Optical Communication Flight Systems

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## Optical Comm Demonstrations and Systems

<table>
<thead>
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<th>Year</th>
<th>System</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2002</td>
<td>LCE (Japan) GEO-Ground</td>
<td>1995</td>
</tr>
<tr>
<td>2002</td>
<td>ALEX (MITLL) Air-GEO</td>
<td>2002</td>
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<tr>
<td>2004</td>
<td>OICETS (Japan) LEO-GEO</td>
<td>50 Mbps 2005</td>
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<td>2005</td>
<td>LEO-Ground</td>
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<td>2006</td>
<td>GEOLITE (MITLL) GEO-Ground</td>
<td>2001</td>
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<td>2007</td>
<td>SILEX (ESA) LEO-GEO</td>
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<td>2008</td>
<td>FOCAL (SAF/MITLL)</td>
<td>Air-Ground 2.5 Gbps 2009</td>
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<tr>
<td>2009</td>
<td>HY-2 (China) LEO-Ground</td>
<td>504 Mbps</td>
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<td>2009</td>
<td>NFIRE/TerraSar</td>
<td>ESA/FRG/MDA LEO-LEO 5.6 Gbps 2008</td>
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<tr>
<td>2010</td>
<td>FALCON (AFRL)</td>
<td>Air-Ground 2.5 Gbps 2010</td>
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<td>2010</td>
<td>FOENEX (DARPA)</td>
<td>Air-Air 10 Gbps Air-Ground 2012</td>
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<td>2012</td>
<td>LLCD (NASA/MITLL)</td>
<td>Moon-Ground 622 Mbps 2013</td>
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<td>2013</td>
<td>OPALS (NASA/JPL)</td>
<td>2014</td>
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<tr>
<td>2014</td>
<td>Alphasat (ESA)</td>
<td>GEO-LEO 1.8 Gbps 2013-14</td>
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<td>2015</td>
<td>SOTA (Japan)</td>
<td>2014</td>
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<tr>
<td>2015+</td>
<td>OSIRIS (DLR)</td>
<td>2016</td>
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<td>2016</td>
<td>EDRS/Sentinal (ESA)</td>
<td>2015</td>
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<tr>
<td>2019</td>
<td>LCRD (NASA)</td>
<td>2019</td>
</tr>
<tr>
<td>2021</td>
<td>DSOC (NASA)</td>
<td>2021</td>
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</table>
Outline

• Near-Earth lasercom systems
  – Charts provided by Frank Heine, TESAT

• Deep space lasercom systems
European Data Relay System (EDRS) and Globenet

Laser comms from low earth orbit systems to geostationary platforms, RF links to ground
11 LCTs up to now
5 already operational in space
The TESAT Laser Communication Terminal LCT

- **High Data Rate full-duplex**
  - 1.8 Gbit/s user data rate
  - 2.8 Gbit/s optical data rate

- **Homodyne BPSK**
  - 1064nm
  - => Single frequency laser (NPRO Byer /Kane)

- **Beacon-Less spatial acquisition**

- **Single unit, SWaP**
  - 60*60*60 cm
  - 50kg
  - 160W max 120 W av.
LCT types

- GEO and LEO (photo April 2016)
Coherent Detection and BPSK

- Received light is mixed with a phase locked single frequency source on a photo diode, transfer of data from 300THz carrier to baseband

\[ i_H = D \left\{ \frac{1}{2} A_c^2 + \frac{1}{2} A_o^2 + A_c A_o \cos (\varphi_o - \varphi_c) \right\} \]

- Photocurrent has DC and AC part, AC part is the information
- Basically the RX light amplitude is multiplied by the strong local oscillator
- Phase locking builds an interferometer over link distance (> 45000 km)
- Receiver is shot noise limited (mW of local oscillator optical power on photo diode)
- Broad band background (Sun) is suppressed, penalty is less than 0.5d dB if Sun is in field of view
- Can detect single photons
- Most efficient system without bandwidth expansion (coding)
- PPM outperforms coherent detection with coding
Questions?

Frank Heine
Head of LCT System Engineering
Frank.Heine@tesat.de
Outline

- Near-Earth lasercom systems
  - Charts provided by Frank Heine, TESAT

Deep space lasercom systems
Deep Space Communications Links

Space Terminal Aperture Gain

\[ P_R = L_R A_R \frac{1}{4\pi R^2} \left( \frac{4\pi A_T}{\lambda^2} \right) L_T P_T \]

Data Rate [bits/sec] = \( \frac{1}{\eta} \frac{P_R}{h \nu} \)

- \( P_{TR} \) = Transmitted/Received Power
- \( L_{TR} \) = Transmitter/Receiver Loss
- \( A_{TR} \) = Transmitter/Receiver Aperture Area
- \( R \) = Range
- \( \lambda \) = Carrier Wavelength
- \( \nu \) = Carrier Frequency
Lunar Laser Communication Demonstration

Tech demo on NASA’s Lunar Atmosphere and Dust Environment Explorer (LADEE)

- 622 Mbps downlink from moon
- 20 Mbps uplink to moon
LLCD Space Terminal on LADEE

Modular design allowed for balanced placement in small spacecraft

LLCD Optical Module

LLCD Controller Module

LLCD Modem Module

Space Terminal mass ~ 30 kg
Space Terminal power ~ 90 W

0.5-W transmitter 4-inch telescope Fully-gimballed Inertial stabilization
 Transmit Aperture Gain

LLCD:
- 10 cm aperture
- 106 dB gain
- 15 µrad beamwidth

DSOC:
- 22 cm aperture
- 113 dB gain
- 7 µrad beamwidth

* At 1550 nm
Beam Size From Moon

- 10-cm transmit aperture
- 15-µrad beam
  - ~0.001 deg
  - ~6 km on Earth

Image from http://www.nasa.gov/lro
Beam Stabilization

Disturbances

- Terminal distortions
- Spacecraft and target motions
- Platform vibrations

Stabilization Methods

- Passive Isolation
- High BW tracking with beacon

* Figure from "Deep Space Optical Communications", H. Hemmati, ed.

BW = Bandwidth
Tracking for Deep Space Optical Comm

- Equivalent tracker at Moon requires 100X more power-aperture than GEO!
- Equivalent Tracker at Mars requires 100,000,000 more Power-Aperture than GEO!

Power received at space terminal with fixed system (Apertures, Power) \( \sim \frac{1}{R^2} \)

Optical tracking bandwidth with fixed angle estimate error \( \sim P^2 \) (or \( \frac{1}{R^4} \))!
Beam Stabilization

Disturbances

Terminal distortions  Spacecraft and target motions  Platform vibrations

0.1  1  10  100  1000

Frequency (Hz)

Stabilization Methods

- Celestial Sources
- Passive Isolation
- Inertial References
- Low BW tracking with beacon
- High BW tracking with beacon

LLCD Approach

* Figure from "Deep Space Optical Communications", H. Hemmati, ed.
• 2-axis gimbal
  – Provides coarse pointing
  – 55 deg az, +/- 10 deg el
• Magnetohydrodynamic Inertial Reference Unit (MIRU)
  – 2-axis angle rate sensors and voice-coil actuators
  – Rejects high-frequency (> ~few Hz) disturbances
• Piezo-electric actuators
  – Transmit fiber point-ahead mechanism
  – Receive fiber nutator for tracking uplink comm signal
• Quadrant detector
  – Detects uplink beacon
  – Coarse tracking during acquisition
Deep Space Communications Links

\[
P_R = L_R A_R \frac{1}{4\pi R^2} \left( \frac{4\pi A_T}{\lambda^2} \right) L_T P_T
\]

DataRate [bits / sec] = \frac{1}{\eta} \frac{P_R}{h \nu}

\[P_{TR} = \text{Transmitted/Received Power}\]
\[L_{TR} = \text{Transmitter/Receiver Loss}\]
\[A_{TR} = \text{Transmitter/Receiver Aperture Area}\]
\[R = \text{Range}\]
\[\lambda = \text{Carrier Wavelength}\]
\[\nu = \text{Carrier Frequency}\]

Receiver Efficiency (photons / bit)
The channel capacity, $C$, for an AWGN channel with bandwidth, $W$, received power, $P_R$, and noise variance $N_0/2$ is:

$$C = W \log_2 \left( 1 + \frac{P_R}{N_0 W} \right) \text{ [bits / s]}$$

For reliable data transfer, the data rate, $R$, over a channel must be less than $C$:

$$R < W \log_2 \left( 1 + \frac{E_b R}{N_0 W} \right)$$

\[\Rightarrow \frac{E_b}{N_0} > \frac{R}{2^W - 1}\]

Power Efficiency \quad Bandwidth Efficiency = \frac{R}{W}

\text{Bandwidth Efficiency} = \frac{\text{Data Rate}}{\text{Channel Bandwidth}}$

\text{AWGN} = \text{Additive White Gaussian Noise}
Shannon Capacity for AWGN Channel

Error-Free Communications Possible

Error-Free Communications Not Possible
Shannon Capacity for AWGN Channel

\[ \text{Power Efficiency (Minimum } E_b/N_0 \text{ dB)} \]

Limit of -1.6 dB for large bandwidth expansion

*BW Expansion = 1 / BW Efficiency*
Optical Comm Efficiency

SNR limited by shot noise, expressed as photons per bit

There exist coding and modulation techniques that can operate arbitrarily close to Shannon limit
Pulse Position Modulation (PPM)

**Source Data**

| 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |

**PPM Symbols**

10
12
3

**PPM Waveform**

- In the absence of background, single photon detection provides $\log_2 M$ bits of information.
- For single-photon detector, pulse detection probability is

$$1 - \exp\left(-\frac{P_R M}{h \nu W}\right)$$
Background-free photon-counting PPM channel capacity is

\[ C = \left[ \frac{W}{M} \right] \left[ 1 - \exp\left( - \frac{P_R M}{h \nu W} \right) \right] \log_2 M \quad \text{[bits / second]} \]

Constraint for photon efficiency \( \eta \equiv \frac{P_R}{h \nu R} \) as a function of bandwidth expansion \( \beta \equiv \frac{W}{R} \) is

\[ \eta > - \frac{\beta}{M} \ln \left( 1 - \frac{M}{\beta \log_2 M} \right) \]
Optical Comm Efficiency

Coherent Receivers
- Excellent efficiency
- Wide bandwidth
- Single spatio-temporal mode

Often used for
- High data rate
- Near Earth
- Space-to-Space

Photon Counting Receiver
- Excellent Efficiency
- Bandwidth Constraints
- Can be multi-mode

Often used for
- Low data rate
- Deep space
- Atmospheric links
Downlink Optical Transmitter

LLCD Space terminal modem functions

- **40-620 Mbps downlink**
  - ½-rate FEC encode
  - 16PPM modulator
  - 0.5-W Erbium-doped fiber amplifier
- **10-20 Mbps uplink receiver**

EDFA = Erbium-Doped Fiber Amplifier

\[ M=2 \]

\[ M=4 \]

\[ M=8 \]
Lunar Lasercom Ground Terminal

**Novel Transportable Design**
- Single gimbal
- Four 16-inch receive telescopes
- Four 6-inch transmit telescopes
- All fiber-coupled
- Air-conditioned globe for optics
- Clamshell dome for weather protection

- Shipping container houses modem, computers, office
- Developed at MITLL, transported to White Sands NASA site for operations
LLCD Photon Counting Detectors

*NbN Superconducting Nanowire Arrays*

- **High detection efficiency** >70%
- **Fast reset time** < 10 ns
- **Low timing jitter** < 40 ps
- **Extremely low noise**

Interleaving multiple detectors results in shorter equivalent reset time.

- **NbN nanowire on SiO₂ patterned in “meander” shape**
  - 14 µm diameter
  - 80 nm width, 4 nm thick

- **PM multi-mode fiber**

- **Measured Timing Jitter**
  - FWHM < 40 ps
  - Receiver achieves ~ 2 bits per detected photon
Measured Performance of LLCD Primary Receiver

Measured Performance of LLCD Primary Receiver

<table>
<thead>
<tr>
<th>Data Rate, Mb/s</th>
<th>*Sensitivity, photons/bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>1.49</td>
</tr>
<tr>
<td>77</td>
<td>1.52</td>
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<tr>
<td>155</td>
<td>1.68</td>
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<tr>
<td>311</td>
<td>1.93</td>
</tr>
<tr>
<td>622</td>
<td>3.48</td>
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</tbody>
</table>

*Sensitivity measures detection efficiency of photons in the fiber
Summary

• Operational near-Earth optical communications systems are being deployed today
  – European Data Relay System

• Optical comm for can enable high data volume delivery from deep space
  – Because of the large transmission distances, alternatives to optical tracking for beam stabilization must be employed
    • Passive isolation
    • Inertial references
    • Celestial sources
  – In some cases, photon-counting optical comm can outperform traditional coherent receiver performance
    • Coherent receivers are typically useful for high-rate / near-Earth links
    • Photon-counting receivers can be useful for medium- to low-rate / deep space links