Development and Demonstration of Laser Communications Systems

David W. Young, Hugh H. Hurt, Joseph E. Sluz, and Juan C. Juarez

ABSTRACT

Free-space optical communications, or laser communications (lasercom), offer a compelling alternative to conventional RF and microwave communications, providing substantially increased data throughput, relief from complex RF spectrum planning and congestion, and improvements in link security. Focusing on the development and demonstration of terrestrial lasercom systems at the Johns Hopkins University Applied Physics Laboratory (APL), this article discusses critical technology development, inspired by information gleaned from field tests of the lasercom systems. The terrestrial lasercom development path has progressed from initial experiments in the lab through complex system-of-systems field demonstrations of multinode airborne hybrid lasercom/RF networks. Field demonstrations of extended-range (>100 miles) air-to-air and air-to-ground communications links and their extensions to the development of networks are discussed.

INTRODUCTION

Research in laser communications (lasercom) has been ongoing for more than 40 years. Significant early efforts in defense lasercom include the Air Force "405B" program in 1972[1] and other efforts at the Air Force Research Laboratory (AFRL).[2] Initial systems were limited by the early development level of the subsystem components used—these systems often had limited operational range or were too heavy for use on most airborne platforms. Lasercom development has seen extensive growth in the past decade, enabled by the availability of robust systems components developed for the optical fiber communications field. Historically, intelligence, surveillance, and reconnaissance applications have driven the requirements for lasercom links because these applications require that large quantities of image or video data be passed from a sensor, typically on an airborne platform, to a location where the information can be exploited. There has been increased interest in the ability of lasercom links to operate in congested or even denied RF environments, not necessarily at the multigigabit-per-second rates that have been demonstrated but in support of communications links that have very low probability of intercept/detection and are jam resistant.

Terrestrial lasercom links, defined as aircraft-to-aircraft, aircraft-to-ground, and ground-to-ground links, have unique performance characteristics compared with most communications links. Atmospheric path attenuation needs to be taken into account; however, clear air attenuation in the 1550-nm band can be quite low (~0.02 dB/km at 20°C, 7.5 g/m^3 water vapor density). This level of atmospheric attenuation is comparable to X-band (10-GHz) path attenuation and is nearly an order of magnitude lower than millimeter-wave systems operating in the atmospheric window at 94 GHz.

Terrestrial lasercom does have limitations when propagating through the atmosphere. Scintillation, beam spread, and beam wander due to atmospheric turbulence are clear-air system penalties. Scattering of the optical beam because of rain is similar to the path absorption in the millimeter-wave region. From a path-attenuation perspective, the major limitations to lasercom links are clouds and fog, which can cause path losses exceeding 100 dB/km. These losses are primarily due to scattering by the water droplets.

As lasercom technologies matured and lasercom link ranges greater than 100 km were demonstrated,[3] it was realized[4] that a hybrid approach was necessary, pairing lasercom with high-bandwidth directional RF systems to enable a long-range, all-weather communications capability. In general, operation of these hybrid links at extended ranges (>100 km) leads to selection of RF carrier frequencies that cannot support high data rates because of component limitations, general link budget considerations, or availability of RF spectrum. The differences in bandwidth between the lasercom and RF systems can be addressed with ad hoc networking techniques that use link diversity as well as quality-of-service markings on the data packets. A recent successful demonstration of multinode hybrid lasercom/RF networks[5] proved that dynamic, reconfigurable mobile ad hoc networks could be used to provide high-availability, high-bandwidth communications even when weather or terrain blockages were a concern.

This article describes technology developments and demonstrations by Johns Hopkins University Applied Physics Laboratory (APL) researchers and their collaborators in the area of terrestrial lasercom systems development and demonstration. The developments described have rapidly driven this technology from short-range, point-to-point links to multimode, self-configuring hybrid lasercom/RF airborne networks capable of providing 10 Gbps of bandwidth over ranges greater than 200 km.[5] The article also discusses current technical challenges with lasercom and ongoing internally sponsored work to help meet some of these challenges.

BACKGROUND

Lasercom, which uses modulated lasers to carry information, has been developed and demonstrated to support both commercial and DoD needs. The ability to provide a communications link without spectrum planning or licensing and at high data rates—effectively providing a fiber-optic-like communications capability without the cost and complexity of running optical fiber—has long been a driver for the lasercom community.

Commercial lasercom systems are available from many manufacturers, but they do not typically address DoD needs, specifically in terms of system mobility, link range, and data rate. DoD applications for terrestrial lasercom include direct download of sensors that require high data throughputs, extended-range (>100 miles) airborne communications links in support of multihop communications backhaul, and communications with low probabilities of being intercepted and jammed.

In terms of data rate, lasercom data rates approaching 100 Gbps have been demonstrated[6] over short ranges from airborne platforms. A data rate of 10 Gbps has been demonstrated in the field multiple times for long-distance applications, in both air-to-ground and air-to-air configurations;[5] this rate aligns well with the 10-Gbps OC-192 standard used by the Global Information Grid. Data rates can be scaled up using wavelength division multiplexing techniques,[3,7] which allow a single link to scale up capacity via the use of multiple wavelengths, each carrying unique data streams.

There has been recent interest in the use of lasercom for command and control in a denied or degraded envi-

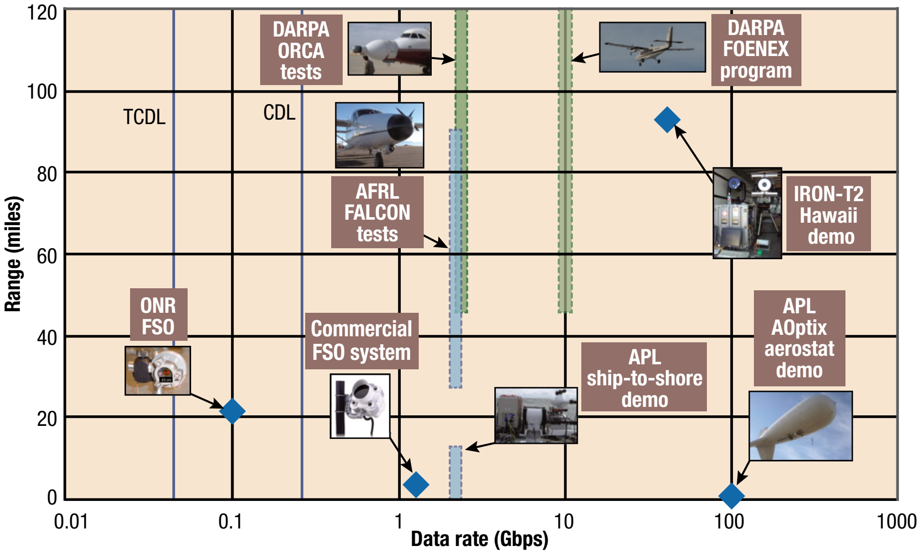


Figure 1. Examples of lasercom link data rates versus link ranges. The diamonds indicate system capabilities/demonstrations where the ranges were fixed, and the vertical bars show the testing done over variable range to airborne platforms. FALCON, Force Application and Launch from CONtinental United States; FOENEX, Free space Optical Experimental Network Experiment; FSO, free-space optical; ONR, Office of Naval Research; TCDL, tactical CDL.

ronment, specifically for applications where RF links are unavailable because of jamming or where a communications link with a low probability of detection is desired. This application has more modest data rate requirements and more modest range requirements, with the trade-off being that the links must propagate near the surface in both land and maritime regimes.

Tactically significant link ranges have been demonstrated from both fixed sites[3,8] and mobile platforms.[4,5,9,10] Figure 1 shows the range versus data rate for terrestrial lasercom programs that APL has participated in as well some reference points to traditional high-rate directional RF communications systems (common data link, or CDL) and other lasercom systems demonstrated by government labs and commercial operators. The diamonds indicate tests with fixed test systems, and the vertical bars indicate systems on airborne platforms where the ranges varied during the test.

BASIS OF TECHNOLOGY DEVELOPMENT—LASERCOM FIELD TESTS

The basis of technology development for the lasercom efforts at APL has always been closely linked to experimental observations made during field tests. The goal of each test was to drive the technology and systems concepts and developments closer to a communications solution that can be provided to the warfighter.

The basis of lasercom development at APL can be traced to an independent research and development (IR&D)-supported field test in 2005.[6] During this test, a lasercom link was closed between a ground vehicle and an aerostat (Fig. 2).

APL was responsible for the experiment design and execution, as well as building the optical modems that provided the interface between the test equipment and the lasercom terminals. A commercial vendor, AOptix Technologies, was contracted to provide the adaptive optic lasercom terminals as well the basic pointing and tracking function. A number of novel concepts were demonstrated during this test: first, the use of a lasercom link for providing communications from an aerostat to a ground station, which provided the basis for use of lasercom links from an unmanned aerial vehicle. The second was the use of wavelength division multiplexing in a lasercom field test. The use of multiple concurrent wavelengths, each with a unique data stream, is common with fiber optic communications systems. This approach was heavily leveraged during this test, with as many as six unique multigigabits-per-second communications channels operating over the lasercom link. During this test it was noted that even though adaptive optics correction of the received optical beam was performed, there was still substantial variation in the received power over short time frames—excursions approaching 20 dB in the millisecond time scale were noted even with a short (1.5 km) link. This made setting the optical power level into the receiver difficult—optical receivers can saturate, or even suffer damage, at low (5–10 mW) optical power levels; this leads to the desire to attenuate the input power to avoid these effects. This approach has an inherent flaw in that the signal not only surged in intensity but also faded, leading to high bit error rates at low received powers. On the basis of this experimental observation, it was clear that some form of high-bandwidth (atmospheric scintillation can produce power variations up to 1 kHz), high-dynamic-range (peak-to-trough power variations of 50 dB have been observed) optical power control was necessary to have a robust lasercom link.

The link ranges tested during the aerostat experiment were limited because the focus of the test was high communications data rates and tracking of a moving airborne target. The next logical step was testing at ranges more typical of those used for high-data-rate (>100 Mbps) RF links. In 2006, under IR&D support and partnering again with AOptix Technologies, APL demonstrated a 147-km lasercom link[3] between Maui and the Big Island in Hawaii. This was a significant step forward in link

Figure 2. Lasercom link between a ground station and an aerostat.

range; however, it was a step backward in link reliability because there were optical receiver failures caused by uncontrolled link power variations as well as significant link data loss due to atmospheric fades. The observed variations in received power reinforced the need identified during the aerostat test for developing a method for dealing with variability in the received power from the optical link before detection of the signal.

Based on these lessons learned, the development of an optical automatic gain control[11] system, specifically to dynamically normalize the received optical power from a fading channel, was undertaken under IR&D support; see the *Technology Development Efforts* section of this article for additional details. The first opportunity to field this technology came with the AFRL Integrated RF/Optical Networked Tactical Targeting (IRON-T2) program. Under this program, APL developed optical modem technology that provided the interface between a hybrid router (capable of supporting concurrent lasercom and RF links) developed by L-3 Communications and a free-space optical (FSO) terminal developed by AOptix Technologies. The goal of this program was to increase the reliability of the lasercom link through the use of lasercom-specific optical modem technologies and the first hybrid lasercom/RF link using lost packet retransmission systems. This was the first demonstration of the "layered defense" method of providing a robust communications link—using a combination of hybridized links, robust optical modem architectures, and packet retransmission methods. The integration and testing of these systems was completed in 2007, with a successful demonstration performed over the 147-km test link in Hawaii. Follow-on testing in 2008 demonstrated the use of forward error correction (FEC) codes over the lasercom link for the first time; the system tested provided 8 dB of additional receiver sensitivity for the 10-Gbps test channel. Other advancements, such as reducing the aperture diameter of the lasercom terminal from 8 to 4 in., proved that compact lasercom terminals could support long-range operation. The 2007 and 2008 tests provided experimental proof that hybrid lasercom/RF systems were a viable approach for providing high-availability communications links through all weather and atmospheric conditions.

The Defense Advanced Research Projects Agency (DARPA) Optical/RF Combined Adjunct (ORCA) program,[4] which was demonstrated in the field in 2009, sought to take the technologies demonstrated over long fixed-site links in 2007 and 2008 and demonstrate them in an aircraft-to-ground link. The program goals were to increase the data rate of the optical link from 3.125 to 10 Gbps as well as develop and demonstrate the core technologies required for airborne hybrid lasercom/RF networks. Northrop Grumman Corporation was selected as the systems integrator for this task. APL, directly funded by DARPA, provided systems engineering and integration experience, as well as the next generation of optical modems capable of supporting hybrid lasercom links at the higher data rate. The system was flight tested at the National Test and Training Range in Tonopah, Nevada. The aircraft is shown in Fig. 3.

Figure 3. DARPA ORCA test aircraft. The lasercom terminal is at the tip of the aircraft nose.

TECHNOLOGY DEVELOPMENT EFFORTS

Optical Automatic Gain Control Systems

One of the fundamental enabling technologies developed under APL's lasercom efforts was the optical automatic gain control (OAGC) system. This technology was developed in response to experimental results from the 2005 aerostat tests and 2006 Hawaii tests. It was noted during these tests that the received optical power measured after the adaptive optical receiver telescope exhibited large power variations. The first generation of the OAGC, developed under IR&D,[11] was capable of providing a constant output power (power out of fiber, or POF) to an optical receiver. This eliminated the problems with optical detector saturation and damage while concurrently providing low-noise optical amplification of the received optical signal. Figure 4 shows a typical received signal from an adaptive optics lasercom terminal (power in fiber, or PIF); in this case, the peak-to-fade variation is 45 dB over the 1-s sample shown. The target output power of the OAGC (POF) was set to –5 dBm and maintained at this level to within 1 dB. The data shown in Fig. 4 were collected on a lasercom link from an aircraft to a ground station during the DARPA ORCA tests;[4] the lasercom link distance was 183 km.

This system has been continuously developed, with improvements in size, weight, and power, as well as reduction in the OAGC noise figure.[12] These systems were successfully field tested during the DARPA Free space Optical Experimental Network Experiment (FOENEX) program.

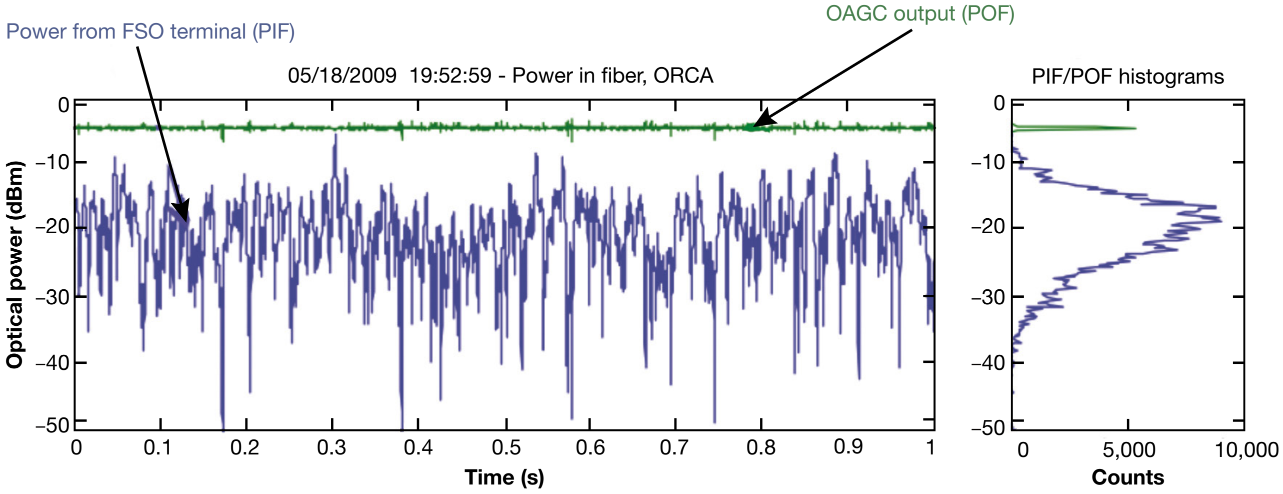


Figure 4. Sample of FSO link data showing the ability of the OAGC to equalize received optical power.

Optical Modem Development

It has been found during multiple field tests that connecting end-user communications or test equipment to lasercom links using COTS optical transceivers creates a poorly performing data link. COTS transceivers do not provide adequate transmitter extinction ratios or receiver sensitivities, even with the use of an OAGC, to form a robust link. To help address that technology gap, APL has been continuously developing new optical modem technologies, with the foremost goal of decreasing the amount of optical power required at the receiver to produce an error-free link. Concentrating on receiver sensitivity is a critical point—transmit power for lasercom has practical limits due to eye safety issues, so simply increasing transmit power is not a viable solution. During the aerostat testing, simple on–off keyed (OOK) using non-return-to-zero (NRZ) coding was used. At the 10-Gbps data rate, the receiver architecture was error free at received powers of –26 dBm; this receiver sensitivity level was similar during the first test in Hawaii. The optical modem architecture was modified for the DARPA ORCA program such that the receiver was customized to allow optimization of the decision thresholding. FEC coding was also added; an industry standard G.975 I.4 concatenated Reed–Solomon (RS), Bose–Chaudhuri–Hocquenghem (BCH) FEC code was used. These two modifications reduced the error-free received power point to –40 dBm during the ORCA program.

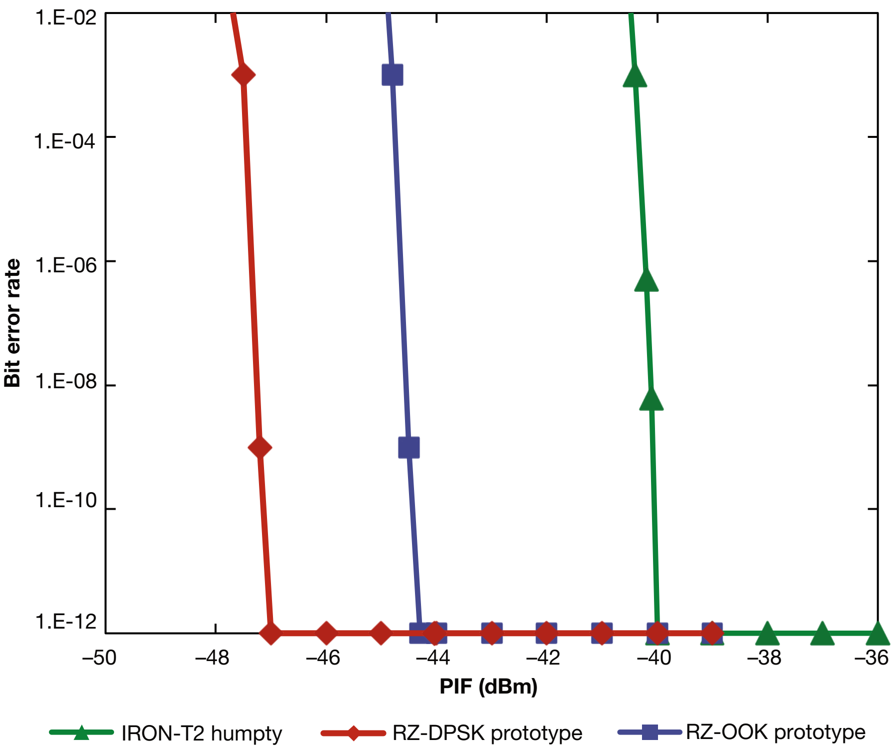


Figure 5. Improvement in receiver sensitivity from the 2007/2008 systems to the second-generation OAGC with RZ-DPSK modulation. FEC is used in all cases.

In 2007, the Air Force asked APL to further research methods to enhance optical receiver sensitivity as well as increase the robustness of lasercom links. Initial research indicated that pulse position modulation (PPM) provided the highest optical receiver sensitivity;

however, PPM is spectrally inefficient—the ratio of the data rate to the electrical bandwidth required is much less than 1 (bit/s)/Hz. PPM also requires very careful clock management because the bit slots used for PPM need to be synchronized between the transmitter and receiver. For lower data rates (<1 Gbps), this method can be successfully used and has demonstrated receiver sensitivities as low as 4 photons/bit.[13] The study found that phase-based modulation, specifically differential phase shift keying (DPSK), provided very good receiver sensitivity while maintaining the same spectral efficiency seen with OOK modulation. This modulation format is similar to binary phase shift keying, except there is no local oscillator used in the receiver. Instead, a demodulator that optically interferes bit n with bit n-1 is used to change from phase-based modulation to OOK.[14] This is effective because the received wavefront only needs to be coherent over the time frame of one bit, which is 0.1 ns at 10-Gbps data rates. The demodulated optical signal is then converted to an electrical bitstream by a differential optical detector. DPSK receivers are 3 dB more sensitive than OOK receivers.[15] Use of a return-to-zero (RZ) amplitude envelope with either DPSK or OOK modulation can add an additional 2 dB of receiver sensitivity. The combination of the OAGC with a RZ-DPSK modulation format, combined with a G.975 I.4 FEC, has been field demonstrated to have a sensitivity (defined at a bit error rate of 10^{-9}) of –47.6 dBm, or 13 photons per bit.[16] The bit error rate curves, which indicate the bit error rate of a communications link as a function of received power, for the first and current generation of 10-Gbps optical modems are shown in Fig. 5.

Regardless of the sensitivity of an optical modem and use of error correction codes, there are times when the fades observed in the link simply provide no usable optical power into the aperture. A method of providing a robust lasercom link is to retransmit the packets that were lost during the fade event. APL established the fundamental architectures and initial demonstration work on packet retransmission systems under AFRL support.[17] This system was specifically designed to support the retransmission of packets lost over a lasercom link (Fig. 6). The system used a circular, or “round-robin,” buffer to hold packets in the transmit buffer until an acknowledgement of packet receipt comes from the receive side. Once the acknowledgement comes through, the buffer space is cleared for the next packet.

This system was implemented in a field programmable gate array; the original system was capable of data rates of 2.5 Gbps. A second implementation was later done at 100 Mbps; this was developed and field-tested under Office of Naval Research support.

Hybrid Lasercom/RF Communications

Lasercom links can provide very large data bandwidth among communication nodes for large distances. However, the difficulties with maintaining long-distance lasercom links in all weather conditions point to the need for a hybridized communication link. To overcome this shortcoming, a more robust and reliable lasercom/

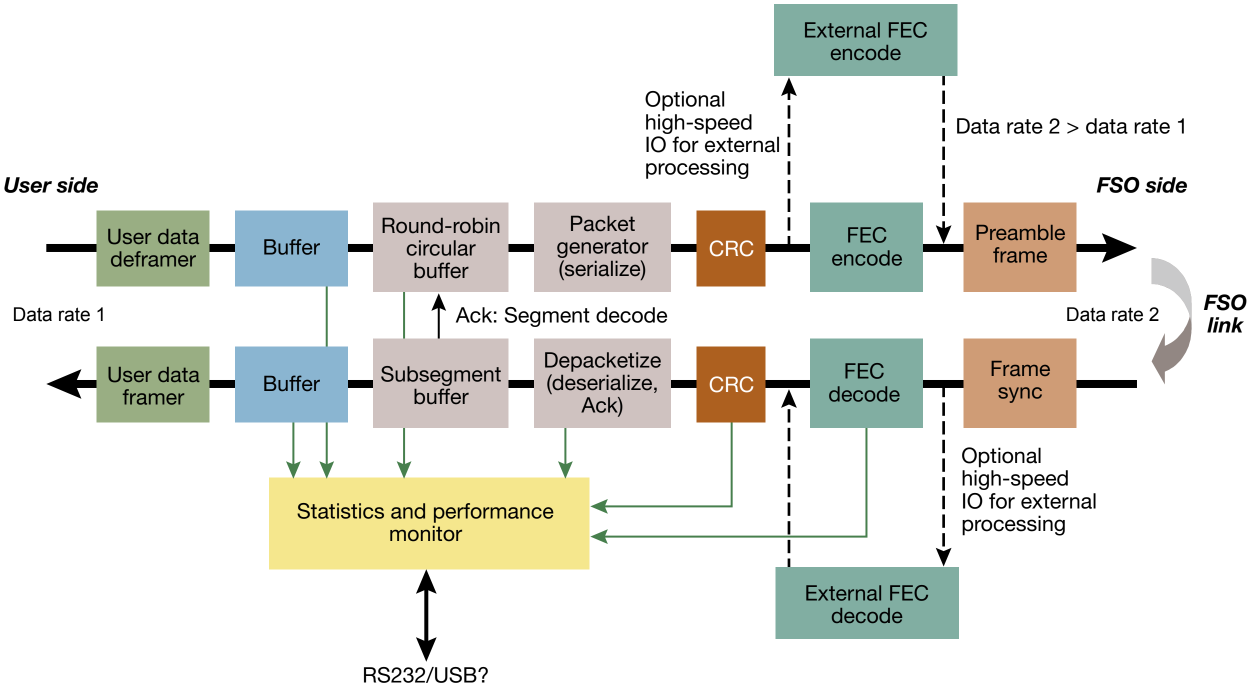


Figure 6. Block diagram for the rateless round-robin packet retransmission system. Ack, acknowledgment; CRC, cyclic redundancy check; IO, input output.

RF hybrid system was developed and tested[4] in partnership with L-3 Communications West and AOptix Technologies. The 2007 test of this system demonstrated the first known hybrid lasercom/RF system fielded over long ranges. The test link, run in Hawaii, was 147 km, from the top of Haleakala on Maui to Mauna Loa on the Big Island. The router, developed by L-3, had the capability to do physical path selection (lasercom or RF), retransmission of lost packets, and prioritization of data via a quality-of-service marking method. The block diagram of the lasercom system tested is shown in Fig. 7. The hybrid router connected to the optical modem through the 1310-nm optical ports. Tunable lasers (TLS) were used to make the system wavelength agile. The polarization was maintained on the transmit side via polarization maintaining (PM) fibers. No effort was made to maintain the state of polarization during transmission through the atmosphere. There are benefits to using polarization from a transmit-to-receive isolation perspective when using single apertures; this system configuration had adequate transmit/receive isolation through the wavelength filtering in the FSO terminal and dense wavelength division multiplexing (DWDM) demultiplexer.

The packet retransmission system, developed by L-3 under AFRL support, was successful in reducing the packet error rate of the lasercom link. Packets were individually numbered and tracked by the routers. When packets were identified as missing, a request for retransmission was made over the RF link. This configuration was an optimal demonstration of hybrid links—the RF link was less susceptible to turbulence and clouds and thus provided a more reliable communications link for requests for packet retransmission. The RF link bandwidth was an order of magnitude less than the lasercom link but had adequate bandwidth to support retransmission requests. This substantially reduced the loss of packets in the lasercom link—the RF system effectively enabled the lasercom link to provide high-availability, high-data-rate communications.

The hybrid link was tested in static 147-km links in Hawaii in 2007 and 2008. The RF link was frequency duplexed to provide bidirectional operation, running in X- and Ku-bands, using a directional antenna. On days when the hybrid link operated close to the atmospheric inversion layer, defined by abrupt changes in the temperature and atmospheric water vapor content, it was

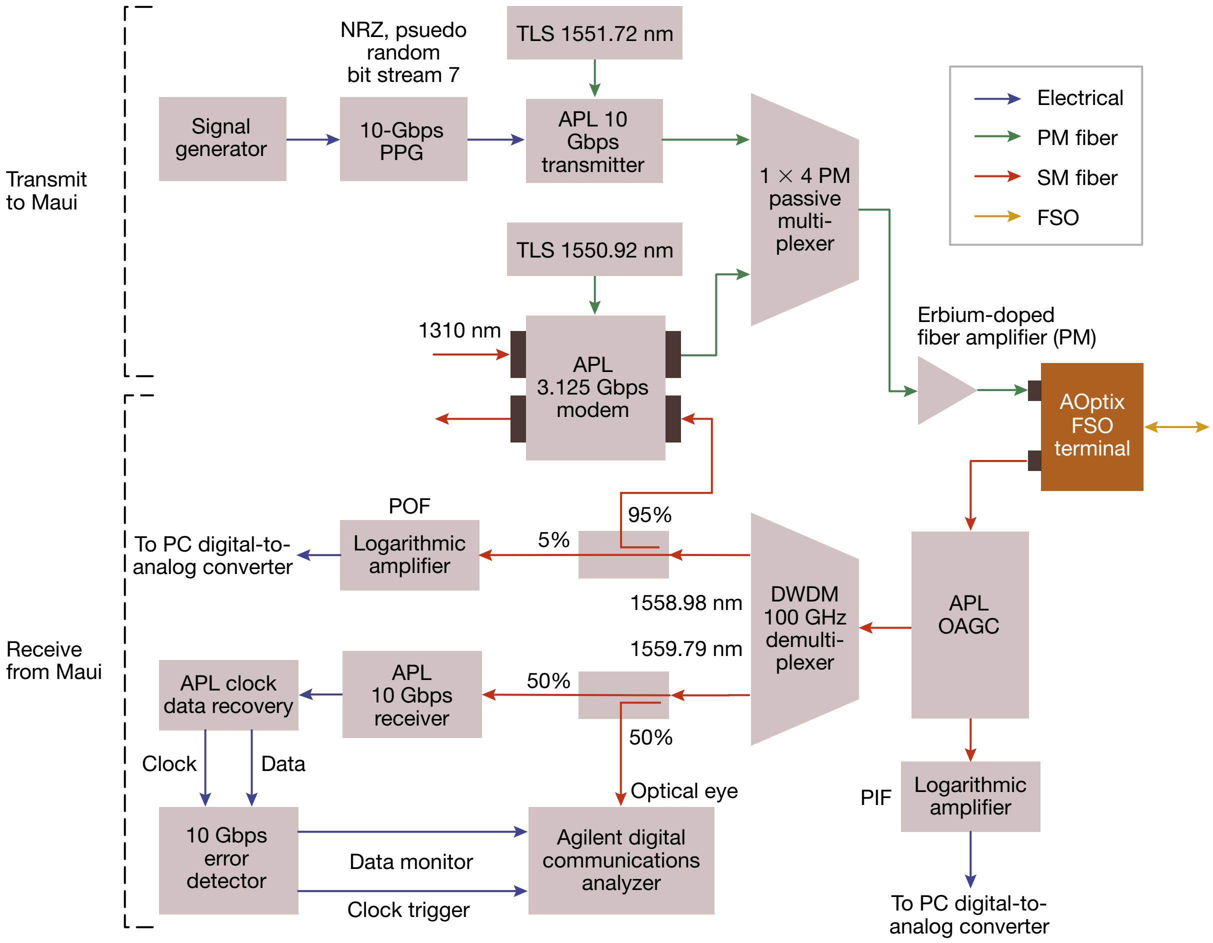


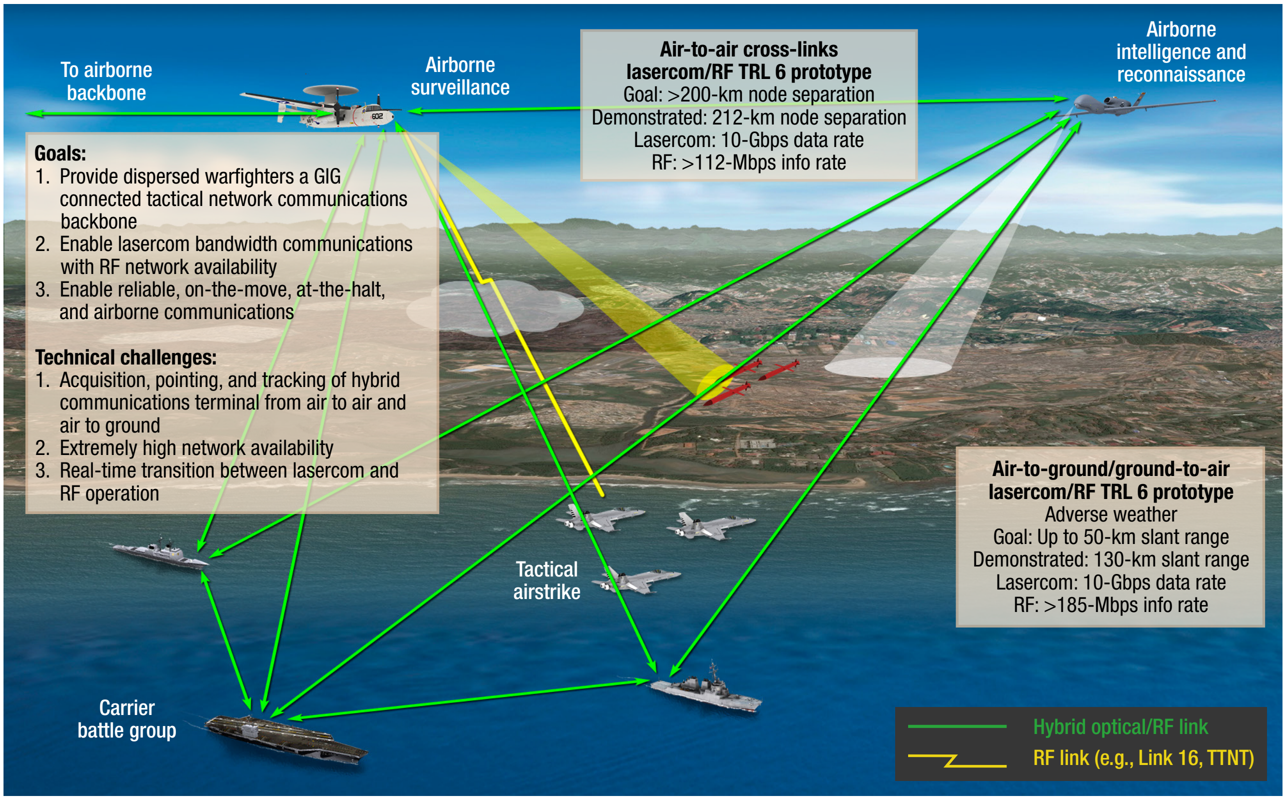
Figure 7. Lasercom optical modem portion of the IRON-T2 hybrid lasercom/RF field-tested system. PPG, pulse pattern generator; SM, single mode.

found that the RF link was impacted by the inversion layer, leading to ducting and multipath problems. This reduction of the RF link availability was conversely not seen with the lasercom link. The complementary nature of lasercom and RF, from a propagation perspective, helped make the resultant communication link more robust than either system alone could provide.

Development of the Hybrid Lasercom/RF Network—FOENEX

Based on performance in the AFRL IRON-T2 and DARPA ORCA programs, APL was selected to be the prime contractor on the DARPA FOENEX program.[5] APL also provided the optical modems and was responsible for technical leadership, systems integration, and test development and management. Program partners were L-3 Communications West and AOptix Technologies. L-3 Communications provided the multirole tactical CDL RF communications systems and developed the network router. AOptix developed the FSO communication terminals used in the aircraft and ground stations. FOENEX, a complex system of systems, was a natural growth of the technologies and methods developed under the point-to-point link tests performed under IRON-T2 and ORCA. The goal of FOENEX was to develop and demonstrate a multinode airborne hybrid FSO/RF communications network. This network included both air-to-air links as well as air-to-ground links. Figure 8 shows an overview of a potential application of the FOENEX system, including the overarching program goals and challenges as well as program targets for data rate and availability (optical and RF) and distances between network nodes.

The FOENEX program was a major step forward in terrestrial lasercom systems development, with a specific target of developing and testing a high-bandwidth communications system that provided robust communications in a dynamic atmospheric and physical environment. The program included the use of technologies shown to be critical for the development of a successful airborne network, specifically the high-sensitivity, high-dynamic-range optical modems; hybrid optical/RF links; lost packet retransmission; and adaptive optic-based lasercom terminals. New in FOENEX was the inclusion of network-level technologies, including deep queuing at the network nodes, link rerouting, and data replay. The network layer of FOENEX was designed to handle outages with durations from milliseconds to multiple seconds. The network router was capable of determining which physical links to close as well as routing the logical paths through the network. This included making decisions on which link to use (lasercom or RF) based on quality-of-service metrics applied to the data as well as predicting the availability of the link with respect to



Goals:
1. Provide dispersed warfighters a GIG connected tactical network communications backbone
2. Enable lasercom bandwidth communications with RF network availability
3. Enable reliable, on-the-move, at-the-halt, and airborne communications

Technical challenges:
1. Acquisition, pointing, and tracking of hybrid communications terminal from air to air and air to ground
2. Extremely high network availability
3. Real-time transition between lasercom and RF operation

Figure 8. FOENEX overview chart. The final program demonstration of the FOENEX network utilized three aircraft and one ground station. GIG, Global Information Grid; TRL, technology readiness level; TTNT, Tactical Targeting Network Technology.

potential platform and/or terrain blockages. The network mesh configuration allowed for data to be routed to/from any points in the network. The network was capable of dynamically reconfiguring as nodes entered and exited the network. The mesh configuration provided overall higher availability of high-bandwidth communications between any two points because the data could transit through other network nodes when direct links were not available. The network could do this without data loss when one link to or from a node was lost.

The system diagram of a FOENEX node is shown in Fig. 9. The main interface to the user was the L-3 XFusion Interface Assembly (XIA)—this was the network router. The XIA provided a 10-Gb Ethernet interface as well as a 1000/100/10 Ethernet interface to the end user. One XIA was capable of supporting two lasercom terminals and two RF terminals concurrently. A hybrid link was formed when a lasercom and RF terminal were available. In the ground system (Fig. 10), there were two lasercom and two RF terminals; thus, two hybridized links were available. The aircraft (Fig. 11) had two lasercom terminals and a single RF terminal; thus, the two available physical links were a hybrid link and a lasercom-only link.

The RF system, which was a production multirole tactical CDL, operated at X- and Ku-bands and had a directional 9-in. dish antenna. The system also had an omnidirectional antenna that was used to provide network discovery information. This was critical for network formation because it provided full state vector information for each aircraft; these data were used to provide initial pointing of the RF and lasercom terminals, which both used highly directional beams.

The FOENEX lasercom terminals used a curvature mode adaptive optics system[18] integrated into a pointer/tracker mount—this system was developed by AOptix Technologies. For the airborne system, an L-3 Wescam MX-15 inertially stabilized gimbal hosted the lasercom terminal. The ground system used a commercial azimuth/elevation pointer/tracker. These systems were selected based on their known ability to form long-distance (>100 km) FSO links in turbulent conditions[3] as well as in flight environments.[18] The FSO systems were able to maintain the pointing accuracy required (<100 microradians) to maintain the lasercom link even during turbulent flight conditions. The implementation of the lasercom terminals in FOENEX was different

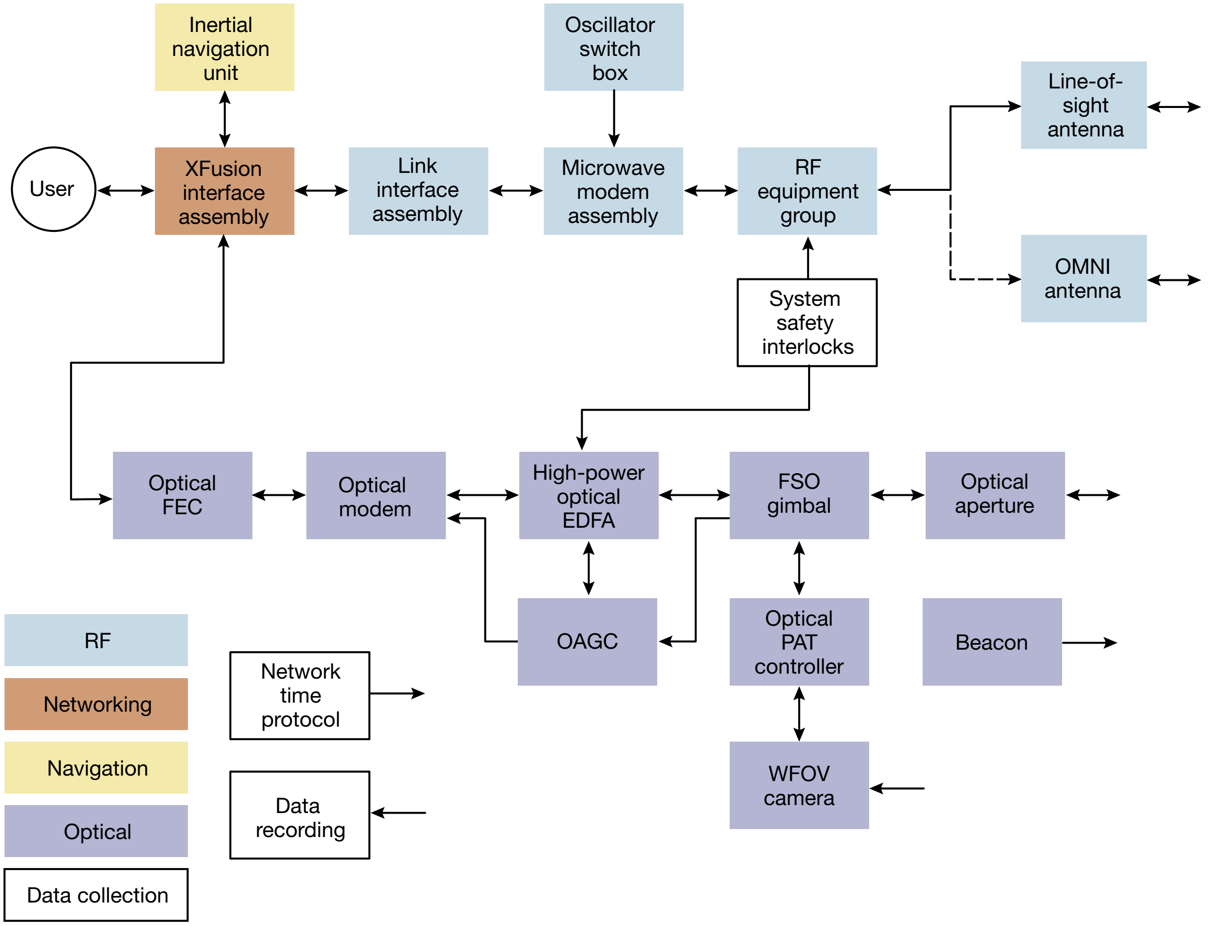


Figure 9. System block diagram of the FOENEX system. EDFA, erbium-doped fiber amplifier; OMNI, omnidirectional; PAT, pointing, acquisition, and tracking; WFOV, wide field of view.

Figure 10. Test configuration of the FOENEX ground station at China Lake Naval Air Weapons Station. Shown are the two lasercom and RF terminals.

Figure 11. One of three FOENEX test aircraft. There are two lasercom terminals, one overwing and one beneath the aircraft nose. The RF radome is beneath the aircraft door. The lasercom and RF terminals on the bottom of the aircraft formed a hybrid link.

from previous efforts as the pointing, acquisition, and tracking was driven by the FOENEX network controller and was fully automated; nodes were automatically discovered and brought into the network, and links (RF, lasercom, or hybrid) were formed autonomously by the system without operator intervention.

FOENEX Field Tests

The field test program was broken into two phases: phase 1 was performed at a civilian airfield in Hollister, California, and phase 2 was performed at the Naval Air Weapons Station (NAWS) in China Lake, California.

In phase 1, multiple air-to-ground and air-to-air links were tested. Initial testing of the mesh network was also completed. The air-to-ground links were always bidirectional lasercom/RF hybrid links, and both hybrid and lasercom-only links were demonstrated during the air-to-air tests. The data rate on the client input/output of the optical modems was 10 Gbps Ethernet (10 GbE). The information rate at the user interface with the XIA during the test varied from 5 to 9 Gbps depending on the test performed. The test data were generated and analyzed with commercial 10-GbE packet testers. The difference between the user information rate and the 10-GbE data rate served as overhead for the XIA to use for retransmitted data or to provide bandwidth for alternate paths through the network. The RF link data rate was varied during testing; the maximum rate used was 240 Mbps. The program goal was to demonstrate a low packet error rate (~4×10^{-6}) air-to-ground FSO and RF link at a range up to 50 km at data rates greater than 1.7 Gbps (FSO) and 185 Mbps (RF).

An example flight profile flown in phase 1 is presented in Fig. 12. The test segment used an information rate of 8.5 Gbps as the aircraft flew outbound from 82 to 130 km. The link throughput and range as a function of time are shown in Fig. 13.

The link was nearly error free over the entire test sequence. The packet throughput as a function of time

Figure 12. Flight pattern used for air-to-ground testing. The testing was primarily over the Pacific Ocean, with the aircraft turning west of the entrance to San Francisco Bay.

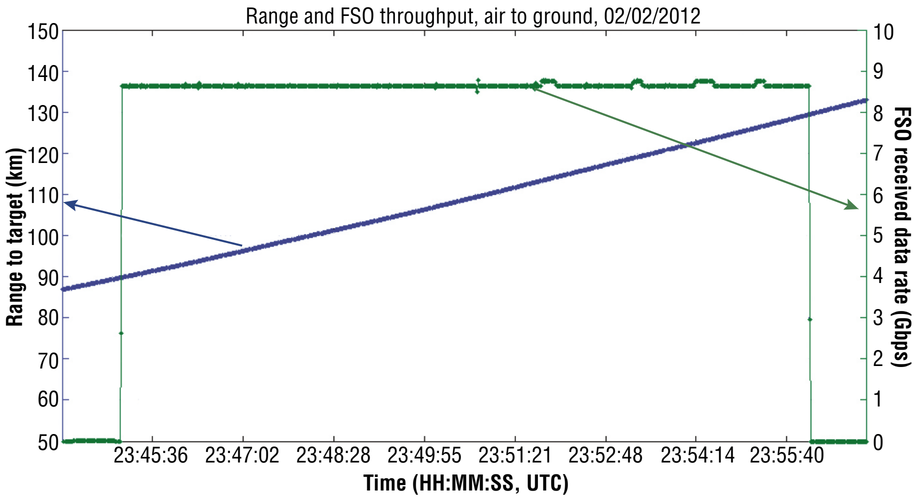


Figure 13. Data rate and range versus time for the air-to-ground high-data-rate test. The test configuration had the aircraft outbound. The data rate, in gigabits per second, was measured as the link distance varied between 90 and 130 km.

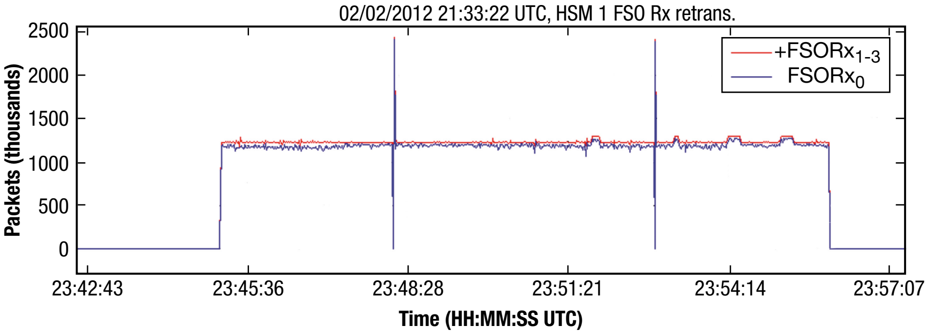


Figure 14. Packet transmission rate versus time for the air-to-ground high-data-rate test. The blue trace indicates packets sent through during the first attempt. The red trace shows retransmitted packets. The difference between the two traces represents the retransmission rate.

is shown in Fig. 14. The packet count sent successfully the first time is shown in blue, and the packet count that was retransmitted is shown in red. In this case it took no more than three retransmissions per packet to transmit the data with no errors; the maximum retransmission rate was ~3%. There are two drops in the data rate that are followed by subsequent data rate increases. This type of behavior was typical of the deep queue operation, where the data lost during an extended link fade were stored at the transmit node and then transmitted at a higher rate when the channel became available. The net result was no loss of client data during the long-fade event.

Air-to-Air Hybrid Lasercom/RF Links

During phase 1 testing, the air-to-air testing used a bidirectional hybrid lasercom/RF link. This configuration used the lasercom terminals mounted above the aircraft wing, which were logically bound to the RF system on the bottom of the aircraft. The information rate used during the test varied from 5 to 6 Gbps depending on the test performed. The goal of the program was to provide a packet error rate of ~1×10^{-6} at a range up to 200 km at data rates greater than 2.25 Gbps. The flight pattern for the first air-to-air tests is shown in Fig. 15. The two aircraft flew in coordinated patterns that had both aircraft either outbound or inbound toward the airfield in Hollister, California; this test configuration provided link performance data over a large variety of aircraft ranges and local (close to the lasercom terminal aperture) atmospheric turbulence conditions. The local turbulence varies strongly with the direction of the airflow across the terminal aperture. When the terminal, which was spherical, faces the same direction the aircraft is flying, the local turbulence is fairly benign; however, when the terminal looks backward, there is a higher level of local turbulence due to the wind vortices.[19] The system was able to maintain a bit error rate of 5×10^{-6} on the outbound leg, which varied from 50 to 212 km (115.5 nautical miles) and was error free on the inbound leg. Note that the flight pattern included over-ocean links and covered more than half of California from an east–west perspective. During this test, the links were turned down during the turns to test the ability of the system to automatically reacquire at extended ranges. In this case, the RF system reacquired the link at 224 km, the lasercom system had initial closure link at 207 km, and the data collection cycle started at 165 km.

The lasercom information rate for this test was 6 Gbps; the information rate for the RF link was 180 Mbps. The choice of the lasercom rate reflected the same rate that was used for the majority of the air-to-ground testing and provided adequate link capacity in the 10-Gbps data bandwidth to support any necessary packet retransmission. Sample data for this

Figure 15. Flight pattern used for air-to-air testing. The maximum range between the aircraft was 230 km.

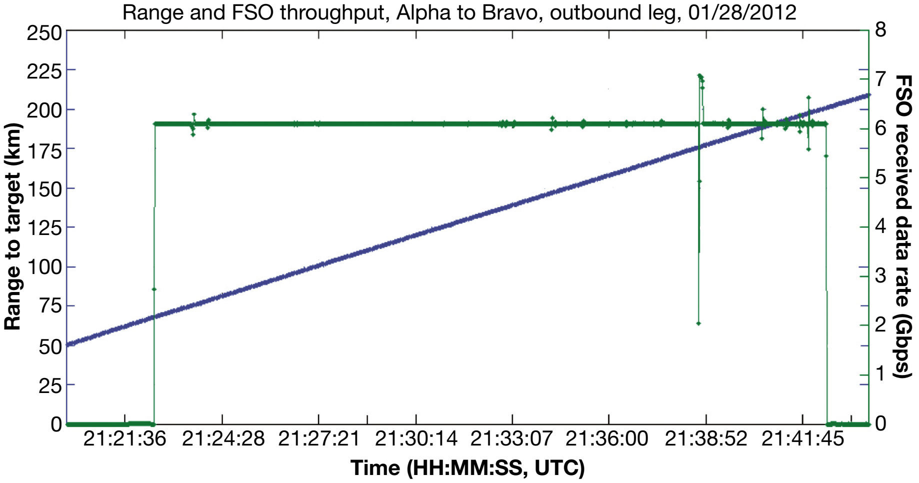


Figure 16. Data rate and range versus time for the air-to-air link test. The aircraft were outbound from each other. Data collection started at the 50-km range and ran through 212 km.

test are shown in Figs. 16 and 17. Figure 16 shows the link performance with the aircraft outbound, showing the data throughput and the link range as a function of time.

The local turbulence for the outbound link was further impacted by propagation through the exhaust of the aircraft's turboprop engines. Figure 18 presents waterfall plots showing the distribution in the receive power out of the optical terminal, referred to as PIF due to the different turbulence conditions. The additional spreading of the PIF distribution due to aero-optic-induced turbulence as well as the exhaust-induced fades on the outbound case (range from 52 to 212 km) are clearly shown, although link performance was nearly error free as discussed above.

Demonstration of the Hybrid Lasercom/RF Network

During the first phase of testing, the air-to-ground and air-to-air test configurations were extended to include an air-to-air-to-ground network. Two different configurations were tested: (*i*) a string network, which consisted of the two aircraft connected to each other and a connection from one of the air nodes to the ground node; and (*ii*) a triangle network, where the ground node was connected to both airborne nodes and the airborne nodes are connected to each other. Figure 19 shows the network-level view of a three-node (two aircraft, one ground station) triangle network captured during flight tests. The ground node was maintaining hybrid lasercom/RF links to each aircraft (red/blue dashed line) and there was a concurrent lasercom-only link (red line) between the two aircraft. The air-to-ground range varied from 40 to 70 km during this test, and the air-to-air range varied from 70 to 110 km. During this test, each node was configured to sink and source a 3-Gbps information stream. The additional link capacity was left available to support rerouting of data from a node that had lost one or both of its data links as well as provide overhead as needed for packet retransmission. Figure 20 shows the various network configurations demonstrated during this test segment. Note that each node transmitted and received 6 Gbps of user data at all times—when all three links are operational each node had a bidirectional 3-Gbps link with two other nodes—this is the case in the first frame of Fig. 20.

Figure 21 shows the data throughput for the two lasercom terminals on aircraft Bravo; the upper portion of the figure shows the data throughput for the lasercom turret that handled the air-to-ground link, and the lower portion of the figure shows the throughput for the lasercom turret that handled the air-to-air link. The first configuration tested was the full hybrid triangle, with each node

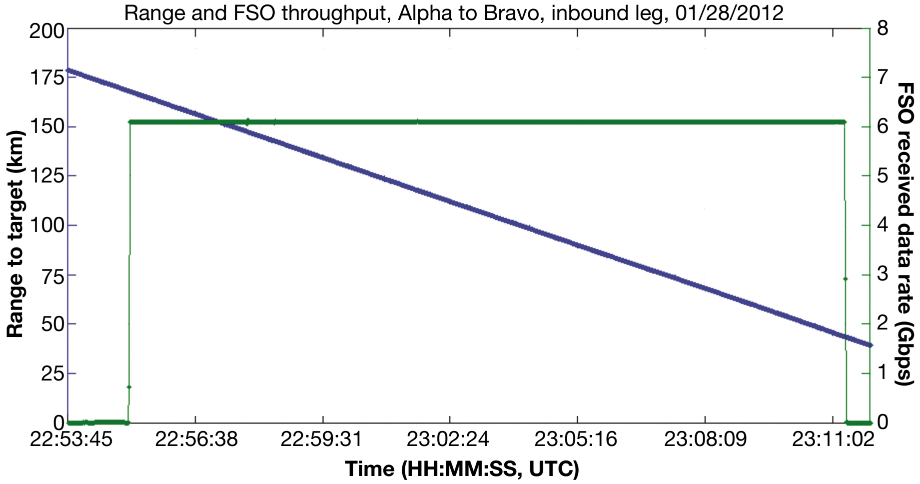


Figure 17. Data rate and range versus time for the air-to-air link test; aircraft were inbound toward each other. The lasercom link automatically established at 183 km, and the data collection was run from 165 to 40 km.

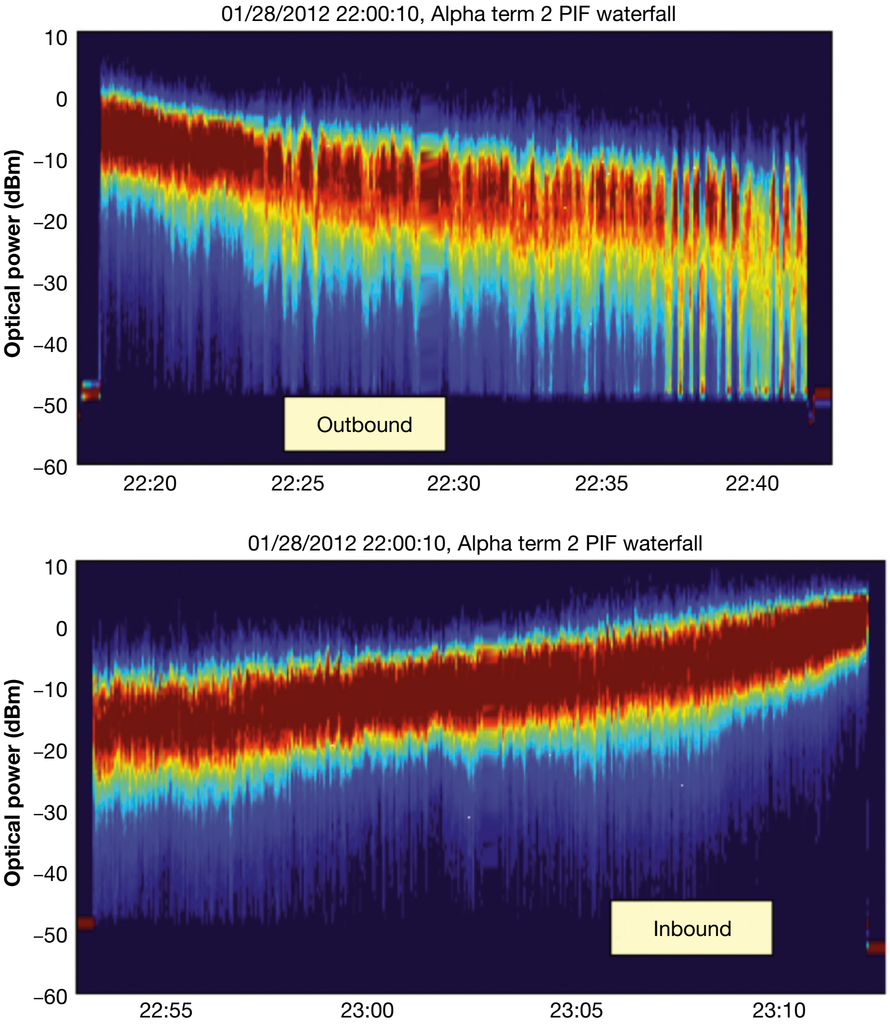


Figure 18. PIF waterfalls for air-to-air testing. Link range was from 40 to 212 km for the outbound case and from 180 to 40 km for the inbound case.

in the network transmitting and receiving 6 Gbps of test data.

The second configuration tested was the loss of the link from the ground system G to aircraft Bravo B. In this case, the data that were carried from ground to Bravo were routed through the ground-to-aircraft Alpha-A link. To carry the additional traffic, the bidirectional rate on the Alpha-to-ground and Alpha-to-Bravo links increased to 6 Gbps; this is shown in Fig. 21 at 02:08 UTC. The rate does spike to greater than 7 Gbps briefly during the transition; this is a result of the system's deep queues bursting out data that were buffered during the reconfiguration of the routes. Figure 22 shows packet loss during the transition on the air-to-ground link; this is likely due to the rerouting of packets inside the XIA router during the network reconfiguration. The network transition on the air-to-air link was error free.

The third configuration tested was the loss of link from ground to Alpha; this occurred at 02:23 UTC. In this case, Bravo becomes the conduit between the ground node and Alpha; the data rate through Bravo increased from 3 to 6 Gbps to handle the Alpha-to-ground load. Figure 22 shows there were no errors during this transition.

The last case during this test flight is the loss of the air-to-air link between Alpha and Bravo. In this case, all data being routed between the two aircraft were sent through the ground station; this occurred at 02:28 UTC. The system remained error free during this transition. These four cases were followed by four rapid transitions (brief link outage from Bravo to ground, which was handled by the system deep queues, back to normal triangle operation, loss of air-to-air, recovery to normal triangle, loss of Alpha to ground). These transitions were all handled automatically, with minimal errors. The estimated bit error rate for this entire segment, including all the network reroutes, was ~1 × 10^{-5}. Because each node was always transmitting and receiving 6 Gbps, the total amount of data transmitted and received over the 35-min test cycle was 12.6 Tb at each node.

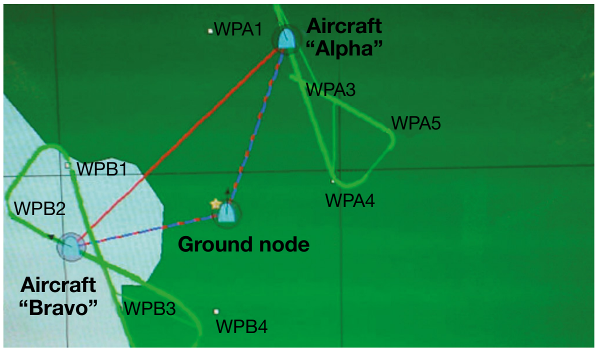


Figure 19. Network-level view of a three-node triangle network as flown near Hollister, California. Aircraft Bravo was flying over Monterey Bay, and Aircraft Alpha was flying over the California Central Valley.

FOENEX Phase 2 Testing

The phase 2 test demonstrated the full mesh network, which comprises three aircraft and one ground station. The testing was executed in March and April 2012. China Lake NAWS provided a different test environment than the Hollister, California, test site. Hollister provided a mix of low mountains and maritime and urban areas to overfly, whereas China Lake provided a desert environment, with 14,000-ft mountains in the flight area. This required the flight altitudes to be increased from 11,000 to 15,000 ft. Because the program range and data rate metrics for the FSO and RF links had been met during the phase 1 testing, the focus of phase 2 was on network testing.

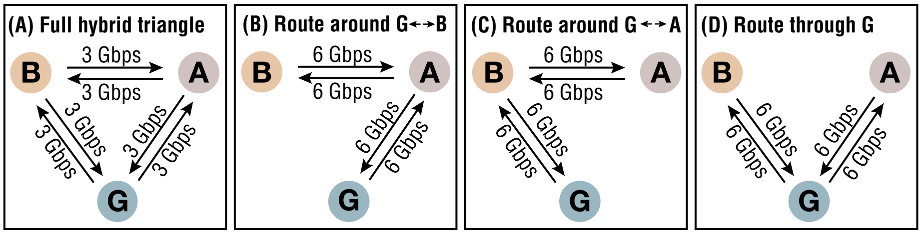


Figure 20. Network configurations formed during a triangle network test. Node A is the Alpha aircraft, B is the Bravo aircraft, and G is the ground station.

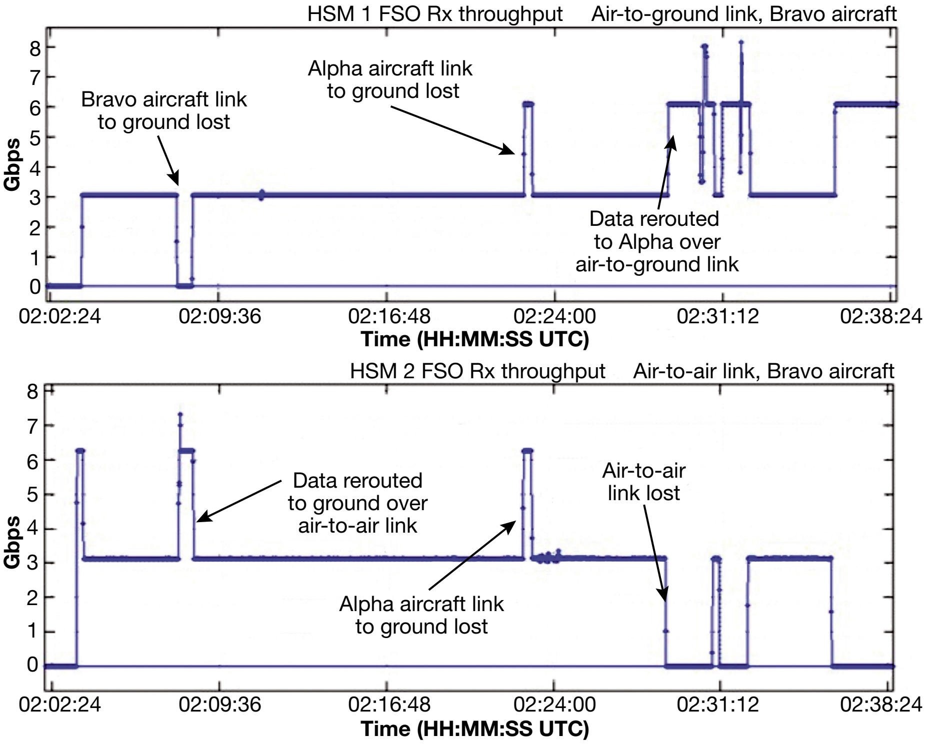


Figure 21. Lasercom network traffic levels measured at the Bravo aircraft during the air-to-air-ground test.

The performance of the network during phase 2 was assessed using quantitative and qualitative methods. As with phase 1, 10-GbE packet testers were used to quantify packet error rates. Two Ethernet cameras, one remotely controllable and one high definition, were added to the three aircraft and the ground station. This allowed video streams from any of the four network nodes to be accessed via a web browser at any other node, as well as in the mission control facil-

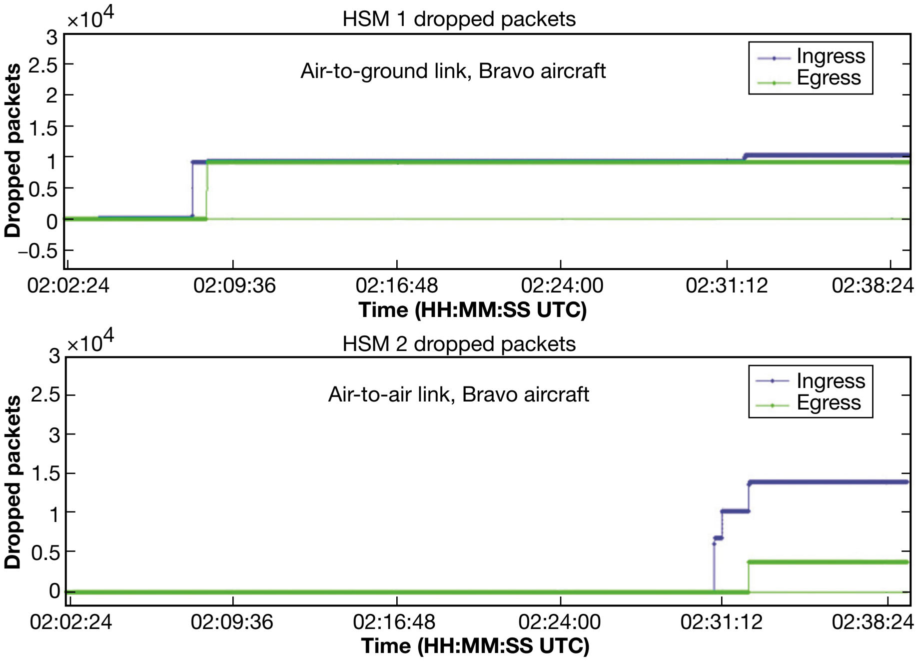


Figure 22. Dropped packets as a function of time from the network test.

ity provided by China Lake NAWS. All nodes also had full voice-over-Internet Protocol (IP) telephony (two phone numbers per aircraft and at the ground station) as well as video conferencing capability, which were used extensively during the test.

The unique data collection event for the phase 2 test was the four-node (three aircraft, one ground station) network. Figure 23 shows a snapshot of a post-test analysis of aircraft location (black triangles), link ranges, and link types (red line, lasercom only; red/blue line, hybrid lasercom/RF). This configuration was successfully demonstrated during a government open house held at the end of the test cycle.

REQUIREMENTS FOR OPERATIONAL SYSTEMS

The performance requirements for an operational system are dictated by the expected environment the system will experience. Lasercom systems suffer from two main penalties: atmospheric turbulence and atmospheric attenuation (clouds and weather). The issues with turbulence are well understood[20] and are the major focus of lasercom development at APL. There are many methods that have been demonstrated to create a robust lasercom link even in high levels of turbulence; however, situations exist where turbulence will fundamentally limit lasercom link availability.

Weather impacts can be reduced using hybrid systems or by proper operational planning. Low-zenith-angle

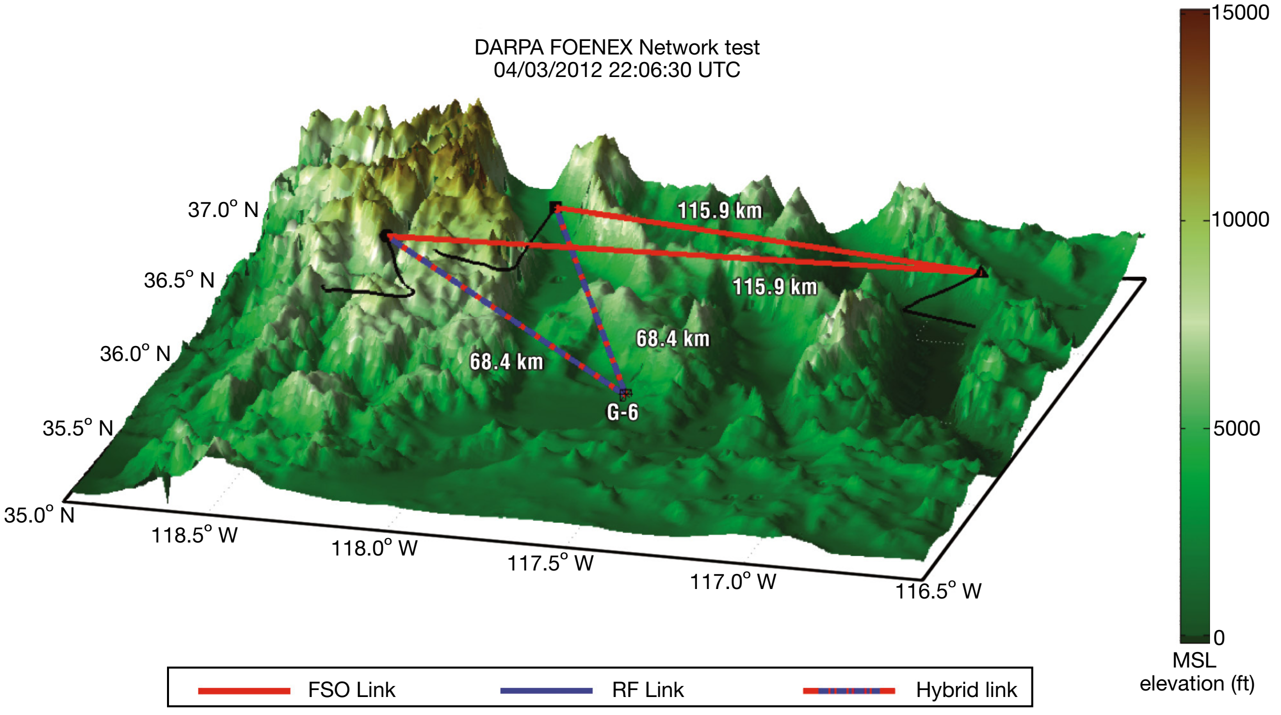


Figure 23. Data showing link configuration and ranges of the four-node hybrid FSO/RF network.

hybrid links will have fairly short paths through clouds and thus will be able to form communications links. Longer links through extended cloud decks will be more problematic—as RF carrier frequencies increase, so does the attenuation per unit distance, reducing the probability of a successful link. Cloud coverage varies both geographically as well as with altitude. Modeling tools exist[21] to estimate situations where cloud-free lines of sight may exist. Models have shown long (>100 nautical miles) links can be supported by lasercom-only links between airborne platforms and, in some cases, air-to-ground links, with the greatest challenge being near the intertropical convergence zone where there is a high likelihood of dense clouds and precipitation over a broad range of altitudes and locations, potentially limiting the capability of lasercom systems.

Operation of lasercom systems without any form of RF emissions is also of interest in situations where there is no available spectrum, such as in an RF-denied or -degraded environment, or when there is a desire to not have the communications link detected. Past systems experiments have included an omnidirectional RF link to pass the location of the lasercom terminal to the rest of the system. This information is used for initial system pointing. Typically lasercom terminals have a built-in optical beacon method for closing the pointing loop once the terminals are pointed within a few degrees of each other. The lack of an RF beacon is not a problem with fixed links or when moving target locations can be accurately estimated. Future systems will require a solution to the problem of the location of a network node being unknown in an RF-denied or -degraded environment.

FUTURE DIRECTION FOR TERRESTRIAL LASERCOM

After successful completion of the FOENEX program, feedback from the DoD community indicated interest in lasercom; the link ranges demonstrated by FOENEX were of interest, but the high data rate was generally applicable to niche applications such as intelligence, surveillance, and reconnaissance data transfer. The potential user base preferred reductions in system size and weight for use on smaller unmanned platforms, which would be better suited for communications relay missions. To address this challenge, APL has invested in the development of reduced-size and -weight lasercom terminals. The target of this effort is a lasercom terminal weighing ~15 lb—the FOENEX lasercom terminal was 115 lb, 90 lb of which was the inertially stabilized gimbal. This development effort, still ongoing, leverages a commercial stabilized gimbal currently used for carrying imaging equipment on unmanned aircraft. This reduction in size and weight carries a range and/or data rate penalty because the launch power needs to be reduced to maintain eye-safe optical power levels. Also, the beam divergence will be greater than the FOENEX system because of the smaller transmit apertures required to fit into the smaller gimbal—this will also impact range performance. The system is undergoing initial pointing and tracking development; Figure 24 shows the system mounted on an extendable mast during development testing.

Figure 24. Prototype compact lasercom terminal on a deployable mast during outdoor tests.

CONCLUSION

This article presents a description of technology developments and field demonstrations of lasercom systems. The continuous improvement in the technologies used in lasercom systems enabled the progression from short-range air-to-ground links through long-range (>100 miles) high-bandwidth airborne networks. Focus on development of technologies for filling the critical gaps in lasercom facilitated the rapid progression of this capability. The net product of this effort was a successful system-of-systems experiment that included demonstration of the longest known terrestrial lasercom links as well as the first demonstration of an airborne hybrid lasercom/RF network. The demonstrated performance gains of lasercom systems open up various potential applications including long-range multigigabit-per-second data transfer and operation in RF-denied environments.

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David W. Young is a member of APL's Principal Professional Staff and was the FSO Communications Chief Engineer in the Air and Missile Defense Sector (AMDS). He is currently the technical lead on a major Office of Naval Research electronic warfare program. He led APL's lasercom efforts from the initial AMDS-funded IR&D efforts through multiple sponsor-supported technology development and demonstration programs. He was the Chief Engineer of the DARPA FOENEX program, which successfully demonstrated the first airborne hybrid lasercom/RF mesh network. **Hugh H. (Harry) Hurt**, a member of APL's Principal Professional Staff, was the Program Manager for the DARPA FOENEX program. He led the programmatic effort for the lasercom developments and provided technical inputs on operational aspects of DoD implementation of the systems. **Joseph E. Sluz**, a member of APL's Principal Professional Staff, was the primary developer of the electronics portions of the lasercom systems. His responsibilities included developing and integrating firmware and software for the systems. He also provided extensive system insights and was a key member of the field testing efforts. **Juan C. Juarez**, a member of APL's Senior Professional Staff, is the current lead engineer for FSO Communications in AMDS. Under the FOENEX program, he led the development of the FSO communications system. He is currently leading ongoing lasercom efforts, including development of compact, high-rate lasercom systems for mobile platforms. For further information on the work reported here, contact David Young. His e-mail address is david.young@jhuapl.edu. For further information on current lasercom efforts, contact Juan C. Juarez at juan.juarez@jhuapl.edu.