LLCD
Lunar Laser Communication Demonstration

Disruption Tolerant Networking Demonstrations over LLCD's Optical Links

Dave Israel and Don Cornwell
NASA Goddard Space Flight Center

IPNSIG Space Technology Innovations Conference, January 24th, 2014
**NASA’s First High-Rate, Two-Way Space Lasercom**

**Lunar Atmosphere and Dust Environment Explorer**

- Space terminal to fly on Lunar Atmosphere and Dust Environment Explorer (LADEE)
- Launch Date: September 6th 2013 from Wallops Flight Facility on Minotaur V
  - First Wallops flight to the Moon
  - First launch of Minotaur V
    - 1 month transfer
    - 1 month lasercom demo
      - From 250 km orbit
    - 3 months science
**LLCD Mission Architecture**

**Lunar Lasercom Ground Terminal (LLGT)**
- at NASA's White Sands Complex (WSC)

**LLGT UPLINK:**
4 x 10 W 1.55 mm EDFA MOPAs to 10 cm EDFA-pre-amp on LADEE
Transmitting 10 or 20 Mbps 4-PPM with ½ Rate code and interleaver

**LLGT DOWNLINK:**
0.5 W 1.55 mm EDFA MOPAs to 4 x 0.4 m telescopes to 16 SNDAs
Transmitting 40 to 622 Mbps 16-PPM with ½ Rate code and interleaver

**Backup Sites (Limited Functionality)**
- (LLOT) – “OCTL” at Table Mtn. CA
- OGS at Tenerife, Spain

**RF Ground Station**
- LADEE Mission Ops Center at ARC
- LADEE Science Ops Center at GSFC

**LLCD Monitor**
- at GSFC

**Lunar Lasercom Ops Center (LLOC) & Mission Analysis Center**
- at MIT/LL

**Echo**
NASA’s science data needs are driving faster download data rates…

To transmit a 1 foot res map of entire Mars surface (1.6e15 points)

- at 1 bit / pixel: 5 Mbps requires 9 years (best Ka-band)
- 250 Mbps requires 9 weeks (JPL’s DOT)

Higher data rates will be required to break through the present-day science return bottleneck

Chart courtesy of Don Boroson, MIT Lincoln Laboratory
Comparing RF and Optical: Equivalent Isotropic Radiated Power

**NASA Deep Space Network**
- 34-m antenna
- S-band (2-2.3 GHz)
- 20-kW transmit power

$\rightarrow$ EIRP = 8.3 GW!

**Lunar Lasercom Space Terminal**
- 10-cm space terminal
- Optical (1550 nm, or 200,000 GHz)
- 0.5-W transmit power

$\rightarrow$ EIRP = 8.1 GW!

Optical’s shorter wavelengths allow for smaller terminals using less power for equivalent or higher data rates...

Chart courtesy of Don Boroson, MIT Lincoln Laboratory
Optical Communications can provide significantly higher data rates with comparable spacecraft mass and power requirements, and no spectrum allocation constraints.

LLCD
- Data rate: 622 Mbps
- Mass: 30.7 kg
- Power: 90 W (Optical)

LRO
- 100 Mbps (RF-Ka-band)

LADEE
- 128 Kbps (S-band)

All lunar missions: data rates are for return link only.
Pointing LLCD’s Beam from the Moon

White Sands Complex

- **Downlink**
  - 10-cm aperture
  - 15-µrad beam
  - ~6-km spot at LLGT

- **Uplink**
  - 15-cm aperture
  - 10-µrad beam
  - ~4-km spot at LLST
Pointing LLCD’s Beam from the Moon

White Sands Complex

- **Downlink**
  - 10-cm aperture
  - 15-µrad beam
  - ~6-km spot at LLGT

- **Uplink**
  - 15-cm aperture
  - 10-µrad beam
  - ~4-km spot at LLST
Pointing LLCD’s Beam from the Moon

- **Downlink**
  - 10-cm aperture
  - 15-µrad beam
  - ~6-km spot at LLGT

- **Uplink**
  - 15-cm aperture
  - 10-µrad beam
  - ~4-km spot at LLST
Pointing LLCD’s Beam from the Moon

- **Downlink**
  - 10-cm aperture
  - 15-µrad beam
  - ~6-km spot at LLGT

- **Uplink**
  - 15-cm aperture
  - 10-µrad beam
  - ~4-km spot at LLST
Pointing LLCD’s Beam from the Moon

- **Downlink**
  - 10-cm aperture
  - 15-µrad beam
  - ~6-km spot at LLGT

- **Uplink**
  - 15-cm aperture
  - 10-µrad beam
  - ~4-km spot at LLST

Ka-band 75-cm HGA from Lunar orbit
Pointing LLCD’s Beam from the Moon
LLCD Fully Integrated on LADEE
The Investigation: LLCD’s Requirement

• Level 0 requirement:
  – Demonstrate duplex lasercom from the Earth to lunar orbit

• Level 1 requirements:
  – Demonstrate 622 Mbps downlink from LADEE to an Earth receiver in at least some atmospheres (>38 Mbps Min)
  – Demonstrate ~20 Mbps uplink from an Earth transmitter to LADEE in at least some atmospheres (>4.5 Mbps Min)
  – Demonstrate 2-way time-of-flight with errors less than 200 psec (<500 psec Min req.)
First Pass (October 17th, 2013): Error-Free 311 Mbps D/L, 10 Mbps U/L
Performance to Date:

- Regular, instantaneous (seconds!) all-optical acquisition and tracking between LLST and LLGT
- Error-free D/L to LLGT at 40, 80, 155, 311 Mbps
- 622 Mbps D/L regularly achieved with a code word error rate (CER) < 1x10^{-5} (Req. < 1x10^{-4})
- Error-free U/L from LLGT at 10, 20 Mbps
- Initial TOF measurements collected and being processed to allow centimeter-class ranging
- Error-free operation at low Moon elevation angles (< 4 degrees at White Sands/LLGT!)
- Operation to within 3 degrees of the Sun at up to 622 Mbps with no degradation in performance!

Operational Achievements to Date:

- LLST U/L commanding sent and LLST telemetry received over optical link
- LADEE spacecraft data downlinked through high-speed data interface to LLST Modem; entire 1 GB LADEE buffer downlinked in < 5 min @ 40 Mbps (LADEE C&DH limit)
- Multiple streaming HD videos transmitted to the Moon and looped back to LLGT at 20 Mbps (limited by U/L rate)
- All-optical (no RF!) Comm passes using automated scripts to awake and point LLST on schedule
A DTN demonstration was performed across the LLCD optical links in November 2013:

- Lunar Relay scenario with BP/LTP transmitted over optical links
- Included CFDP over BP file transfers and other multi-hop bundle flows
- DTN was not implemented onboard the spacecraft itself
- DTN traffic was limited to 1 – 3 Mbps due to terrestrial bottlenecks and other LLCD requirements

Successfully demonstrated DTN protocols providing complete automated multi-hop data transfers with a real optical link segment subjected to cloud and scheduled disruptions.

Provided experience and better understanding of requirements for future relay payload, ground station, and network control center systems.

The data is being analyzed to verify the DTN functionality and to plan possible future experiments.
Mutual Visibility Timelines

- Visibility times determined by STK using LADEE ephemeris, selected lunar surface locations, and LLCD schedules
- All terrestrial DTN nodes connected at all times
- Links between lunar surface nodes and the lunar relay were connected based on the schedule
- Links between lunar relay and Earth were connected by real LLCD optical links
  - Data loopback (Full demodulation, decoding, encoding, and modulation onboard)

Notional Mutual Visibility Timeline
LLCD DTN Demo Network

DTN Nodes implemented on Linux PC’s using ION 3.1.2
Bundle Delivery Across LLCD Optical Links (18 Nov 2013)
LLCD DTN Demo (20 Nov 2013): Relay Data Source Only
LLCD DTN Demo (20 Nov 2013): Tranquility Base Only
DTN Network Management Visualization Tool

- This realtime graphical display was developed in the LLCD ops center as a tool to provide the ability to monitor the DTN bundle flows
- Identified the needs for such a tool and have since begun enhancements
  - Scheduled and/or active links
  - Data staleness
  - Predicted/expected states for out of contact nodes
NASA Lasercom Scenarios

Deep Space to Earth (LLCD Demo)
- Low SWaP
- Higher BW than RF
- Based on PPM
- Only 30 day demo for LLCD

Near-Earth Relay (LCRD Demo)
- “TDRS” Architecture
- High BW > 1 Gbps with DPSK
- 2 to 5 years of Ops for LCRD

Additional Scenarios:
- Very high data rate (> 10 Gbps) direct LEO-to-Ground
- Very low SWaP for small spacecraft (e.g., Cubesats)

All scenarios benefit from Disruption-Tolerant Networking (DTN)
Laser Communication Relay Demonstration (LCRD) Mission Architecture

- STMD/SCaN Mission
- Commercial Spacecraft Host
- Flight Payload
  - Two LLCD-based Optical Modules and Controller Electronics Modules
  - Two Modems capable of PPM (up to 311 Mbps) and DPSK (up to 1.24 Gbps)
  - High Speed Electronics to interconnect the two terminals and to interface with the host spacecraft
- Two Optical Communications Ground Stations
  - Upgraded JPL Optical Communications Telescope Laboratory (Table Mountain, CA)
  - Upgraded LLCD Lunar Laser Ground Terminal (White Sands, NM)
- LCRD Mission Operations Center
- Two years of operational network experiments
LCRD Flight Representation

**LCRD Flight Payload**
- Will be hosted on a SSL built satellite; operator selection expected Q1 FY15
- Target launch date is March 2018 and the host satellite will be placed into geostationary orbit at a longitude between 63°W to 161°W
- On-orbit experiment and operations will occur for two years following launch and on-orbit checkout

**LCRD Host Accommodations**
- LCRD Flight Payload will be hosted on a SSL built satellite; operator selection expected Q1 FY15
- The target launch date is March 2018 and the host satellite will be placed into geostationary orbit at a longitude between 63°W to 161°W
- On-orbit experiment and operations will occur for two years following launch and on-orbit checkout
Conclusions

• The LLCD experiment has successfully demonstrated high rate bi-directional optical communications to a spacecraft in lunar orbit
• A demonstration of DTN functionality was added to the LLCD experiment
• Space optical communications performance and functionality can be enhanced by the inclusion of DTN
  – Reliable communications over varying length outages due to atmosphere or clouds
  – Rate buffering
  – Multiplexing and de-multiplexing data over trunklines
Acknowledgements

LLCD Team
• Don Cornwell/GSFC
• John Guineau/MIT LL
• Bryan Robinson/MIT LL
• Don Boroson/MIT LL
• Paul Swenson/GSFC SPOCC
• Cory Heiges/GSFC SPOCC
• Tiffany Navas/GSFC SPOCC
• Jennifer Sager/GSFC SPOCC
• Robert Lafon/GSFC LLGT

DTN Demonstration Team
• Dave Israel/GSFC
• Greg Menke/GSFC
• Leor Bleier/GSFC
• Mark Sinkiat/GSFC
Connect with LLCD!

National Aeronautics and Space Administration

Lunar Laser Communication Demonstration
NASA's First Space Laser Communication System

Lunar Laser Communication Demonstration
Goddard Space Flight Center, Code 450.2
Greenbelt, MD 20771

http://llcd.gsfc.nasa.gov
www.nasa.gov

Connect with LLCD
facebook.com/NASA.ESC
twitter.com @NASA_GSFC_ESC

NP-2013-05-028-GSFC
Space Terminal Optical Module

10-centimeter telescope
Transmit and receive free-space-to-fiber connections
2-axis gimbal

Launch Latch

107.6 mm Diameter Duplex Beam (through Solar Window)
Space Terminal Internal Modules

- **Uplink functions**
  - Selectable 10, 20 Mbps
  - Command, data, and test pattern demux
- **Downlink functions**
  - Selectable 40-620 Mbps
  - Mux terminal telemetry, looped-back uplink, spacecraft data, test patterns
- **Enables time-of-flight**

Controller Electronics Module

- Controller functions
  - Spacecraft controls interface
  - Space terminal configuration
  - Digital controls for PAT