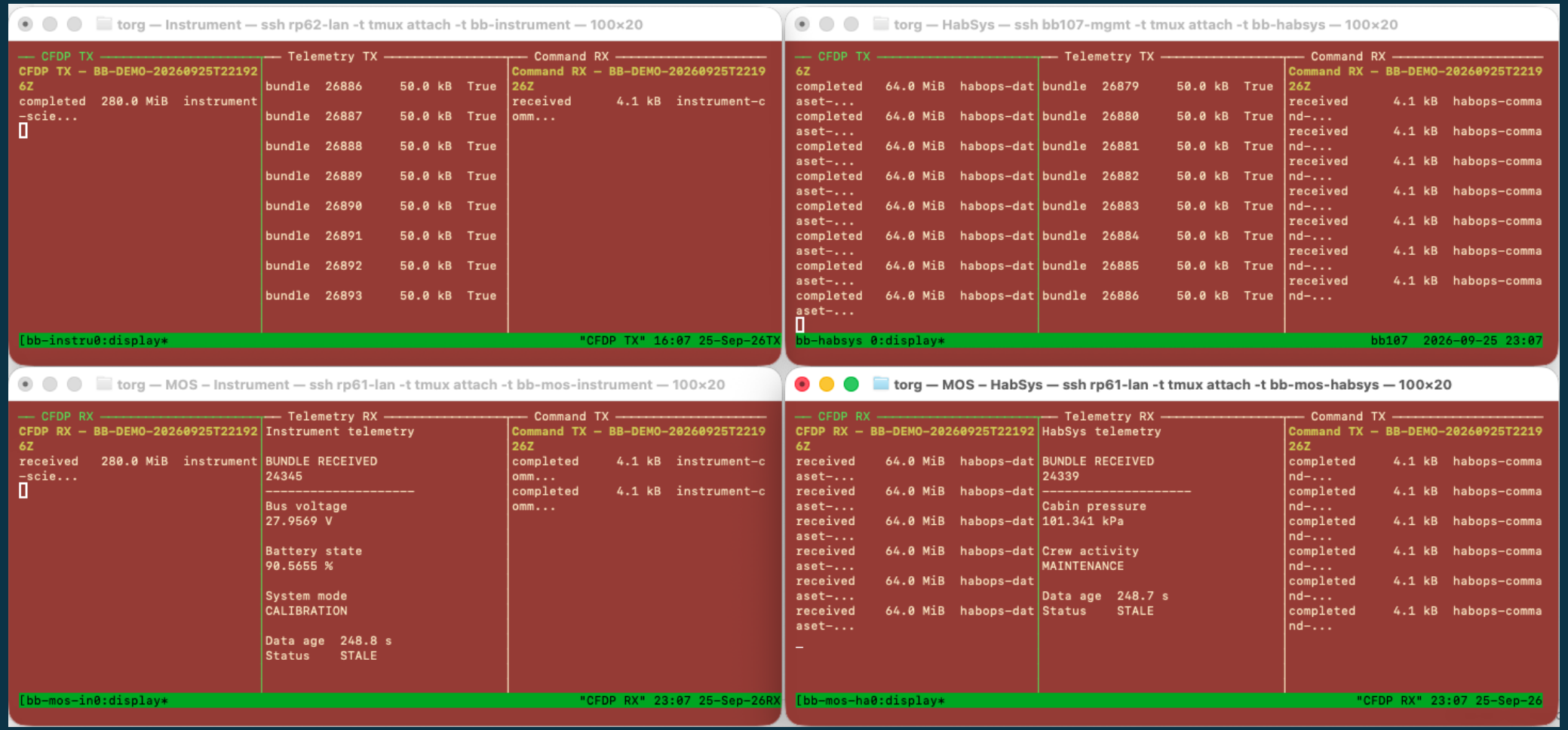
(To watch data/telemetry simulation software)

Instrument Node on Lander

Habitat Systems

Data sims Sent

Data Received



Reference Implementation Observatory

Web formats for Public Observation of DTN Reference Network Operations

A window into the network.

Observe ION nodes, interface traffic and Bundle Protocol activity.
Live measurements from the BundleBone **DTN Network Reference Implementation**.

22:22:18
UTC · OBSERVATION TIME

● **NMC feed connected** 10 of 10 fresh node observations · last feed 2s ago — SHARED FEED / 1 SEC

01 Network overview | 02 Node resources | 03 Bundle activity

FRESH OBSERVATIONS	OBSERVED INTERFACE RX	OBSERVED INTERFACE TX	HIGHEST OBSERVED SDR USE
10 /10	170.628 Mbit/s	164.880 Mbit/s	1.5%
Source measurements under 30 seconds old	Sum across nodes · includes management traffic	Interface rate, not application goodput	ION storage · fresh observations only

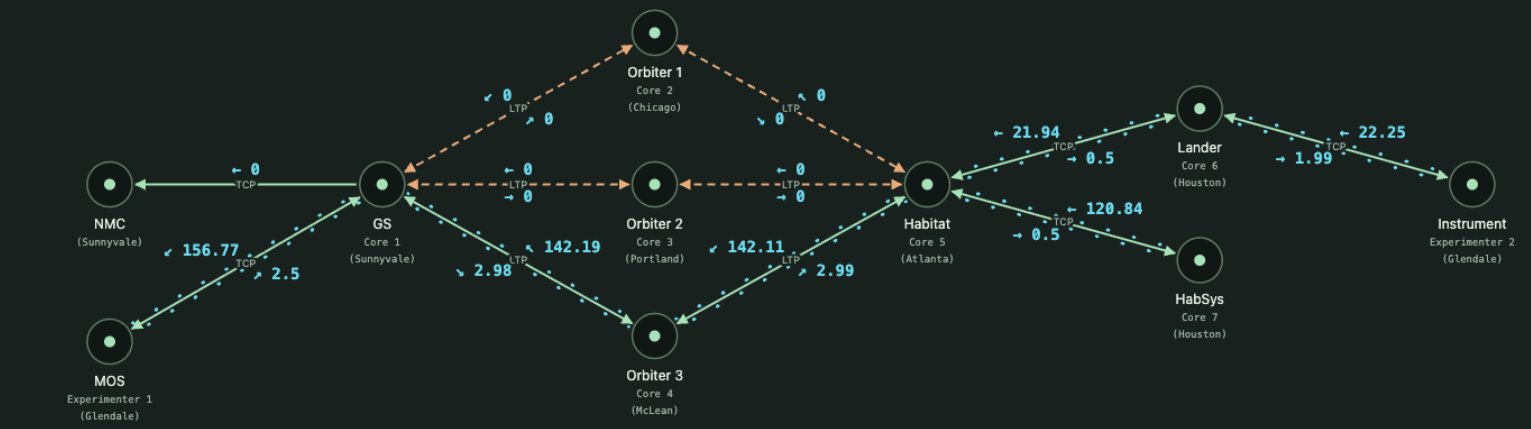
NETWORK MAP

NMC CONTACT TABLE

Contact Plan: BundleBone-LunaNet-Continuous-Relay · 100Mbps-30s-handoffs-5s-overlap

Scheduled state sampled 22:22:15 UTC. Link colors describe the plan's expectations, not traffic or measured connectivity.

→ Observed rates, bundles/sec (each direction)
GS–Orbiter one-way light time: 1.3 s (simulated lunar delay in each direction; 2.6 s round trip).



— Scheduled open --- Scheduled closed — One direction open --- Unknown ● Moving dots = recent dispatch on scheduled-open links LTP / TCP = configured transport · ? = unknown

Moving cyan dots: 12 scheduled-open directions with recent observed dispatch. Closed or unknown links show no activity dots; numeric rates remain recent measurements. Dot size is uniform; the numbers show measured rates. Each arrow labels that direction's observed bundles/s; counts and ages are in directional details. Includes management bundles; handoff to transport does not confirm delivery.

A window into the network.

Observe ION nodes, interface traffic and Bundle Protocol activity.
Live measurements from the BundleBone **DTN Network Reference Implementation**.

22:22:39
UTC · OBSERVATION TIME

NMC feed connected 10 of 10 fresh node observations · last feed 1s ago — SHARED FEED / 1 SEC

01 Network overview | 02 Node resources | 03 Bundle activity

FRESH OBSERVATIONS	OBSERVED INTERFACE RX	OBSERVED INTERFACE TX	HIGHEST OBSERVED SDR USE
10 /10	254.413 Mbit/s	259.432 Mbit/s	1.5%
Source measurements under 30 seconds old	Sum across nodes · includes management traffic	Interface rate, not application goodput	ION storage · fresh observations only

Node resources

Latest source values · stale values remain labeled

Node	Observation	CPU	Memory	Root disk	SDR storage	Source age
NMC	live	9.4%	13.1%	54%	0.097%	6s
GS	live	16.3%	10.3%	26%	0.287%	7s
Orbiter 1	live	1.2%	10%	29%	0.489%	9s
Orbiter 2	live	1.2%	10.1%	29%	0.717%	14s
Orbiter 3	live	16%	9.9%	29%	0.453%	6s
Habitat	live	19%	12.7%	36%	0.731%	9s
Lander	live	14.1%	10.8%	38%	0.128%	10s
HabSys	live	8.3%	15.1%	7%	0.019%	10s
MOS	live	12%	23.2%	19%	1.5%	9s
Instrument	live	4.8%	17.5%	10%	0.071%	9s

SDR is ION's Simple Data Recorder. CPU, memory and disk describe the host. Board-specific hardware sensors are excluded from this public view.

HOW TO READ THIS

Delay-tolerant networking lets nodes retain bundles of data for forwarding when a connection becomes available. This observatory shows current node measurements; a quiet interface can mean an idle network. Missing observations do not prove a node is down.

A window into the network.

Observe ION nodes, interface traffic and Bundle Protocol activity.
Live measurements from the BundleBone **DTN Network Reference Implementation**.

22:22:53
UTC · OBSERVATION TIME

NMC feed connected 10 of 10 fresh node observations · last feed 1s ago — SHARED FEED / 1 SEC

01 Network overview | 02 Node resources | 03 Bundle activity

FRESH OBSERVATIONS	OBSERVED INTERFACE RX	OBSERVED INTERFACE TX	HIGHEST OBSERVED SDR USE
10 /10	247.458 Mbit/s	187.733 Mbit/s	1.5%
Source measurements under 30 seconds old	Sum across nodes · includes management traffic	Interface rate, not application goodput	ION storage · fresh observations only

Bundle Protocol counters

Per-node cumulative totals · counters may reset

Node	Core processes	Received	Forwarded	Delivered	Expired	BP sample age
NMC	Reported running	12	12	12	0	8s
GS	Reported running	36,735,242	36,734,027	0	5,351	9s
Orbiter 1	Reported running	12,272,921	12,274,790	0	228	10s
Orbiter 2	Reported running	12,240,536	12,242,289	0	866	15s
Orbiter 3	Reported running	12,222,642	12,223,246	0	1,484	12s
Habitat	Reported running	36,736,541	36,746,846	6	1,037	9s
Lander	Reported running	5,876,699	5,874,976	24	1,742	12s
HabSys	Reported running	308,482	30,552,356	308,479	0	14s
MOS	Reported running	36,112,438	617,127	36,112,438	142	12s
Instrument	Reported running	308,489	5,569,872	308,489	3,729	15s

Counts are observations at each node, not unique end-to-end deliveries. "Delivered" means delivery to a local Bundle Protocol application; it does not establish mission-level completion. Old or unavailable BP samples are hidden. Queue depth, contact state and mission goodput are not yet connected.

HOW TO READ THIS

Delay-tolerant networking lets nodes retain bundles of data for forwarding when a connection becomes available. This observatory shows current node

Example Performance Results from Recent Tests

Typical Test Run Results – bent pipe (15 min passes):

Continuous End-to-End Path (with 2 sec OWLT in LTP link from GS to Orbiter): Runs 74 and 75

With continuous connectivity, ION delivered more than **50 Mbps of application goodput** both without impairment and with **0.005% frame/packet erasure***. Induced loss increased LTP repair traffic and drain time, but caused no application loss or session cancellation. Workload ~ 11.5K telemetry frames, 78 CFDP data files.

Performance measure	Run 74 — Lossless	Run 75 — 0.005% erasure
Active space link rate	100 Mbps	100 Mbps
Offered application load	57.569 Mbps	57.569 Mbps
Injected frame/packet erasure	0%	0.005%
Observed erased datagrams	0	472 / 9,421,858
Goodput during 15-minute source window	53.371 Mbps	52.177 Mbps
Eventual goodput through final receipt	52.312 Mbps	51.192 Mbps
Drain after source cutoff	90.430 s	112.090 s
Application payload delivered	6.476 GB	6.476 GB
Data-segment retransmissions	33	945
Checkpoint retransmissions	0	4
Report retransmissions	0	3
UDP receive-buffer errors	0	0
LTP cancellations	0	0
Unrecovered application items	0	0
Result	PASS — exceeded 50 Mbps	PASS — exceeded 50 Mbps and recovered all induced loss

** Ethernet loss rate of .005% equates to an LDPC frame error rate of 2.5 times the usual 1E-5 frame error rate for CCSDS 16384 bit AOS frame size*

Typical Test Run Results – LunaNet sim (15 min passes):

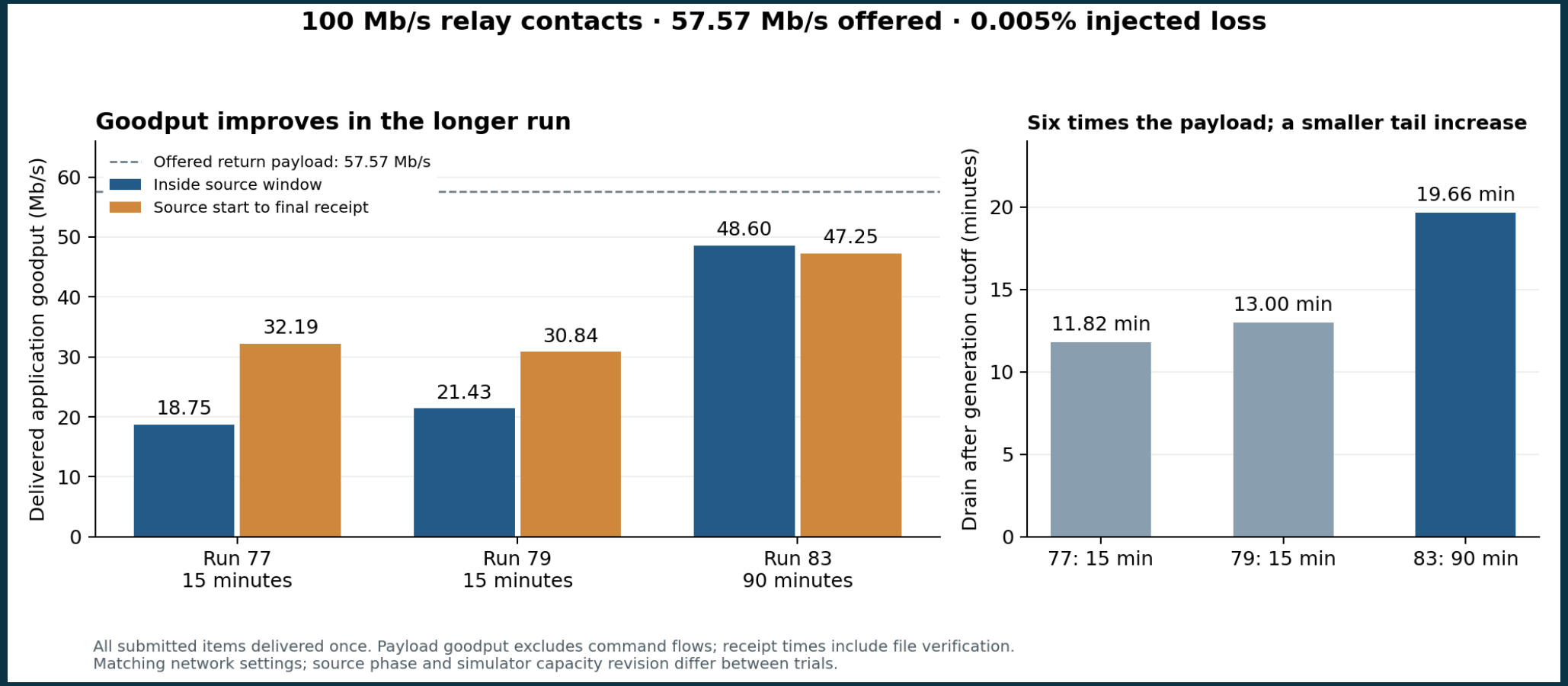
Scheduled Three-Orbiter Relay Scenario: Runs 76 and 77

Both relay runs delivered and verified **every application item**. The intermittent contact schedule, rather than packet loss, dominated wall-clock performance: adding 0.005% erasure greatly increased LTP repair activity but left eventual goodput and drain essentially unchanged.

Performance measure	Run 76 — Lossless	Run 77 — 0.005% erasure
Active space link rate	100 Mbps	100 Mbps
Offered application load	57.569 Mbps	57.569 Mbps
Injected frame/packet erasure	0%	0.005%
Observed erased datagrams	0	500 / 9,422,188
Goodput during 15-minute source window	21.355 Mbps	18.746 Mbps
Eventual goodput through final receipt	32.172 Mbps	32.193 Mbps
Drain after source cutoff	710.423 s	709.384 s
Application payload delivered	6.476 GB	6.476 GB
Data-segment retransmissions	12	1,038
Checkpoint retransmissions	1	129
Report retransmissions	0	1
UDP receive-buffer errors	0	0
LTP cancellations	0	0
Unrecovered application items	0	0
Result	Complete delivery	Complete delivery and loss recovery

90 minute run results – relay topology, 2.5x expected loss rate corrected by LTP

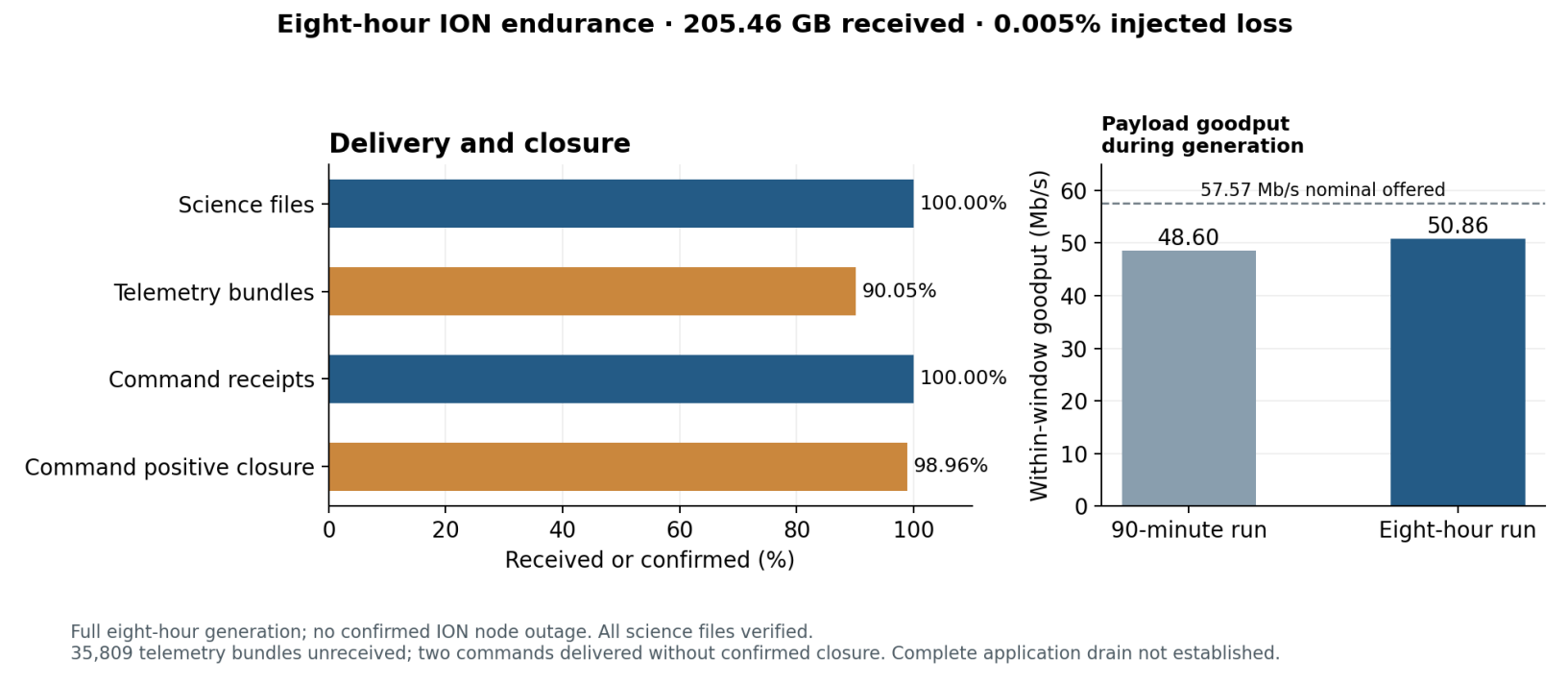
Total data goodput 38.86 GB



Why the improvement in the 90-minute run? Its **first 15 minutes averaged 20.18 Mb/s**, while the **remaining 75 minutes averaged 54.28 Mb/s.** This demonstrates an initial pipeline-fill penalty that dominates short trials and becomes less significant over longer runs.

8-hour run results – relay topology, 2.5x expected loss rate corrected by LTP

Total data goodput 205.46 GB



(In these runs, full data load is offered right up to the 8-hr pass cutoff, so in a relay scenario as modeled, some data ends up stranded. In real life, data flow will be planned to accommodate actual pass conditions.)

Demonstrates long-term stability of ION and efficacy of LTP

BPSec Testing – Successful and semi-complete for now

The BPSec Native implementation tested in dtn-lab for ION 4.1.2 was successful; BPSec Native implementation is the Bpsec that was integrated in ION, but did not yet encompass all of the BPSec Bluebook requirements, because APL decided to package their BPSec software in a BPSec library and then integrate that with ION.

The native-ION BPSec test campaign completed its five primary steps and six second-tier groups. Testing covered the APL-documented supported cases, cryptographic failure behavior, AES-GCM IV uniqueness, three-node roles, protected store-carry-forward persistence, restart persistence, overlapping policy selection, CFDP payload boundaries, sustained bidirectional application traffic, malformed policy input, resource characterization, and ARM/x86 repeatability.

The tested implementation successfully generated and processed payload and Bundle Age BIBs and BCBs; detected wrong keys at BIB verifier and BIB/BCB acceptor roles; preserved already-protected bundles across relay and endpoint interruptions; maintained keys and policy rules across a retained-state restart; selected exact rules over broader wildcard rules; protected objects from zero bytes through 18 MiB; and completed sustained bidirectional SCTelem and CFDP workloads through the complete eight-host dtn-lab path.

BSL v1.1.1 tested in ION 4.2.0; Final release of ION 4.2.1 will include support for BSL 2.0, and once that's released in final form, we will complete all BPSec testing on the BundleBone.

Ongoing Work:
Next Steps

Phases: Next Steps

Phase 4b – Complete BPSec testing with BSL 2.0

Phase 5 — Addition of DTN Asynchronous Management Protocol (DTN-AMP)

Install, test and demonstrate DTN-AMP with DTN-AMP Agents on bb101-106, rp61 & rp62,
and the DTN AMP Manager on bb-nmc; demonstrate DTN-AMP reports, command and contact graph updates
Via DTN-AMP. Using Command Line interface at NMC computer; AMMOS Network Management System (ANMS) by APL may be implemented (TBR)

Phase 6 — Tests with DSN and ESA for Interoperability ***Reference Implementation Milestone***

Phase 7 — Public (or selected researcher) Use of DTN Network Reference Implementation

After satisfactory demonstration and testing of Reference DTN Network in the two topologies, Phase 7 will entail the design of processes and procedures to make the DTN Reference Network open to select external experimenters – all plans TBD at this moment!

- Issues to resolve:
  - Access Security
  - Size of VMs and feasibility of duplication
  - Use of Tailscale in current setup
  - IRF development and testing (impacts how CGR routing will work from end-to-end)