ABSTRACT

The Edwards Air Force Base Undergraduate Clinic Team at Harvey Mudd College designed, built and tested a laser-based telemetry system for use on test aircraft at the EAFB Flight Test Center. The system was designed to communicate from an aircraft to a stationary, terrestrial receiver at a distance of up to 60 miles while traveling at speeds up to 230 mph. The transmitter system is restricted to the size of a standard 4' tall 19" wide equipment rack. The transmitter is designed to maintain a constant laser footprint diameter of 100 meters at the receiver and use both coarse acquisition and closed-loop fine tracking systems. The minimum data rate is 10 Mbps.

Sub-system testing and integration was not completed. Completed sub-systems included GPS/INS-based tracking (for coarse-tracking), position-sensitive-detector (PSD) optics (a fine-tracking system component), a transmitter gimbal assembly, software used to integrate and control hardware at the transmitter and receiver, and a complete receiver system. A PSD-based tracking system and an automatic collimation system were designed and constructed, but only partially tested.

Key Words: Telemetry, laser, communications, dynamic, optical

INTRODUCTION

Clinic is a projects-based course at Harvey Mudd College for juniors and seniors. The projects are real-world problems suggested by the sponsoring organization. A team of typically five students works to design, build, and test a device or system with the assistance of a company liaison and a faculty advisor. This paper reports on the results of the 2006-2007 Clinic project for Edwards Air Force Base (EAFB). EAFB also sponsored a similar project during the 2005-2006 academic year to develop a proof-of-concept system. The 2005-2006 project demonstrated the feasibility of optical communications, but did not provide a system that could be used on an aircraft during movement.
Current air-to-ground telemetry systems use radio communication and maintain a communication link approximately 80% of the time. The increasing complexity of telemetry data has generated a demand for higher data-transfer rates, while the restriction on radio frequency allocations has created a limitation on bandwidth. The data-transfer bottleneck has influenced EAFB to explore Laser-Communications Technology (LCT). LCT has the potential to increase the data rate and eliminates spectrum-allocation problems. LCT can increase resistance to jamming, may reduce the radar profile, and can decrease signal interference and the probability of unauthorized interception of telemetry data.

**SYSTEM DESIGN OVERVIEW**

The system design overview is split into three sections: data flow design, optical systems design, and tracking systems design. A list of system components used to fulfill the design is presented in summary.

*Data Flow Design*

The data path is the signal flow from signal generation in the transmitter station to demodulation at the receiver station. Figure 1 is a block diagram of the data path.

![Figure 1: Data Path](image-url)
Inside the transmitter, the laser beam is generated, modulated by the data signal and aimed at the receiver. The receiver system tracks the transmitter dynamically, receives the optical signal, converts it to a voltage signal, and performs bit-error-rate analysis.

The transmitter system is designed to transmit data at 10 Mbps. The receiver photodiode’s response limits the maximum modulation frequency to 100 MHz.

The laser is fiber-coupled to a randomly-polarized EAR-1K-C fiber amplifier, with a 0-to-1.3 Watt output range and a bandwidth of several GHz. The amplifier output is fiber-coupled to a fiber collimator—beam expander pair. The collimated beam is sent out into free space.

The receiver consists of a telescope, an optical bandpass filter, a focusing lens and a photodiode. These optics filter optical noise from the received signal and focus the modulated laser beam onto the active area of the photodiode.

The receiver can be equipped with one of three PIN InGaAs photodiodes which optimize the trade-off between bandwidth and sensitivity to light. The received signal is processed by a bit-error-rate device and a bit synchronizer to measure bit-errors.

**Optical Systems Design**

The transmitter laser beam is generated, modulated and amplified, then sent out through a beam expander into free space. At the receiving station, it is collected by a 10″ Meade telescope and focused onto a small photodiode for optical to voltage signal conversion.

The laser beam is generated by a single-mode pig-tailed 2 mW 1550 nm laser diode. A single-mode laser is used for higher spatial uniformity than in a multimode beam. 1550 nm is used for two reasons: 1550 nm is the location of one of the atmosphere’s optical windows, where atmospheric attenuation (absorption and scattering) is minimized; also, equipment for this wavelength is widely available and inexpensive because of its use in the telecommunications industry.

The diameter of the footprint of the transmission laser beam at the receiver is actively controlled by the beam expander (an automatic-collimation system) to remain at 100m regardless of the distance between receiver and transmitter. A constant footprint diameter maintains steady signal power at the receiver, but does require a dynamic beam divergence. At a distance of 1 mile, a footprint with a 100m diameter requires a 31 mrad (1.8º) divergence; at 60 miles, it requires a 0.5 mrad (.03º) divergence.

The laser beam is initially collimated with a fiber collimator, coated for use in the 1050-1600 nm wavelength range. A beam expander is used to expand the beam and control its divergence. This wider beam can be collimated to a greater extent that would be possible with a narrow beam.

The transmitter optics include a fine-tracking system utilizing a position-sensitive-detector (PSD). The PSD has a 3 mm active area for receiving an optical signal. It provides four outputs that can be used to calculate the location of the centroid of an incoming beam on the PSD's active area. The PSD system design includes an optical train that collects, focuses, and filters
incoming light. The design of the PSD optical train is focused on providing the necessary angular accuracy given the displacement resolution of the PSD while taking up as little space as possible on the gimbal. To this end a multiple lens system is used to increase the effective focal length (allowing for higher angular resolution) while minimizing physical length.

The receiver optics mitigate geometric power losses by focusing light from a large collection area onto the active area of the photodiode. The large collection area also mitigates the effects of scintillation (an atmospheric effect that causes small regions of zero optical power temporarily). A 10\textdegree\ aperture telescope is used. An optical bandpass filter centered at 1550 nm decreases noise from ambient IR radiation. A final lens focuses light onto the active area of the photodiode. The position of the photodiode can be adjusted with both an X-Y translator and a Z-translator to ensure that the beam of light is properly focused onto the active area.

A 1557 nm infrared laser is held in a three-axis positional translator above the telescope on the receiving station and is aligned with the other receiver optics. This laser serves as a beacon signal for the transmitter and is collimated by a fiber collimator prior to being sent into free space and into the transmitter PSD system. The transmitter system adjusts its pointing vector based to match the orientation of the incoming beacon signal.

**TRANSMITTER AIMING SYSTEMS**

The transmitter aiming system aims the transmitter laser beam towards the receiver. This system is composed of several components; the relationships between these components are shown in Figure 2.

![Figure 2: Tracking System Flow Chart](image)

Coarse transmitter aiming uses position and orientation data inputs received from an integrated GPS/INS unit. Position is estimated to within five meters with increasing accuracy as the number
of received satellite signals increases. Rotational attitude is estimated to within 5 mrad (0.286º). These data are sent from the MMQG via a serial port at a rate of 10 Hz into a rack mount computer for processing in LabVIEW. The desired azimuth and elevation angles of the transmitter laser beam are calculated in LabVIEW. These angles are sent to the integrated gimbal drivers/controllers which actuate the rotation of the azimuth and elevation gimbal stages to precisely point the laser beam.

High frequency turbulence is expected on the air vehicle, and an update rate of 10 Hz is not sufficient for tracking under these conditions. For this reason, a position-sensitive-detector is used to create a high frequency, high precision aiming method.

The four analog output channels from the PSD are filtered through a lock-in amplifier to increase the SNR and sampled at a rate of 100 kHz using a DAQ. The LabVIEW software calculates the angular error from the filtered signals and corrects the pointing of the gimbal. This precise tracking takes precedence over coarse tracking once the received beacon laser beam signal strength reaches a threshold value.

Additionally, the divergence of the transmission laser beam is controlled by the auto-collimator to maintain a 100 m beam footprint on the target. The rotation of the auto-collimator is actuated by a stepper motor controlled through LabVIEW software.

**Receiver Tracking Accuracies and Link Budget**
The GPS/INS system on the transmitter tracks the receiver to within 5 mrad (0.3º). Because a 100 m footprint is desired at the receiver, the max allowable error in the transmitter tracking is 0.05 mrad (.003º), and the PSD tracking system provides this additional precision. Given the displacement resolution of the PSD active area, this level of angular accuracy required the PSD optics to have a focal length of approximately 200 mm. The optical system is designed to achieve this resolution. The field-of-view of the PSD system has to exceed the 5 mrad (0.06º) angular error of the coarse tracking system to ensure that the beacon laser beam illuminates the PSD. With a 200 mm focal length and a 3 mm active area, the PSD system has a field-of-view of approximately 15 mrad (0.86º), substantially above the minimum requirement.

Based on a link budget analysis (over a distance of 60 miles), with the initial laser power of 30 dBm, the received power is −39.5 dBm or approximately 112 nW. This amount of power is above the noise floor and should be detectable at the receiver.

**Receiver Tracking Actuation**
Tracking of the receiver is effected by the gimbal system. The gimbal system is shown in Figure 3.
The gimbal system consists of two single-axis rotational stages. The elevation stage is mounted to the azimuth stage at a 90° angle using a precision-machined L-bracket. A precision-machined spacer plate is used for connecting the L-bracket to the azimuth stage. The precision machined spacer plate ensures the axes of rotation of the two stages are as close as possible to being orthogonal, which is a design requirement.

These stages are used because of their high rotational precision (0.00224º, 0.000039 rad), angular velocity and acceleration characteristics, load bearing capability, movement operating frequency, and relatively low cost. Rotating these stages moves an aluminum plate assembly mounted to the elevation actuator; this assembly holds the beam expander, PSD, and collimator control motor. The rotating stages can aim the laser and beam expander in any desired direction.

The aluminum plate assembly is rigid (1/2" aluminum plates are used), allows for permanent field-of-view alignment of the PSD and beam expander, does not exceed weight or torque tolerances of the stages, and incorporates an automatic collimation-adjust system for maintaining the laser spot size at the receiver. An adjustable set screw design is used to align the beam expander and PSD optics.

The automatic collimation-adjust system is incorporated to control the divergence of the laser beam as it leaves the beam expander. To automate this process, a stepper motor is installed next to the beam expander. The stepper motor is computer-controlled, and a McMaster-Carr antistatic belt (not shown in Figure 3) transfers torque from the stepper motor shaft to the beam expander focus.
TRANSMITTER TRACKING SYSTEMS

The receiver system uses a geared pedestal to track the transmitter. The pedestal is mounted on a tripod and controlled by a computer. EAFB personnel provided this tracking system and left a bare plate on top for the receiver telescope, beacon laser and optical train. The telescope and beacon laser are both mounted on the pedestal and are manually alignable. A digital video camera is also mounted on the pedestal which can be used for visual reference, but is not necessary for dynamic tracking. The equipment necessary for the operation of the pedestal is mounted on a cart to make the receiver as portable as possible.

**Transmitter Tracking System Control**

A LabVIEW auto-tracking program provided by EAFB uses the position data received by the RF modem from the transmitter to calculate the azimuth and elevation angle to which the pedestal must move. The pedestal updates its position at 10Hz as new coordinates from the transmitter are received. The system also allows for manual tracking using a Cohu video camera mounted on the top of the pedestal. A joystick moves the pedestal with the video image output displayed on the computer monitor.

**Transmitter Tracking Accuracies and Link Budget**

To receive the signal from the transmitter, the telescope must have a field of view larger than the max angular error of the transmitter. The field of view of the telescope is 17.4 mrad (0.997°), which is more than sufficient given that 5 mrad (0.286°) was the max error of the transmitter. The pedestal mount system at the receiver tracks the moving transmitter to within 1 mrad (0.057°). Given this error, the beacon laser requires a divergence of at least 1 mrad (0.057°) to ensure that the PSD system will receive a signal. At 60 miles, this divergence results in a footprint of approximately 200 m.

The received power based on a link budget analysis (over a distance of 60 miles) is estimated at –58.1 dBm or 1.5 nW. Because the received signal is very small, the system has a lock-in amplifier at the output of the photodiode, which improves the signal-to-noise ratio. Due to the high cost of commercial lock-in amplifiers, a custom lock-in amplifier is designed for use in the system from inexpensive components. Estimates indicate that a signal 30dB below the noise floor can be detected with a high-quality commercial lock-in amplifier.

**SYSTEM COMPONENTS SUMMARY**

The following tables are lists of the components used to fulfill the system design.

**Table 1: Transmitter Component List**

<table>
<thead>
<tr>
<th>Part</th>
<th>Function</th>
<th>Manufacturer and Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Driver / Temp.</td>
<td>Power, Control Laser</td>
<td>Thorlabs ITC 502</td>
</tr>
<tr>
<td>Controller</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butterfly Laser Mount</td>
<td>Dissipate laser heat, allow for direct modulation</td>
<td>ThorLabs LM14S2</td>
</tr>
<tr>
<td>Laser Amplifier</td>
<td>Increase beam power</td>
<td>IPG Photonics EAR-1K-C</td>
</tr>
<tr>
<td>250 kHz Photodiode</td>
<td>Convert light signal to voltage</td>
<td>IGA-020-H/250kHz</td>
</tr>
<tr>
<td>20 MHz Photodiode</td>
<td>Convert light signal to voltage</td>
<td>IGA-010-H/20MHz</td>
</tr>
<tr>
<td>100 MHz Photodiode</td>
<td>Convert light signal to voltage</td>
<td>IGA-003-H/100MHz</td>
</tr>
</tbody>
</table>
Laser Diode | Generate laser beam | Thorlabs LDM5S750
---|---|---
Position Sensitive Detector | Track beacon signal | Electro-Optical Systems IGA-030-PSD-E4
Optical Bandpass Filter | Reduce IR optical noise | Thorlabs FB1550-12
Large Lens | Focus beam onto PSD | Thorlabs LA1740-C
Lens Tubing | Structural support | SM1L10, SM3A1, SM3L10
Diverging Lens | Increase effective field of view | Lambda Research Optics BCC-25.4N-025
Beam Expander | Adjust divergence | Thorlabs BE05X
Collimating Lens | Reduce divergence | ThorLabs F240APC-1550
GPS Antenna | Estimate position | Trimble GPS Antenna
Rack-Mount Computer | Runs LabVIEW software | SuperLogics SL-R1U-MB-MINI-LC-B
GPS/INS | Monitor position/attitude | Systron Donner MMQG GPS/INS
Data Acquisition | Sample PSD inputs | NI USB-9215
Data Acquisition | Send motor commands | NI USB-6501
Gimbal (6 in.) | Azimuth actuation | Aerotech ART315-M-G54-BMS-HC
Gimbal (4 in.) | Elevation actuation | Aerotech ART310-M-G54-BMS-HC
Gimbal Driver/Controller | Control gimbal stages | Aerotech SOLOIST10-AUXPWR
L-bracket | Connect gimbal stages | Aerotech HDZ3M
Data Acquisition | Sample PSD inputs | NI USB-9215
Stepper Motor | Adjust beam expander focus | Anaheim Automation 14Y
Antistatic Belt | Connect motor, beam expander focus | MMC 6082K51
Ethernet Hub | Connect computer, rotational stages and controllers | MMC 3787T2
RF Modem | Transmit position data | Provided by EAFB

**Table 2: Receiver Component List**

<table>
<thead>
<tr>
<th>Part</th>
<th>Function</th>
<th>Manufacturer and Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodetector</td>
<td>Convert light signal to voltage</td>
<td>Electro Optic Systems IGA – 030</td>
</tr>
<tr>
<td>XY Translator</td>
<td>Adjust photodiode</td>
<td>Thorlabs LM1XY</td>
</tr>
<tr>
<td>Video Camera</td>
<td>Confirm tracking</td>
<td>Cohu</td>
</tr>
<tr>
<td>Optical Bandpass Filter</td>
<td>Reduce IR noise</td>
<td>Thorlabs FB1550-12</td>
</tr>
<tr>
<td>Telescope</td>
<td>Collect optical signal</td>
<td>Meade LX200 series</td>
</tr>
<tr>
<td>Beacon Laser</td>
<td>Generate beacon laser beam</td>
<td>Qphotonics QLDM-1550-500</td>
</tr>
<tr>
<td>Pedestal</td>
<td>Aim telescope</td>
<td>RPM-PSI PG503A</td>
</tr>
<tr>
<td>RF Modem</td>
<td>Receive position data</td>
<td>Provided by EAFB</td>
</tr>
<tr>
<td>Telescope Mounting Rings</td>
<td>Mount telescope on pedestal</td>
<td>Parallax PA-10IN</td>
</tr>
</tbody>
</table>

**Table 3: Gimbal Assembly Component List**

<table>
<thead>
<tr>
<th>Part</th>
<th>Function</th>
<th>Manufacturer and Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Plate</td>
<td>Structural stability</td>
<td>MMC 8975K221</td>
</tr>
<tr>
<td>Shoulder Bolt</td>
<td>Distribute weight of gimbal assembly</td>
<td>MMC 94035A542</td>
</tr>
<tr>
<td>Bearing</td>
<td>Bear gimbal assembly weight</td>
<td>MMC 6383K214</td>
</tr>
<tr>
<td>Set Screws</td>
<td>Adjust orientation of PSD</td>
<td>Thorlabs F3ES25</td>
</tr>
<tr>
<td>Threaded Bushing</td>
<td>Hold set screws</td>
<td>Thorlabs F3ESN1</td>
</tr>
<tr>
<td>Spring Plunger</td>
<td>Keep PSD against set screws</td>
<td>MMC 2277A512</td>
</tr>
</tbody>
</table>

**Table 4: Lock-In Amplifier Component List**

<table>
<thead>
<tr>
<th>Part</th>
<th>Function</th>
<th>Manufacturer and Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-Locked Loop (PLL)</td>
<td>Lock onto beacon signal</td>
<td>Exar XR2212</td>
</tr>
<tr>
<td>Analog Multiplier</td>
<td>Lock-in amplifier operation</td>
<td>Analog Devices AD534JH</td>
</tr>
<tr>
<td>Trim Potentiometers</td>
<td>Adjust locking frequency</td>
<td>Bourns, Inc. 3059P-1-503LF</td>
</tr>
<tr>
<td>Op-Amp</td>
<td>Lock-in amplifier operation</td>
<td></td>
</tr>
</tbody>
</table>
RESULTS

All of the subsystems were constructed and tested. However, the integration of these subsystems was much more difficult than anticipated, and was not completed. Initially, a full system ground test and flight test had been planned for early March of 2007, but the system was not finalized in time. At the time of this report, a successful full system test has not been achieved on the ground or in the air. Before the system can be flight tested, a successful ground test must occur.

Data Path and Optics Results
The receiver was demonstrated capable of receiving and demodulating frequencies between 10 kHz and 60 MHz. All three photodiodes of different bandwidths were used during separate tests and each successfully received transmitted square waves at frequencies within their respective bandwidths. Due to time constraints, no bit-error-rate testing was attempted. At a distance of roughly 70 meters a 5 Vpp square wave with roughly 50 mV of noise was registered on the 250 kHz bandwidth photodiode from a 0.3 Watt laser beam modulated at 100 KHz. The laser beam was collimated to 0.887 degrees (15.5 mrad) divergence and the photodiode was set to low-gain. The link budget predicts approximately a 1 Vpp signal, which is within an order of magnitude of the actual result. Similar results were achieved at higher bandwidths, but received signal amplitude was lower as data frequency increased. No quantitative data was recorded for the two higher bandwidth photodiodes.

The PSD optical train was tested by aligning the un-collimated beacon laser beam and the PSD optical train over a distance of one meter. Due to time constraints, no quantitative value for the PSD optics’ field-of-view was experimentally determined, but the system appeared to function as expected.

Tracking Systems Results
The automatic target tracking software and hardware for the receiver was designed and constructed by EAFB personnel. EAFB designed a plate and ring system to hold the HMC telemetry equipment. Tests conducted by EAFB personnel verified the automatic tracking accuracy to be within 1 mrad (0.06°).

The gimbal assembly was machined and assembled. The key design characteristics were evaluated, including center-of-mass placement, beam-expander orthogonality with the rotational axes at the zero position, and set-screw alignment effectiveness.

The GPS/INS based automatic tracking system was tested and is functional under both static and dynamic conditions. Both static and dynamic tests were conducted by securing the transmitter in the bed of a pickup truck and tracking a receiver location with known GPS coordinates.

Static and dynamic tests of the GPS/INS-based tracking system were conducted successfully. The MIGICOM software (provided by Systron-Donner for customers to control their MMQG GPS/INS units) was used to send initialization commands to the GPS/INS unit. With increasingly rapid changes in motion, the GPS/INS unit provided greater position accuracy.
The PSD-based tracking system was designed and implemented, but only partially tested. Time constraints prevented complete testing and successful demonstration of PSD receiver tracking. The automatic collimation-adjustment system was successfully built and integrated into the full system.

**Full System Integration, Testing, and Results**

Full system testing was limited due to problems encountered with subsystems and subsystem integration. Full system testing was conducted by placing the transmitter in the back of the pickup truck, which simulated an aircraft. Static transmission testing was successful but not tested at long ranges. Range testing was demonstrated in the previous academic year. Dynamic transmission using the GPS/INS system was not attempted, although dynamic tracking was functional. PSD-based tracking was not attempted due to problems with subsystems.

In summary, extensive subsystem integration was conducted, but the system was not fully integrated. The transmitter data path, optics and tracking systems were successfully integrated but not completely functional. All receiver subsystems, including the optics and tracking systems, were successfully integrated and demonstrated. Should EAFB decide to continue the project, all that remains is testing and some limited system hardware and software modifications.

**ACKNOWLEDGEMENTS**

We would especially like to thank our liaisons at Edwards Air Force Base, Nathan Cook, Ronald Streich, Saul Ortigoza, and Glen Wolf for suggesting the project, arranging the on-base field tests and the facilities tours, and answering innumerable questions from the theoretical to how to connect the oscilloscope. We would also like to thank the Engineering Department Staff at Harvey Mudd College for their assistance with facilities and procurement.

**REFERENCES**


Hecht, Jeff, Understanding Fiber Optics, Pearson Education Inc., Upper Saddle River, New Jersey, 2006