Long-Haul Atmospheric Laser Communication Systems§

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Abstract: Optical communications provides an attractive means of achieving wideband data transfer over long distances. We review perceived challenges and enabling technology developments that promise to facilitate a new era of free-space laser communications.

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1. Introduction

The substantial benefits of free-space laser communications have been well known to system designers for quite some time, c.f. [1]. The free-space channel, similar to the fiber channel, provides many benefits at optical frequencies compared to RF including extremely wide unregulated bandwidth and tightly confined beams (i.e. narrow beam divergence), both of which enable low size, weight and power (SWaP) terminals. In addition, light propagating through the free-space channel does not suffer from well-known fiber-channel detriments such as chromatic dispersion, polarization-mode dispersion and nonlinear interactions. However, significant challenges are still perceived: stochastic intensity fluctuations in a received optical signal after propagating through the atmosphere, power-starved link mode of operation, and narrow transmit beams that must be precisely pointed and tracked.

Since the late 1970’s the United States [2], Europe [3] and Japan [4] have actively been developing lasercom technology motivated primarily for long-haul spaceborne communication systems. While early efforts were focused on maturing lasercom technology, the past decade has seen significant progress toward demonstrating the practicality of lasercom for multiple applications. The first high-rate demonstration of lasercom between a satellite in Geosynchronous (GEO) orbit and the ground was achieved by the US during the GeoLITE experiment in 2001 [5]. A short time later, the European Space Agency (ESA) demonstrated a 50-Mbps lasercom link operating at 800-850-nm wavelengths between their Artemis GEO satellite and: i) another ESA spacecraft in Low-Earth orbit (LEO) in 2001 [6]; ii) a ground station located in Tenerife, Spain in 2001 [7]; and iii) an airplane flying at altitudes as low as 6,000 meters outfitted with a lasercom terminal developed by France’s Astrium EADS in 2006 [8]. These demonstrations also included successful international interoperability for a GEO-to-LEO link between the ESA’s Artemis GEO spacecraft and a LEO spacecraft with a lasercom terminal developed and launched by the Japan Aerospace Exploration Agency (JAXA) in 2005 [9].

These early demonstrations provided a basis for even more challenging lasercom ‘proof-of-concept’ demonstrations being undertaken today. In 2008, Germany’s Tesat successfully established a 5.6 Gbps coherent lasercom link operating at 1064 nm between two fast-moving German and US LEO satellites [10]. In the US, the unique missions planned by the National Aeronautics and Space Administration (NASA) have resulted in some of the most challenging communication requirements for which lasercom technology is being developed, c.f. [11],[12]. For the extreme link ranges required for NASA’s deep-space missions, optical beam pointing, acquisition and tracking (PAT) and high-sensitivity receiver requirements are particularly challenging. Also in the US, high-bandwidth readout from airborne sensor platforms requires a lasercom link to be established from an aircraft to a ground site through extremely challenging (i.e. nearly horizontal path) atmospheric channels [13].

Previous papers have described the general challenges associated with free-space lasercom systems, c.f. [14]. In this paper, we review these challenges and describe free-space lasercom technologies developed by MIT Lincoln Laboratory that enable practical mitigation of atmospheric fading, transmitters and receivers that efficiently deliver and detect an optical signal, and stable beam pointing and tracking.

2. Atmospheric Fading Mitigation

For an optical signal propagating through the Earth’s atmosphere, light collected at a receiver is impacted by multiple physical effects including slowly-varying loss due to absorption or scattering and fast-varying intensity fluctuations due to atmospheric turbulence. This latter effect is caused by inhomogeneities in the temperature and pressure of the atmosphere that lead to variations of the refractive index along the transmission path. These fluctuations produce optical path differences over the beam cross-section that can be a significant fraction of an optical wavelength. The resulting phase aberrations diffract to become intensity fluctuations, known as scintillation,

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in the far field [15]. A point receiver in the far field will see time varying irradiance that can vary as surges of several dB and fades of several 10's of dB [13]. If fading mitigation technology is not included in the design of a lasercom terminal, scintillation on the received signal has been experimentally observed to result in failure of the tracking loop and/or communication link [16].

Various techniques have been developed for mitigating the impact of atmospheric fading. Optical techniques for reducing fade depths seen at the receiver include spatial diversity (i.e. multiple transmit or receive terminals spatially separated by more than the atmospheric coherence diameter) [13], adaptive optics for near-field receiver wave-front phase correction [17], and straightforward link margin via excess transmitter power [18]. Electronic techniques for mitigating the impact of scintillation at the receiver include temporal diversity implemented via channel interleaving and forward error correction [11]-[13],[19]. The lasercom terminal subsystems related to the atmospheric mitigation approaches described here are highlighted pink in Figure 1.

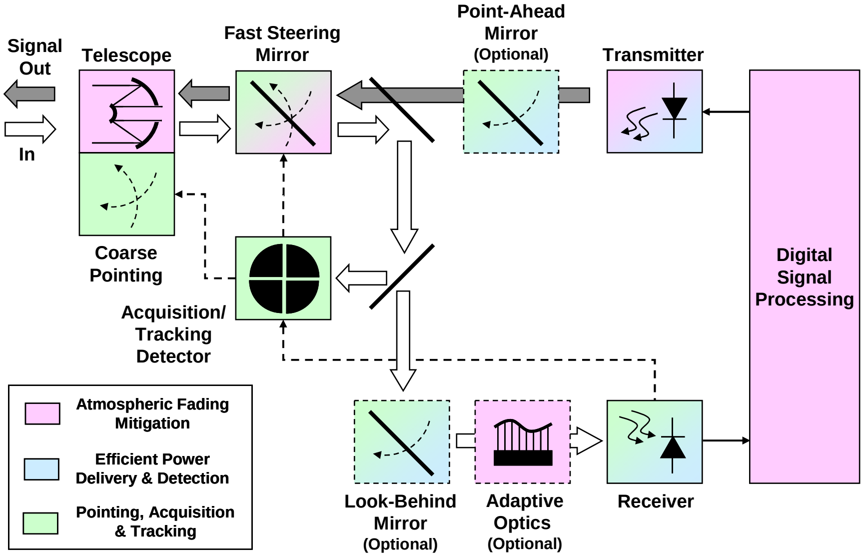

Figure 1 – Lasercom terminal functional block diagram with subsystem utility identified for achieving: atmospheric mitigation; efficient power delivery & detection; and pointing, acquisition & tracking.

3. Efficient Power Delivery & Detection

Since in-line amplification is impractical in free-space applications, long-haul lasercom links are generally operated in a power-starved mode which requires the transmitter (Tx) to efficiently deliver optical signal photons to a receiver (Rx) that operates using as few incident photons as possible. A practical approach to implementing Tx and Rx technologies can be achieved via a careful selection of modulation format and forward error correction code rate for specific channel characteristics as governed by Shannon capacity analysis [20]. Operation near theoretical limits, combined with the use of efficient Tx and Rx technologies can enable lower SWaP terminals with improved performance, simpler platform integration and reduced PAT constraints [13]. The lasercom terminal subsystems related to the efficient photon delivery and detection described here are highlighted blue in Figure 1.

A wide variety of Tx/Rx modem architectures can be considered for lasercom applications. Pre-amplified direct-detection modems benefit from a robust fiber telecom component base; have demonstrated lasercom heritage for long-haul applications, c.f. [6],[13]; and have demonstrated performance near theoretical capacity limits [21]. While coherent modems theoretically provide the highest sensitivity for bandwidth constrained modulation formats [22], photon-counting technologies combined with M-ary orthogonal modulation formats have been theoretically and experimentally shown to achieve superior detection efficiencies [23],[24] and will be deployed in the near term as the ground receiver for the Lunar Laser Communications Demonstration [12].

4. Pointing, Acquisition & Tracking

Narrow beam divergence at optical frequencies enables high-directivity low-SWaP lasercom terminals. However, narrow beams require precise open-loop pointing for reliable acquisition and active tracking to reduce pointing jitter to a fraction of a beamwidth. Often, a communications link is established between two lasercom terminals via the following PAT process: i) Terminal 1 scans a broadened beacon toward Terminal 2; ii) Terminal 2 detects light from Terminal 1 on its acquisition sensor and directs a narrow communication beam to Terminal 1; iii) Terminal 1 detects the narrow beam from Terminal 2, hands-over to active tracking and directs its narrow communication beam to Terminal 2; iv) after illumination by the narrow beam from Terminal 1, Terminal 2 hands-over to active tracking and communication begins [25]. During this process, pointing errors are caused by imprecise knowledge of Tx terminal orientation and position and the initial position of the Rx terminal. Tracking errors are caused by residual loop error (i.e. noise equivalent angle) and uncorrected line-of-sight jitter.

In order to achieve a robust PAT system, long-haul lasercom terminals are typically designed with multiple control loops that work together to provide stable beam pointing and precision tracking, c.f. [26]. Various technologies have been developed to enable stable pointing, e.g. passive vibration isolators [27], and precision active tracking, e.g. fast steering mirrors [28], fiber nutators [29] and inertial-stabilization [26]. The lasercom terminal subsystems related to PAT described here are highlighted green in Figure 1.

5. Conclusion

Historically, significant barriers were perceived for long-haul lasercom systems related to atmospheric fading, power-starved communications and narrow beam pointing and tracking. Today, many of the critical technologies required for robust lasercom terminals have been developed and tested in various field demonstrations, making a new era of wideband free-space communications over ultra-long distances possible.

6. References

[1] R. F. Whitmer, *et al.*, "Ultra-Wide Bandwidth Laser Communications: Part I-System Considerations for a Satellite Link," *Proc. IEEE*, vol. 58, pp. 1710-1714, Oct. 1970.

[2] G. A. Koepf, *et al.*, "Space Laser Communications: A Review of Major Programs in the United States," *Intl. J. Electon. Commun.*, vol. 56, pp. 232-242, 2002.

[3] Z. Sodnik, *et al.*, "Optical Satellite Communications in Europe," *Proc. of SPIE*, vol. 7587, pp. 758705-1:9, 2010.

[4] M. Toyoshima, *et al.*, "Free-Space Laser Communications: The Japanese Experience," *in ECOC 2009*, paper 10.6.2, 2009.

[5] http://www.nro.gov/PressReleases/prs_rel49.html

[6] T. T. Nielsen, *et al.*, "In-Orbit Test Result of an Intersatellite Link Between ARTEMIS and SPOT4, SILEX," *Proc. of SPIE*, vol. 4635, pp. 1-15, 2002.

[7] M. Reyes, *et al.*, "Preliminary Results of the In-Orbit Tests of ARTEMIS with the Optical Ground Station," *Proc. of SPIE*, vol. 4635, pp. 38-49, 2002.

[8] http://www.esa.int/esaTE/SEMN6HQJNVE_index_0.html

[9] T. Jono, *et al.*, "OICETS On-Orbit Laser Communication Experiments," *Proc. of SPIE*, vol. 6105, pp. 13-23, 2006.

[10] B. Smutny, *et al.*, "5.6 Gbps Optical Intersatellite Communication Link," *Proc. of SPIE*, vol. 7199, pp. 719906-1:8, 2009.

[11] D. M. Boroson, *et al.*, "MLCD: Overview of NASA's Mars Laser Communications Demonstration System" *Proc. of SPIE*, vol. 5338, pp. 16-28, 2004.

[12] D. M. Boroson, *et al.*, "The Lunar Laser Communication Demonstration (LLCD)," *in Third IEEE Intl. Conf. on Space Mission Challenges for Info. Technol.*, pp 23-28, 2009.

[13] F. G. Walther, *et al.*, "Air-to-Ground Lasercom System Demonstration Design Overview and Results Summary," *Proc. of SPIE*, vol. 7814, pp. 78140Y-1:9, 2010.

[14] P. Winzer, *et al.*, "Spaceborne Optical Communications - A Challenging Reality," *in Proc. LEOS*, pp. 393-394, 2002.

[15] L. C. Andrews and R. J. Phillips, *Laser Beam Propagation through Random Media*, 2nd Edition ed.: SPIE Press, 2005.

[16] R. Lange, *et al.*, "142 km, 5.625 Gbps Free - Space Optical Link Based on Homodyne BPSK Modulation," *Proc. of SPIE*, vol. 6105, pp. 6105A-1:9, 2006.

[17] B. M. Lavigne, *et al.*, "Horizontal Line-of-Sight Turbulence Over Near-Ground Paths and Implications for Adaptive Optics Corrections in Laser Communications," *Appl. Opt.*, vol. 37, pp. 4553-4560, 1998.

[18] M. Toyoshima, *et al.*, "Long-Term Statistics of Laser Beam Propagation in an Optical Ground-to-Geostationary Satellite Communications Link," *IEEE Trans. Antennas and Propag.*, vol. 53, pp. 842-850, 2005.

[19] G. D. Forney, Jr., "Burst-Correcting Codes for the Classic Bursty Channel," *IEEE Trans Commun. Technol.*, vol. COM-19, pp. 772-781, 1971.

[20] D. M. Boroson, "A Survey of Technology-Driven Capacity Limits for Free-Space Laser Communications," *Proc. of SPIE*, vol. 6709, pp. 670918-1:19, 2007.

[21] D. O. Caplan, *et al.*, "Ultra-Wide-Range Multi-Rate DPSK Laser Communications," *in Proc. CLEO 2010*, paper CPDA8, 2010.

[22] M. L. Stevens, *et al.*, "Optical Homodyne PSK Demonstration of 1.5 Photons per Bit at 156 Mbps with Rate-1/2 Turbo Coding," *Opt Express*, pp. 10412-10420, 2008.

[23] B. S. Robinson , *et al.*, "1.5-photons/bit Photon-Counting Optical Communications Using Geiger-Mode Avalanche Photodiodes," *in 2005 Digest of the LEOS Summer Topicals*, paper TuA3.1, 2005.

[24] E. A. Dauler, *et al.*, "1.25-Gbit/s Photon-Counting Optical Communications Using a Two-Element Superconducting Nanowire Single Photon Detector," *Proc. of SPIE*, vol. 6372, pp. 637212-1:8, 2006.

[25] I. M. Teplyakov, "Acquisition and Tracking Laser Beams in Space Communications," *Acta Astronautica*, vol. 7, pp. 341-355, 1980.

[26] J. W. Burnside, *et al.*, "A Hybrid Stabilization Approach for Deep-Space Optical Communication Terminals," *Proc. IEEE*, vol. 95, pp. 2070-2081, 2007.

[27] J. Boyd, *et al.*, "Performance of a Launch and On Orbit Isolator," *Proc. of SPIE*, vol. 4327, pp. 433-440, 2001.

[28] G. C. Loney, "Design of a High-Bandwidth Steering Mirror for Space-Based Optical Communications," *Proc. of SPIE*, vol. 1543, pp. 225-235, 1991.

[29] T. E. Knibbe, *et al.*, "Spatial Tracking Using an Electro-Optic Nutator and a Single-Mode Optical Fiber," *Proc. of SPIE*, vol. 1635, pp. 309-317, 1992.