DEVELOPMENT OF LASER CROSSLINK FOR AIRBORNE OPERATIONS

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ABSTRACT
The requirement to send ever increasing amounts of tactical military information between sensor aircraft and information processing facilities for command and control purposes has begun to press the limits of present airborne data links, even when data compression techniques are used. Utilization of optical data links is under consideration by the United States Air Force and development of a possible airborne laser data link is under way by the United States Air Force Research Laboratory Sensors Directorate (AFRLISN). This technology development program is being conducted in two phases. The first phase included the design and evaluation of a laser data link ground demonstration carried out in August and September 1995 between a laser terminal on Mount (Mt.) Mauna Loa on the island of Hawaii and a similar laser terminal on Mt. Haleakala on the island of Maui located 150 kilometers (km) away. The laser terminals used in this ground demonstration were capable of 1.1 gigabits per second (GBPS), full duplex communications. A motion and vibration base was used to simulate an aircraft environment and the terminal instrumentation was also used to collect atmospheric effects data. Results of the ground demonstration including signal acquisition, tracking stability and scintillation were used to modify the design of the laser terminal for follow-on air-to-air operations. The second phase of the AFRLISN development program is the transition of the ground demonstration results into a refined terminal design for installation into two business size jet aircraft. Flight demonstration of the laser data link between these two kinematic aerial platforms will be performed at distances up to 500 km. The implications these flight demonstrations will have on possible laser terminal installations in high altitude aerial platforms and the resultant ability to use advanced airborne sensors generating very large amounts of raw data in near real-time means that command, control and decision making can be made based on a more timely and thorough database of information.

INTRODUCTION
The modern battlefield uses a variety of airborne sensors to gather data on enemy assets and capabilities. Very large amounts of data can be collected from some sensors such as a synthetic aperture radar (SAR). Storing the collected data on the sensor platform requires additional electronics with the attendant space, weight and power requirements. Real-time transmission of the raw collected data off the platform to a safe point is advantageous in reducing the sensor asset cost, increasing sensor payload and reducing the probability of data loss. Currently, sensor platforms are limited to using radio frequency (RF) means for transmitting the raw data. RF techniques and their associated hardware are beginning to limit sensor capability due to the their size, weight, power requirement and maximum data rate limitations. Efforts to use microwaves for transmitting compressed data from airborne sensors have been under development and this work should provide a large increase in data rate over present RF techniques. However, laser data links will be able to provide major performance advantages in weight, size, power, covertness and data rate capability over microwaves. Laser data links do have the recognized limitation of being degraded by weather and that may limit their atmospheric use to applications where transmission is relatively certain, such as at mid to high altitudes. This may not be a significant limitation since these altitudes are the normal operational environment of the aerial sensor platforms.

Earlier laser data link work by AFRLISN on the HAVE LACE (Laser Airborne Communications Experiment) Program in the mid-1980s demonstrated data rates of 19.2 kilobits per second (KBPS). These relatively large terminals were flown on two KC-135A aircraft at altitudes of 20,000 to 25,000 feet (ft) with link ranges out to 160 km. The most significant result of the HAVE LACE flights was the difficulty of initial signal acquisition between the two moving platforms, since it had to be performed manually. However, once signal acquisition was accomplished, tracking proved to be robust and communications performance was consistently measured at $10^{-6}$ bit error rate (BER) or better.

More recent work by AFRLISN in September 1995 demonstrated laser communications at 1.1 GBPS over a range of 150 km from Mt. Haleakala on the island of Maui to Mt. Mauna Loa on the big island of Hawaii at an altitude of approximately 10,000 ft. This experiment was performed with one laser communication terminal (LCT)
mounted on a motion platform simulating the flight and angular vibrational motion of a high altitude aircraft. The other LCT was mounted on a stationary platform. The two LCTs used for this ground demonstration were originally built by ThermoTrex Corp. of San Diego, California for the Ballistic Missile Defense Organization (BMDO) Innovative Science and Technology (IST) office to evaluate space based laser crosslinks and were only slightly modified for the Hawaii ground demonstration. Automatic signal acquisition and beam tracking were successfully accomplished throughout the ground demonstration. Communication error rates of better than $10^{-6}$ were achieved during simulated motion. However, it was apparent from the overall system operation that terminal design changes would be required to operate a laser data link in a kinematic airborne environment.

Building upon the successes shown in the Hawaii ground demonstration, AFRL/SN is presently conducting a program to develop a new LCT which will be mounted in a turret on the underside of the fuselage of a T-39A (or Sabreliner 40) test aircraft (Figure 1). Two of these aircraft will be used in the summer of 1999 to demonstrate full duplex laser data link communications at data rates of 1 GBPS, at ranges between 50 and 500 km and at altitudes up to 40,000 ft. These flights will also be used to collect data about atmospheric and airflow effects upon laser beam propagation, scintillation and jitter.

**SYSTEM PERFORMANCE**

The primary performance goal for the LCT system is to communicate between two aircraft at 40,000 ft altitude and ranges of 50 to 500 km at data rates of 1 GBPS with a BER of $10^{-6}$ or less. The time to acquire and establish the link is within 10 seconds from initiation from the master control aircraft. The acquisition process will require the sharing of global positioning system/inertial navigation system (GPS/INS) position data via a RF data link which will be established long enough to exchange a single data packet on aircraft position and velocity. Reacquisition will be automatic to accommodate atmospheric dropouts when beacon tracking is lost. The LCT must be able to operate within temperature ranges of $-62^\circ$ to $+55^\circ$Celsius (C) and be able to survive in humidity varying from near zero to heavy rain.

**SYSTEM DESCRIPTION**

The new LCT being developed by AFRL/SN is mounted in a two axis, 47 centimeter (cm) diameter spherical turret which is located in the escape hatch area on the lower fuselage of a T-39A test aircraft in front of the leading edge of the wing. The turret is designed to have $\pm 190^\circ$ of rotation in azimuth and $+10^\circ$ to $-90^\circ$ of rotation in elevation. This will provide a slightly greater than hemispherical field of regard (FOR) during flight operations. The turret has a 20 cm diameter spherical window for the lasers and receiver apertures, which can be stowed to a protected position during takeoff and landing. The turret assembly (Figure 2) and its mounting mechanics are made of 6061-T6 aluminum to minimize weight and fabrication cost. The turret drive mechanism uses a gear drive on both axis with a steel ring gear on the turret axis and a steel pinion gear on the drive motor. Turret angular position is determined using two speed resolvers having an accuracy of $\pm 10$ arc seconds (arcsec). The turret is designed to track through zenith or nadir as the LCT assembly could be mounted either on the top or the bottom of an operational sensor aircraft.

**Figure 1. T-39A Test Aircraft with Laser Communication Terminal**

**Figure 2. Turret mechanical design**

The optical subsystem (Figure 3) consists of a communication and coarse tracking telescope with its array sensor, an atomic line filter (ALF) and communication sensors, two beacon lasers, a fine tracking telescope and sensor, four communication lasers, a visible viewing camera, a fast steering mirror, a two axis rate sensing gyro, and the optical beam train elements for the lasers and fine tracking receiver. These elements are all attached to a composite structure called the optical bench (Figure 4). This complex structure is fabricated with low coefficient of expansion (near zero) carbon composite
materials and uses Invar 36 inserts for mounting the various optical hardware elements. Electronics for operation of the two charge coupled device (CCD) sensors, the communication sensors, the beacon lasers, the ALF and various temperature and pressure sensors are also mounted on the optical bench assembly.

Resolvers having an accuracy of ±10 arcsec are used on each axis to determine angular position.

The LCT optical subsystem (Figure 3) includes: the Coarse Tracking Beacon, the Coarse Tracking Receiver, the Fine Tracking Beacon, the Fine Tracking Receiver, two Communication Transmitters, the Communication Receiver and the Visible Monitoring Camera. All of these subsystems are mounted on the optical bench mounted within the turret assembly.

The Communication Receiver and Coarse Tracking Receiver share a 134 mm diameter f/5 Maksutov collection telescope. This telescope consists of a spherical aberration correcting, antireflection (AR) coated, meniscus window; a f/1.2 gold coated spherical primary mirror and a f/1.5 gold coated spherical secondary mirror (the reflectorized central obscuration of the Maksutov corrector). The corrector and primary mirror are mounted in a composite tube with a composite spacer for thermal stability. The two beam paths are separated by a dichoric beamsplitter that sits in the central hole of the primary mirror. This dichroic transmits the 852 nm tracking signal and reflects the 810 nm communication signal. The coarse tracking optics and CCD are positioned behind the primary mirror in a composite tube and consist of the following in order of light propagation:

- Dichroic beamsplitter (852 / 810 nm)
- Interference filter
- 1/4 waveplate
- Polarcor linear polarizer
- Atomic line filter cell
- Polarcor linear polarizer
- Variable retarder (liquid crystal)
- Polarcor linear polarizer
- Imaging lenses
- CCD

The optical bench assembly is mounted on a two axis aluminum gimbal (Figure 5) having a motion of approximately ±6° on each axis. The two axes of the Figure 5. Turret mechanical design gimbal are parallel to the azimuth and elevation axis of the turret assembly. The gimbal is positioned using two voice coil actuators on the elevation axis and one on the azimuth axis. Single speed
The communication receiver optics are positioned in the central obscuration of the corrector plate and consist of the following in order of light propagation:

- Pinhole aperture (field stop)
- Collimating lens
- Interference filter (20 nm)
- 1/4 waveplate
- Polarizing beamsplitter cube
- Right angle prism
- Fold mirrors
- Imaging lens
- APD

The turret assembly (Figure 2) is mounted on an aluminum structure that fits into the escape hatch opening of the T-39A aircraft thus requiring minimal modification to the aircraft structure. The turret assembly is not pressurized and a pressure bulkhead at the escape hatch provides the outside air to cabin interface. This bulkhead provides the mounting surface within the aircraft cabin for the turret assembly, servo drive electronics and various data interface electronics. This bulkhead also serves as the mounting for the closely coupled GPS/INU which is the attitude reference for LCT stabilization in addition to providing aircraft location and velocity.

The rest of the LCT system electronics are mounted in an equipment rack within the cabin of the aircraft. This equipment rack has a VERSA Module Europe (VME) 6U rack for the system processor, the quad digital signal processor, the array sensor interface electronics and equipment for multiplexing video and audio signals onto the laser communication system. The equipment rack also contains the flight test instrumentation system, a RF transceiver for communication with the other test aircraft and power sequencing equipment. A laptop computer is connected to the LCT equipment for operator control and diagnostic evaluation of the system. A second laptop computer is connected to the flight test instrumentation system to display real-time flight test data and control the onboard data recorders.

**SYSTEM TESTING**

The hardware components and software making up the LCT are undergoing a series of laboratory tests that increase in complexity as the components and software are assembled into subsystems and then into the complete LCT. The completed LCTs are being tested in the laboratory by placing the complete turret assembly within an environmental chamber which is able to simulate the operating altitude (1/3 atmosphere) and temperature (+55 to –62°C). The system is also being tested both in and out of the chamber using distant (10 km) beacon sources to demonstrate acquisition and tracking. This constitutes part of the formal acceptance tests that AFRL/SN is conducting to confirm safe system operation and suitability to be operated in an airborne environment (i.e., flightworthiness) prior to their installation into the two flight demonstration aircraft.

Ground integration testing of the LCTs will then be accomplished on the aircraft to confirm total system operation and to calibrate and align the various test instrumentation sensors on the LCT and the aircraft. This testing will ensure the electrical power, environmental temperature control and operator controls/displays compatibility of the installed LCT. These tests will include coarse alignment and boresight calibration checks which will be accomplished using a Terminal Simulator. Complete integration and checkout of the flight test instrumentation system will also be accomplished during this time period.

**FLIGHT DEMONSTRATION**

The two T-39A aircraft will be modified in early 1999 and a LCT integrated into each aircraft. Flight testing is scheduled to begin with aircraft flightworthiness tests in May 1999. This will be followed by a series of flights at Crestview, Florida to evaluate beacon signal acquisition and tracking, communication signal acquisition and quality, link atmospheric effects, aircraft kinematics and airflow effects, and operational mission requirements. The demonstration flights are an integral part of the LCT development process; therefore, the LCT is extensively instrumented and each test aircraft contains a complete and comprehensive onboard flight test instrumentation system to monitor in real-time LCT operation and laser data link quality. Each test mission is expected to consist of approximately 2 hours of data gathering at various test conditions. The content of the 1 GBPS communication signals will consist of four video/audio channels, a serial digital data stream and a BER generator data stream. Initial air-to-air data link operations will be controlled by an onboard test engineer and monitored by an onboard systems engineer. A pilot and copilot/test director will also be part of the onboard crew. Later flights, such as the operational mission requirements flights, will delete the onboard engineers as the LCT is operated in an autonomous mode. The saving in aircraft gross weight by their deletion will allow higher altitude flight and subsequent longer laser data link ranges.

**CONCLUSION**

The data collected during the demonstration flights should prove the ability of a 1 GBPS wideband laser data link to communicate between aerial platforms in the upper atmosphere at ranges up to 500 km with a BER of $10^{-6}$. This ability to communicate very large amounts of information (the complete Encyclopedia Britannia in less than 8 seconds or 180 standard format television color...
pictures in 1 second) in near real-time should allow new processes to be formulated which take into account the timeliness and large amount of information available for command and control decision making. Present data communication rates such as the T1 link at 1.5 MBPS and even newer RF links at 274 MBPS require data compression techniques be utilized to communicate some types of sensor data, whereas use of a laser data link would not constrain the type or number of sensors an aerial platform could carry and operate simultaneously. The flight demonstration will verify the ability of an extremely narrow beam laser data link to acquire and track another aircraft from a moving aircraft. However at the ranges and altitudes involved, the moving aircraft could just as easily track a low earth orbiting satellite and communicate with a similar laser terminal on the satellite. Several of the commercial low and medium orbit satellite data communication systems plan to use laser crosslinks to exchange data within their satellite constellation. Use of these satellites in conjunction with future airborne communication architectures containing laser data links could provide very large amounts of data from any location on earth to any other location on earth almost instantaneously.