Ground and Air Test Performance of the Laser Event Recorder

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ABSTRACT

The primary objective of this effort is to develop a low-cost, self-powered, and compact laser event recorder and warning sensor for the measurement of laser events. Previously we reported on the technology and design of the Laser Event Recorder. In this paper we describe results from a series of ground and airborne tests of the Laser Event Recorder.

Keywords: laser detection and wavelength measurement, laser dosimeter, laser sensor, laser eye safety, diffraction grating, focal plane array, CCD, CMOS, GPS

INTRODUCTION

The need still exists for a low cost detector for laser dosimetry, particularly in light of the recent spate of laser illumination incidents in commercial aviation. Laser exposure effects on the eye are highly dependent on illumination wavelength, energy level, and duration and can range anywhere from mild discomfort, glare and flash blindness, up to and including serious injuries such as cornea damage and retinal burn. Perhaps the biggest current issue in dealing with injuries from exposure is the large variation in symptoms for a given exposure, which is largely due to the lack of knowledge concerning the exposure.

The Laser Event Recorder (LER) has been developed in response to the need for accurate laser exposure information. The LER is a low-cost, self-powered laser sensor that detects the presence of a laser illumination; extracts irradiance, wavelength, pulse duration, pulse repetition frequency, time and location of exposure, and an image of the scene containing the laser; warns personnel as to whether the exposure level poses a hazard to eye safety; and saves the exposure and scene information to a file that can be downloaded for analysis. Specific details on the design of the

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device have been reported previously[1]. In this paper we present an overview of testing that accompanied the development of the LER including some specific test results.

TEST OVERVIEW

Detailed design of the LER occurred over a two year period and took the system from paper concept to fully functional prototypes. Concurrent with the design was an outdoor test program that consisted of three ground tests and one flight test. The test philosophy was based on a series of incremental development cycles followed by a ground test, in each case testing out the fundamental operating principals of the device with more advanced hardware and software. In the first ground test, representative off-the-shelf hardware was integrated and configured with simple laser detection algorithms and performance was measured in an all static environment; in the second ground test the key custom components were integrated into the hardware along with detection algorithms based on data from the first ground test and performance was measured in both static and dynamic environments; in the third and final ground test fully functional LER prototypes were tested in both static and dynamic environments and effectively represented a dry run for flight testing. More than 100 hours of ground testing were logged against the various LER prototypes and over 11 hours of flight testing.

GROUND TESTING

Location

Ground testing was performed at the Naval Air Station Webster Field Annex in St. Inigoes, Maryland. Figure 1 depicts the layout of the airfield and also shows the location of the hardware for a typical test scenario. Head-on testing was performed on the runway highlighted in the image and aspect testing was performed using the runway that is close to perpendicular. The airfield allowed for testing ranges from about 500 feet between the source and LER to about 4500 feet maximum separation.

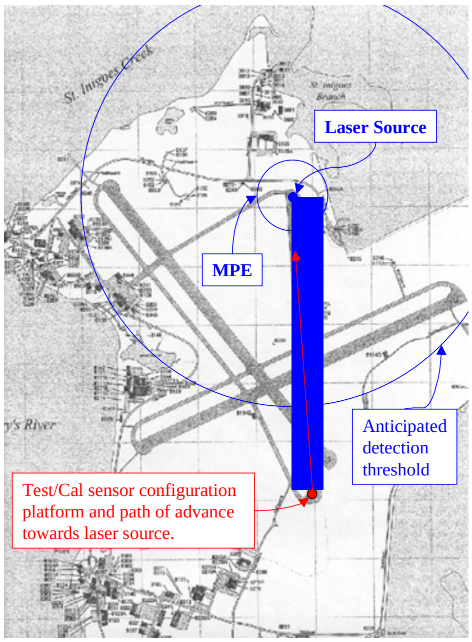


Figure 1 Location of ground testing, Webster Field Annex, St. Inigoes, Maryland

Sources

Table 1 shows the sources used throughout the three ground tests of the LER. The laser configuration was provided by Naval Health Research Center (NHRC) Detachment Brooks City-Base. The lasers were mounted on a tripod and bore sighted with telescopic CCD and thermal imagers. The laser configuration also included video recording with GPS timestamp in order to synchronize the shooter′s view with the data collected by the LERs. Figure 2 shows an image of a laser configured for testing the LER.

Source	Type	Wavelength
Laser 1	Continuous	532 nm
Laser 2	Pulsed, 20 ns, 20 Hz	1064 nm
Laser 3	Continuous	830 nm

Table 1 Ground Testing Source List

LER Test Hardware

The goal of the design for the initial prototype was to achieve functionality of the fundamental operating requirements in a modest package. Figure 3 shows an image of the initial prototype during the first ground test. The key components tested using this prototype were laser detection, pulse length and pulse repetition frequency (PRF) measurement using a Silicon photodiode, and data transfer and archival to a removable CompactFlash storage media. All the components in the prototype were commercial off the shelf parts. The unit did not perform scenery capture and geo-positioning.

In preparation for second ground test, the prototype was retrofitted with hardware that had been selected for the final design. Key items added or updated included the attenuation filters, diffraction grating, custom collection optics, and an InGaAs photodiode to take high-speed pulse detection out to 1600 nm. The system also integrated GPS technology and allowed for geo-positioning and synchronization of the laser event measurement with distance from the source. Data from each frame processed was streamed to a file at a 15 Hz update rate and allowed for detailed analysis of collected event information.

The third ground test used three fully functional prototypes based on the final system design. The hardware included all the functionality of the ground test two hardware along with the scenery capture capability. The units were configured for operation in two modes: data streaming and final. Data streaming was similar to ground test 2 with data from each frame being saved to a file. In final mode the system collects and processes event statistics in real time throughout a laser event. Event duration is the time period over which a series of laser detections are measured with no more than two seconds delay between any two adjacent detections. At the end of each event a summary of the event information is saved to text file along with an image of the scene.

Figure 4 shows an image of the three final prototypes taken during the third ground test. Note that the brackets were designed to place the two outer prototypes at the edge of the system field of view. The packaging of the prototypes was rated for operation in harsh environments and was indeed tested during ground test 3 as operating conditions were bitter cold temperatures with periods of rain, snow, sleet, and ice.

Figure 2 Laser source configured for testing the LER

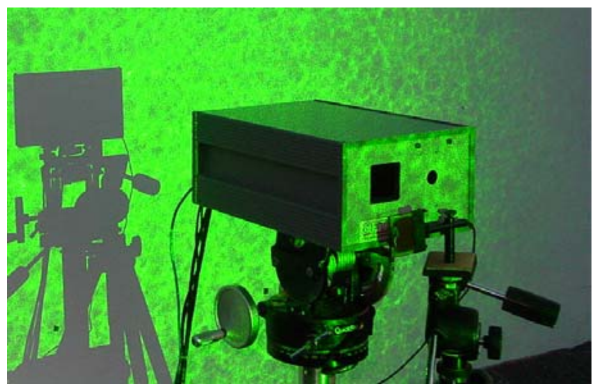


Figure 3 First prototype used in ground testing the LER

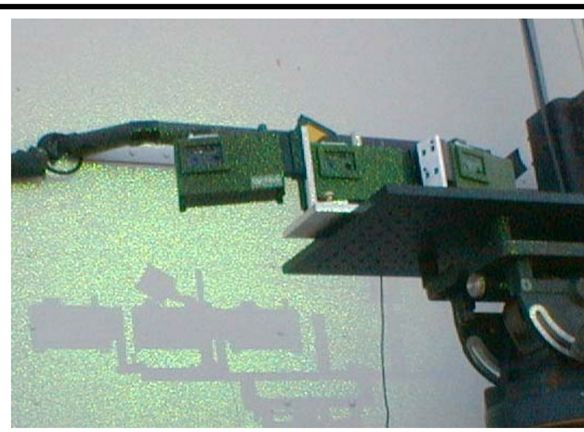


Figure 4 Final LER prototypes used in the third ground test and flight test

Test Results

All the lasers were correctly identified in each of the ground tests in a variety of static (non-moving) and dynamic (moving) scenarios. False alarm testing was performed against a variety of manmade sources as well as natural sources such as sun glints, none of which produced any false alarms.

Figure 5 shows a comparison of measured irradiance of Laser 1 for all three final prototypes. The range to the source was 2000 ft and the source intensity was sequential stepped through different power levels, which is clearly shown in the data. Two of the prototypes were positioned such that the source incident angle was at the edge of the system field of view and one was orientated directly toward the source. In general, a good overlay of measurements is seen between the three sources, with the slight decrease for the offset prototypes due to the onboard conversion process from counts to irradiance not yet taking into account source angle of incidence.

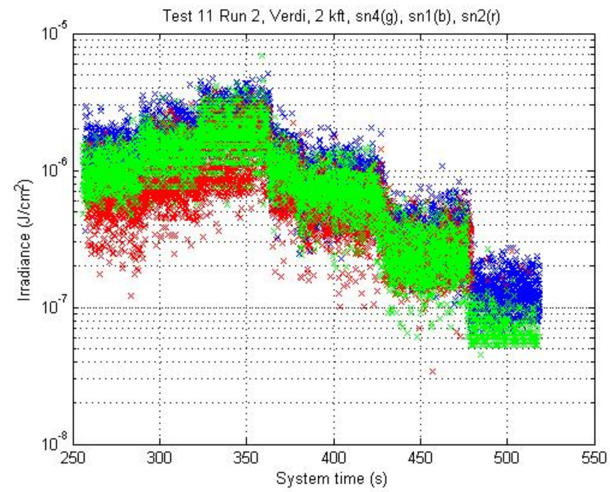


Figure 5 Laser 1 irradiance measurement comparison of the three prototypes at 2000 ft from the source

Figure 6 shows the wavelength measurement history of two final prototypes from a dynamic aspect run against Laser 1. The relative angular offset between the two sources was 40 degrees, which resulted in a handover between the two prototypes when the line of sight to the source relative to the mounting platform went through 90 degrees. The data shows wavelength accuracy at the desired 10 nm level across the field of view.

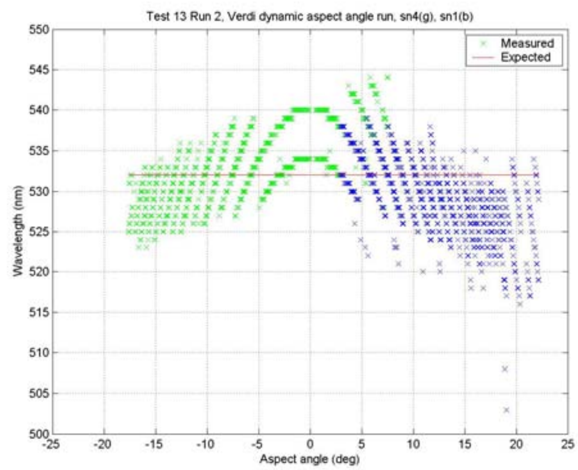
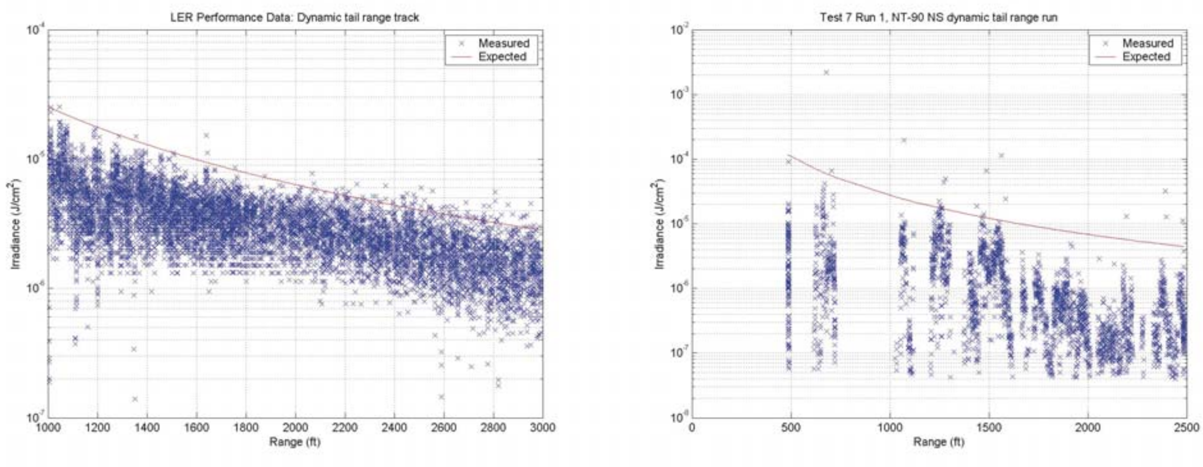


Figure 6 Laser 1 wavelength measurement comparison for two prototypes across a range of incident angles

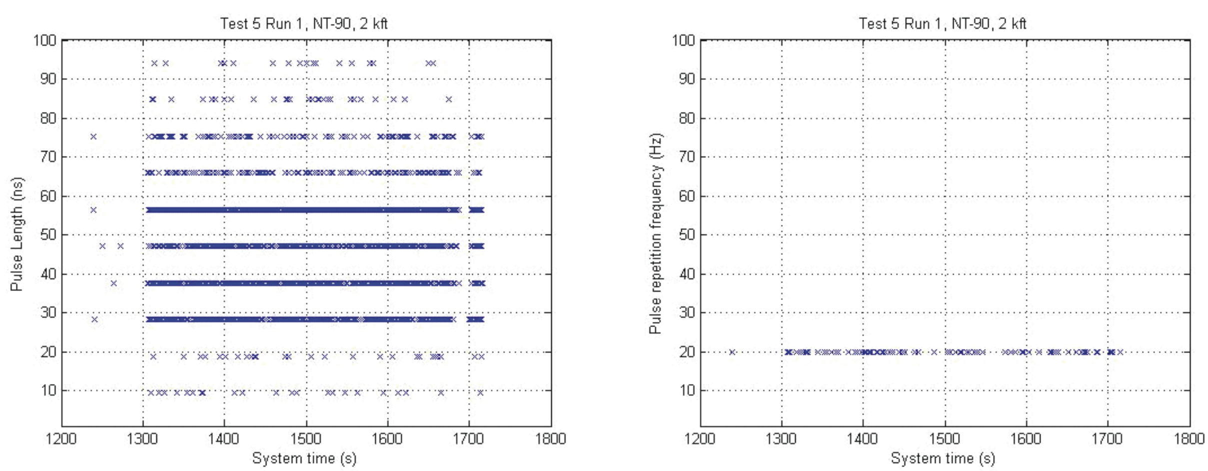
Figure 7 shows irradiance measurements as a function of range from Laser 1 (Figure 7a) and Laser 2 (Figure 7b). A solid curve is also included and is the expected level of irradiance based on source configuration and range. The variation in irradiance levels is due to the source being swept on and off the LER during the run and atmospheric scintillation effects. The low duty cycle and repetition rate of Laser 2 also further degraded the LER capture rate for that scenario.

Figure 8 shows pulse length (Figure 8a) and PRF (Figure 8b) measurements against Laser 3 at a range of 2000 ft. The LSB of the pulse measurement electronics results in quantization at approximately 10 ns, which is the minimum measurable pulse length. The pulse length data also shows pulse stretching due to saturation of the detector. The PRF measurements show the 20 Hz repetition rate was correctly measured by the LER.



(a) **(b)**

Figure 7 Measured irradiance plotted as a function of range from the source, as recorded by the LER, under illumination from Laser 1 (a) and Laser 2 (b)



(a) **(b)**

Figure 8 Recorded pulse data for Laser 2. The left hand figure (a) shows the measured pulse length and the right hand figure (b) shows the measured PRF

FLIGHT TESTING

Location

Flight testing was performed with the cooperation of the Naval Strike and Air Warfare Center at the Naval Air Station Fallon, NV, in accordance with the US Navy laser safety[2] and flight testing instruction[3]. Figure 9 shows the location of testing and indicates the four flight paths used during LER testing. Flight paths 1 and 3 were head-on approaches going west and north respectively. Flight paths 2 and 4 were approaches that resulted in the incident angle of the LER varying across the system field of view. The direction of the flight paths also allowed testing against the source with the sun in the system′s field of view at the end of the day. Each flight path started 2 Nmi from the source and ended 1 Nmi from the source, with the helicopter flying at an altitude of 200 ft.

Sources

Table 2 shows the sources used for flight testing of the LER. The laser configuration was again provided by NHRC Detachment Brooks City Base, with a similar mounting and operating configuration as used in ground test.

Source	Type	Wavelength
Laser 1	Continuous	532 nm
Laser 2	Pulsed, 20 ns, 20 Hz	1064 nm
Laser 3	Continuous	830 nm

Table 2 Flight Testing Source List

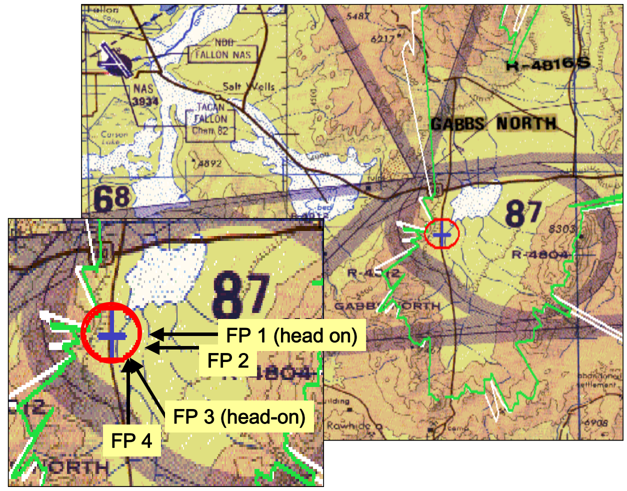


Figure 9 LER flight test location and layout of the four paths flown during testing

Aircraft Platform

Flight testing of the LER was provided by the HH-60H HCS Rescue Hawk Helicopter. Figure 10 shows the mounting configuration of the LER inside the cockpit of the helicopter. An LER was mounted to both the port and starboard side of the aircraft with the units aligned 10 degrees in azimuth relative to straight ahead, which provided a region of angular overlap between the two units. One unit was configured in data streaming mode (port) and the other in final mode (starboard).

Figure 10 LER mounting in the HH-60H Helicopter. The batteries and CompactFlash card were easily accessed and exchanged by removal of the panel on the bottom of the LER, as shown in the image on the right

Test Results

The LER correctly captured all three laser sources in the various test scenarios during three days and nights of flight testing. Occasional false alarms were recorded due to direct viewing of the sun. Also, while ambient temperatures above 40 C did not result in false alarms it did occasionally corrupt laser event statistics due to increased sensor noise.

Table 3 shows an excerpt of final mode data obtained from testing Laser 1. The data for each separate event is summarized in a single row of information in the table. *Image Number* provides a pointer to the scenery image for the event. *Source Type* has two values: *C* for continuous source and *P* for pulsed source. *Column* and *Row* provide the pixel location in the Focal Plane Array of the laser's location in the scenery image. *Wavelength* provides the laser wavelength in nanometers. *Event Irradiance* provides the summed total energy irradiance (J/cm^2) measured over the duration of the event. *Pulse Length* and *PRF* contain high speed data for pulsed sources, and *Pulses* provides the total number of pulses detected over the duration of the event. Note that for continuous source events the high-speed data defaults to zero. *Event Duration* provides the elapsed time from the first to the last laser detection that was recorded during the event. The remaining columns provide position and time data obtained from the onboard GPS. Note that the GPS units were unable to synchronize with enough satellites inside the cockpit, which resulted in the old, non-varying data being downloaded to the file. The unit does contain a GPS battery backup that provides time information in the event of loss of synchronization with satellites. It is clear from the data that the LER accurately quantified the laser source. It is also clear from the duration data that the shooter did a good job of maintaining track during the flight run.

Image Number	Source Type	Column	Row	Wavelength (nm)	Event Irradiance (J/cm^2)	Pulse Length (ns)	Prf	Pulses	MPE	Event Duration	Latitude	Longitude	Altitude	Date	Time
240	C	168	332	534	2.68E-05	0	0.0	0	0	6.20	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:33:37
241	C	122	345	531	6.73E-06	0	0.0	0	0	2.43	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:33:47
242	C	268	315	528	9.71E-05	0	0.0	0	0	10.20	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:36:08
243	C	302	345	540	2.99E-05	0	0.0	0	0	2.30	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:36:15
244	C	92	328	526	1.01E-03	0	0.0	0	0	20.70	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:36:42
245	C	266	335	536	1.11E-03	0	0.0	0	0	5.27	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:38:55
246	C	36	343	531	1.66E-04	0	0.0	0	0	15.60	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:39:36
247	C	212	369	537	6.27E-05	0	0.0	0	0	3.63	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:41:52
248	C	199	327	533	2.57E-05	0	0.0	0	0	1.40	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:41:58
249	C	108	298	529	5.77E-04	0	0.0	0	0	16.10	34:44:00.0000N	135:20:60.0000E	0	1/5/2002	22:42:21

Table 3 Final mode data obtained in flight testing Laser 1

Figure 11 shows a scenery image taken during an event that the LER detected Laser 1. As is clear from the figure, the laser was being directed onto the LER during scene capture and can be seen in the lower right hand portion of the figure. The image shows that there is some blooming in the array in the region adjacent to the image of the laser source, but that it was not enough to degrade the overall information content of the image.

The next generation LER system will integrate an overlay on the image that contains the event information summarized in the previous table, thus providing a succinct summary of the operating parameters and visual location of the laser source detected by the LER. The image and data will be saved in the standard JPEG format, allowing for quick post-mission dissemination.

Figure 11 Scenery image obtained during flight test of Laser 1

SUMMARY

OPTRA, Inc. has successfully designed, developed, built, and tested a laser event recorder towards the objectives established by NAVAIR. The LER was proven suitable for use in ground and air applications through a series of outdoor tests culminating in the detection of continuous visible and pulse infrared lasers in flight aboard an HH-60H helicopter through the cooperation of NHRC Detachment Brooks City-Base and Naval Strike and Air Warfare Center.

Table 4 shows a summary of the measured performance compared to the original set of specifications. Work continues towards optimizing the accuracy of radiant exposure, detection rate and false alarm rejection, maximization of dynamic range, and aircraft mounting options. Testing also continues in support of military applications such as high energy laser development. Delivery of updated LER units to the US Navy is planned for later this year.

Parameter	Specification	Measured Performance
Wavelength (nm)	400 - 1600	532, 830, 1064, and 1318
Wavelength Resolution (nm)	10	7
Exposure Duration (s)	10^{-8} - continuous	8×10^{-9} - 10
Exposure Level (MPE) MPE: Maximum Permissible Exposure	MPE/100 - 100×MPE	MPE/100 - 100×MPE
Pulse Length (ns)	10	8, 20
PRF (Hz)	0.5 - 20000	0.5 - 20
Field of View (deg)	≥ 40	40
Dynamic Range	10000:1	4400:1
Operating Lifetime (hours) /Data Storage (events)	6 / 60	7 / 100
GPS Time (s) /Location (m)	≤ 1 / ≤ 20	1 / 20
Unit Cost ($)	≤ 500	≤ 3000 (100 unit lot build)
Aircrew Warning	Below/Above MPE	Yellow (below) / Red (above)
Environmental	Military aircraft	HH-60H helicopter

Table 4 LER Final Performance Summary

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[3] Chief of Naval Operation Instruction and Commandant of the Marine Corps Order OPNAV INST 5100.27 / MCO 5104.1A, CNO N45/CMC(SD), 30 Aug 2002