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FIELD-TESTING OF AN ACTIVE LASER TRACKING SYSTEM (ALTS)

Vladimir Markov, Anatoliy Khiznyak, Dirk Woll
MetroLaser Inc., 2572 White Rd., Irvine, CA, 92614-6236

Shiang Liu
The Aerospace Corporation, 2350 El Segundo Bl., El Segundo, CA, 90245

Roberta Ewart
Air Force Space and Missile Systems Center, LAAFB, CA, 90245

ABSTRACT

A prototype of an active laser tracking system (ALTS) has been developed with its operation based upon the fundamental principles of the non-linear optical phase conjugation. The key element of the ALTS is the phase conjugate mirror (PCM) that enables to compensate aberrations in the optical cavity and the laser system to operate in atmospheric turbulent environment. Although the current prototype design serves to prove the concept of its operation, i.e. tracking the remote target, when fully integrated, it should be capable to quantify target's 3D state vector and velocity, as well as characterize its maneuvering operations and vibration features. This paper outlines the first field-test execution of the ALTS, and in particular, it discusses the rational, the concept, development of the test plan and some details in its realization.

1. INTRODUCTION

Reliable and consistent capabilities in space surveillance as well as tracking and characterizing the space-borne objects are critically important to national security and many phases of military operations. Numerous space surveillance functions that require active tracking, pointing and discriminating the space targets are currently performed by and large using various radar systems. The increasing density of the space objects, as well as new type of the space-based multi-station terminals requires the technique with increase accuracy and capabilities for tracking their 3D state vector and velocity. Classical RF-based radiometric methods typically can not satisfy the desired requirements and provide the needed accuracy.

An alternative solution to this problem can be achieved by using optical systems for tracking remote targets. Passive optical space surveillance with telescopes is a classic astronomic technique that is nowadays getting a boost due to continuous improvement in the imaging quality with adaptive optic systems. This enables passive optic systems to perform better space object characterization (direct image, radiometry, colorimetric, etc.). For example, passive-operation Space-Based Visible program [1] made considerable contribution to the space surveillance through its real-time tracking capabilities and improved measuring accuracy. There is however an important deficiency in passive systems with their failure of direct reading the velocity of the space objects, the parameter of primary importance for a trajectory analysis. In addition, most if not all ground and space based passive optical tracking systems perform well with a sunlight illuminated objects [2,3,4] thus limiting surveillance of the objects that are in eclipsed phase or shadowed.

Use of a laser to illuminate the space objects for its subsequent tracking and characterization from the ground, airborne or space based platforms is an alternative technique that has some advantages as it allows for active operations that can be essential for space surveillance, space control or protection missions. This technique however faces difficult technical challenges due to the great distances involved and high speed and trajectory variations of a target [5]. In addition, atmospheric turbulence remains an crucial factor as it introduces substantial losses in signal fidelity [6]. There are basically two laser techniques to implement surveillance functionality: passive and active.

Passive laser tracking of the satellite is an established technique that is made possible by collecting the light scattered off a target illuminated by specially directed laser beam [7]. The Satellite Laser Ranging (SLR) is the reputable international program that through the International Laser Raging Service (ILRS) provides their users with the information on orbital details of the satellites associated with this program [8]. The primary mission of the ILRS is to support, through the satellite and lunar laser tracking data and related products, geodetic and geophysical research activities. The technique enables range measurements with resolution of the order of 10^{-3} m. Low return signal is the key problem with laser ranging, and therefore it uses retro-reflectors on the satellite and operates in the photon counting regime for the returned signal. This inevitable restricts the operation of such a technique to the cooperative target mainly. In addition, like with other passive optical tracking and surveillance methods, lack of the information on velocity of the target is an important SRL limitation, as it doesn't allow foreseeing target trajectory and its variations in real-time.

An alternative solution to this problem is with an active laser tracking technique. Compensation of atmospheric turbulence can be accomplished by introducing the perturbations with an exactly opposite sign to that of the atmospheric turbulence in the wavefront of the propagating beam. As a result, mutual compensation of these perturbations may result in an increase of the power density on the target, and therefore in an increase of the returned signal intensity, leading to an improved system resolution and improved tracking efficiency. Although various types of systems, including deformable mirrors and spatial light modulators have been suggested for such wavefront pre-distortion [9], the most general solution to this problem can be achieved by using Optical Phase Conjugation (OPC), the technique that was experimentally proven capable for turbulent atmosphere compensation [10].

An OPC-based active laser tracking system (ALTS) has been discussed before [11,12]. The ALTS comprises of several platforms, integrating a laser, its drivers and controllers, beam steering and detection units. The hybrid laser configuration [13] is the heart of the ALTS, and is conceptualized in the design of a coupled-cavity architecture. The coupling of the cavities is achieved through the phase conjugate mirror (PCM), generated through a four-wave mixing effect in an optically non-linear medium. The use of a gain medium in the phase conjugate leg of the cavity compensates for the low return signal intensity. The four-wave mixing effect enables to apply the fundamental principles of optical phase conjugation to compensate for spatial inhomogeneities of the atmosphere. The innovative ALTS concept makes it possible to retrieve the information that can provide the real-time measurements of the angular position, distance and velocity of the target. A detailed description of the ALTS analysis, design and results of its laboratory evaluations was given in [11,12,14]. However, the conclusive assessment on performance capabilities of its preliminary design can be obtained only after a series of field tests performed in an environment similar to real operational, making such tests a necessary step in further system development and enhancement.

2. TEST PLAN AND IMPLEMENTATION

2.1. Background

The ALTS test effort entails the development of a system for tracking, identification and discrimination of a remote target. According to this Plan the prototype system should be tested for its ability to self-track a steady (and possible, moving) object positioned at a variable distances from the sensor's platform. It incorporates and consolidates previously developed technologies, as well as technologies that are currently under development, for an improved single-platform system for optical tracking the remote target. These technologies include an innovative coupled-cavities active laser sensor system with its operation based on the principles of optical phase conjugation. An accompanying paper entitled *Integrated multi-sensor system for space surveillance – design, engineering, integration and test*, by S. Liu et al. [15] describes the integration of passive visible-near IR (VNIR) and mid-IR (MVIR) sensors into ALTS for enhanced performances. The ultimate goal of the test is to validate the ALTS concept and assess its potential for space surveillance application.

2.2. Test Objective

The main objective of the field test was to evaluate the performance of the ALTS in an environment comparable with realistic deployments. Subjects of specific interest include the range of operation at the current level of design and system functionality and operation with a cooperative target as outlined in the Test Criteria (see **Table** 1**)**.

At the current stage of ALTS design it is essential to verify whether its conceptual architecture would be able to support and sustain tracking operation in a cluttered environment of the air filled up with a fine dust along the line of sight on the path to target, and in a gusty wind conditions, making mutual passion of the ALTS and the target very unsteady. These factors, although being essential for test field operational settings, were not outlined in the original plan for the top-level Specific Test Objectives (STO) (shown in **Table** 1**)**, as they were not well foreseen before the factual test-field conditions were realistically observed.

The STO were established, based upon their priority. As such, the STO outlines a step-by-step test evolution from tracking the “high-contrast” targets (short range), then the “realistic” targets in tactical conditions (mid-range), culminating with the targets at extended operating conditions (long-range), including such complicating factors as atmospheric turbulence, partial obscurants along the line of sight, and mutual displacement between the ALTS and target platforms. STO completion was verified through practical examination of system performance at various operational scenarios, which are defined by the distance to the target, target orientation and visibility, as well as environmental factors.

Table 1. ALTS Test Criteria and Objectives.

General ALTS Test Criteria	
1.	Range validation – ALTS performance in realistic environment.
2.	Demonstration of ALTS performance: a. Steady target at different distances along tracking path. b. Variable target orientation. c. Moving target upon the test location resources.
3.	ALTS responsivity to the targets with different characteristics from “idealized” to “realistic.”
Specific Test Objectives (STO)	
STO 1	Demonstrate the ALTS short-range performance (≤ 500 m). Use cooperative/enhanced targets to optimize the links. The main goal of this test is to initially verify the ALTS capabilities in non-laboratory field environment.
STO 2	Demonstrate the ALTS capability of coupling to mid-range targets (≤ 2000 m). Multi-sensors suite operation check-up.
STO 3	Evaluate the ALTS performance under extended operating conditions (longest possible range) as defined by mission requirements. Evaluate tracking capabilities in realistic deployments that may include multiple targets within the system field of view, background clutter, and simulated noise.
STO 4	Demonstrate the ALTS performance under extended operating conditions, including atmospheric turbulence, partial target obscurants, and motion.

2.3. Test System Description

The ALTS in its present configuration consists of several modules, including a high-energy laser module (active sensor) that functions as an active sensor for long-range target tracking, with a suite of passive (visible and IR) sensors and data processing and control interfaces, as shown in **Figure 1**.

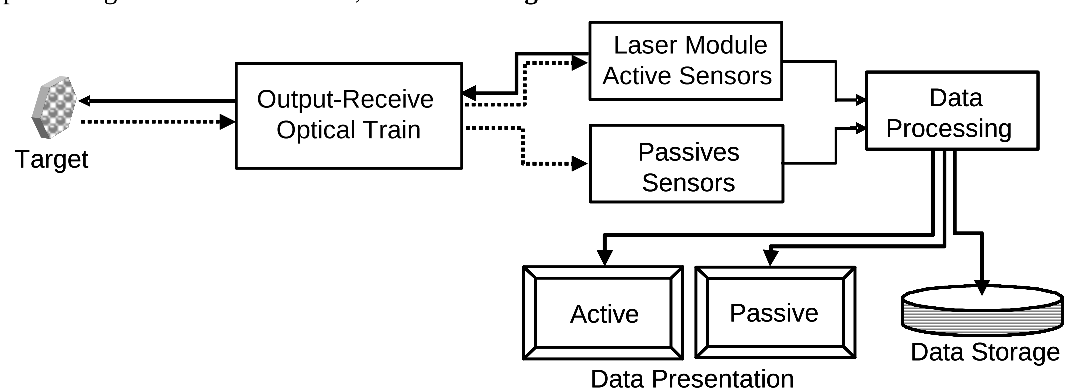


Figure 1. Block Diagram of ALTS and its operation.

For this tests the prototype ALTS was mounted on a movable platform (inside the track). After deployment, the optical train of the ALTS transmits to and receives to the sensing module the signals arriving from a set of targets. Several targets were set together, for these field-test experiments, including the retro-reflector for an active laser module and visible–IR target to be seen by passive sensors. This set of targets were mounted on a mobile platform (the vehicle), with latter to be repositioned in the course of the test along the selected test path at various distances from the tracking/detection platform.

While the pulse laser module of the ALTS was set to operate only with the retro-reflector, the passive detectors (CCD and IR cameras) looked at the target constantly. The lasing energy that circulates along the ALTS-target platforms path is defined by the pump level of the laser system and does not exceed 500 mJ/pulse. The divergence of the laser beam is less than 10 mrad. The ALTS' operation, including the pump level and circulating energy, data retrieval and signal processing, is entirely computer controlled. The processed data are then presented for review on a human-machine interface, which displays situational information to an operator. In addition, this interface serves for a steady visual control of the test field, thus preventing presence of non-authorized personnel in this zone during system operation. All test data are archived in a storage module.

2.4. ALTS Deployment and Resources

The Precision Impact Range Area (PIRA) at Edwards AFB was chosen as the location of this field test with ALTS deployment at Jackrabbit Hill and target poisoned or moved along the specified path around that area. **Figure 2** illustrates schematically the test location at Jackrabbit Hill at Edwards AFB, system deployment, positioning of the targets, and ray tracing from the ALTS to the target.

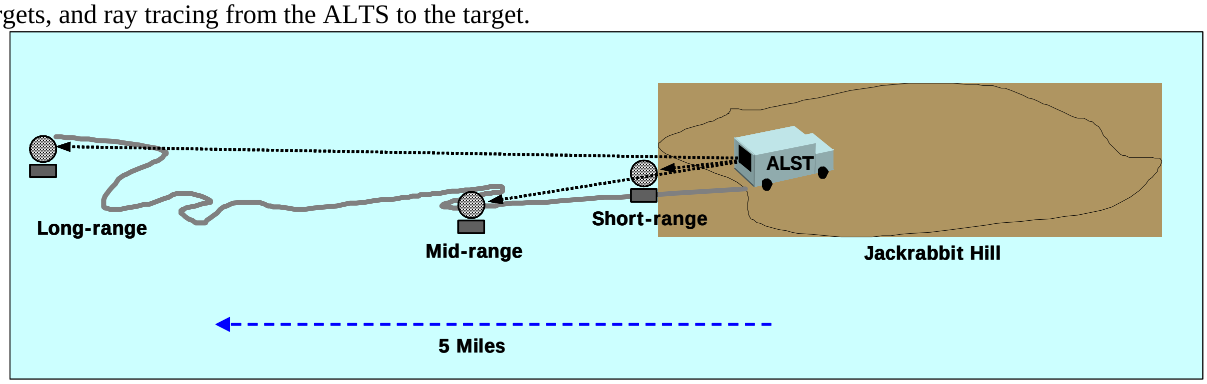


Figure 2. ALTS and Targets Deployment Scheme

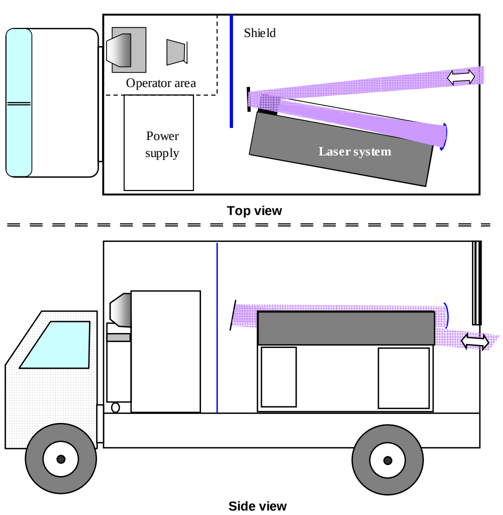


Figure 3. The schematic (a) and practical implementation (b) of the track loaded ALTS.

For this filed tests experiments the track-mounted ALTS operated through the hatchback door (see schematic in **Figure 3a**). The laser module of the ALTS was directed towards the target by a pointing system and is coupled to the target through an optical telescope. One of the mirrors of this telescope was set in a computer-controlled precision 2-axis gimbal attached to the ALTS bench.

As the name implies, the Active Laser Tracking System uses the advantages of laser technology for high-resolution tracking of the distant (in full capabilities, a remote) target. The actual ALTS to be tested is a solid-state Nd:YAG laser that oscillates at 1064.1 nm (see laser characteristics in Table 2). The laser module is an assembly of two cavities, (i.e. master and slave) that are coupled together in a single resonator and operate synchronously. The link between the cavities is achieved through the phase conjugate mirror (the coupler) that is generated in an optically non-linear medium (NLM) positioned in the master laser cavity. Interaction of the photons circulating in the master cavity with the spontaneous emission of the slave cavity results in formation of a dynamic (real-time) holographic grating in the volume of NLM. This grating couples the master-slave legs of the ALTS. Although the coupling efficiency is very low, its level is sufficient to launch the oscillation in the slave cavity once its output coupler (that is, the target) is in the field of view (FOV) of the system.

Table 2. Characteristics of the ALTS laser unit.

1.	Type of Laser	Nd:YAG Solid-state laser operating at 1064.1 nm.
2.	Mode of Operation	A free-running pulsed laser oscillation, Pulse duration ≤ 3 msec.
3.	Average Output Power	≤ 5 W
4.	Output Energy	≤ 500 mJ/pulse
5.	Type of Oscillation	Multi-mode, multi-frequency
6.	Repetition Rate	Single pulse to 10 Hz
7.	Emergent Beam Diameter	Defined by the exit system telescope, ≤ 8”
8.	Beam Divergence	≤ 10 mrad
9.	System FOV	≤ 17 mrad
10.	Required Electrical Supply	30 kW @ 208V; 3 phases, 60 Hz
11.	External Chiller	Not required
12.	Manufacturer's Name & Model #	MetroLaser custom design
13.	Laser Classification (ANSI Z136.1)	Class 4
14.	Potential Hazardous Range	ANSI Z136.1 Nominal Ocular Hazard Distance: 110 m

Both interacting platforms (the ALTS and the “target”) are equipped with the Garmin GPS 18 PC modules, which enable us to derive their local coordinates and mutual position. By using the NMEA-0183 protocol we were able to achieve an accuracy better than 30 cm in the retrieved spatial coordinates.

The ALTS operator and the field team were set on a local communication network through the walkie-talkies provided by range specialists.

2.5. Test Methodology and Operational Sequence

Various targets (visible, IR, and the laser retro-reflecting unit) were installed on the field positioned target platform (vehicle). Driving the vehicle from location to location will serve to extend the range between the target and the tracking (ALTS) platforms. Operating the ALTS with the target on the mobile platform can serve to simulate tracking of the moving target.

The test includes operation of the ALTS with the target positioned at an incremental range L from the laser platform. We start first with examining the system performance at a short range, positioning the target at the distance L about several hundreds meters from ALTS (operation at L ≤ 350 m has been tested in lab environment). Then we gradually increase the range to an extent that is defined by the operational capabilities of the laser tracking module. The proposed test of the ALTS requires the supporting assets from the range control facilities (electrical plugging), as well as range safety personnel operations and safety support.

Operation of the ALTS is as follows: Initiation of the master laser results in a steady injection of the photons into the slave cavity through the NLM. As described before, lasing in the slave cavity (which operates as the tracking leg) can be achieved only under the conditions when the target is in its FOV, which, in the current system design, is 17 mrad. Therefore, obstruction of the clear path of the slave cavity should result in an immediate termination of its lasing. Ultimately, no emission can be detected outside the ALTS when there is no target in its FOV. The prototype ALTS underwent a comprehensive testing at MetroLaser facilities. The results of these tests confirmed that no lasing energy leakage occurs outside of the solid angle, which is well-defined by the relative position of the target and its range from the laser platform. In a final system design, the ALTS software will retrieve the signals generated from an active (laser) and passive (Visible, NIR, MWIR and other possible) detectors, providing relevant imaging data on the target and laser performance.

The following sequence of the events illustrates a typical algorithm for the test:

1. System examination and setup.
2. Target setup at the test position.
3. Target location from passive sensors.
4. ALTS initiation and target engagement.
5. System performance optimization to minimal threshold and lasing energy.
6. Target repositioning.

2.6. Hazard Evaluation for ALTS Field-Test Experiments

One of the vital factors of the concern whenever the laser system is involved in the test with the personnel in the field is the spatial distribution of the lasing energy immediately around the laser platform, along the tracking path, and around the target. A Laser Hazard Zone (LHAZ) analysis was conducted to assess the Eye Safe Requirements. The performed Hazard Evaluation is based on the instructions ANSI-Z136.1-2000 [16], spread sheet for the ALTS listed in Table 2, and system deployment scheme, as illustrated in Figure 4. The latter one gives an explication of the parameters that are critical for hazard evaluation. For the laser system with the above sated characteristics the following parameters are essential and should be clarified: Maximal Permissible Exposure for Skin and for Eye. It is essential to admit that no oscillation can be achieved along the Target-ALTS path if there is no target in the FOV of the latter. In our current design, this target (the output coupler) is imitated by a small-size (diameter less than 1") multi-facet retro-reflecting element that is mounted on the vehicle.

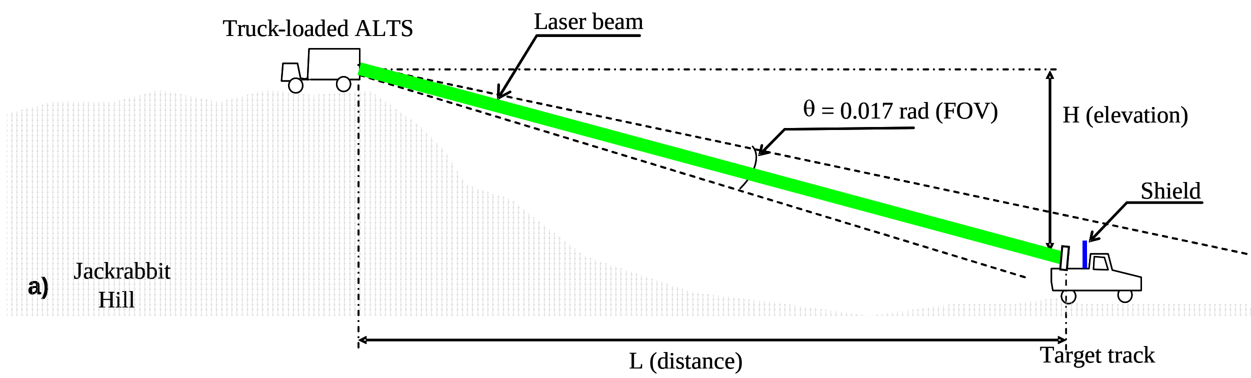


Figure 4. The ALTS deployment scheme

1. ***Maximal Permissible Exposure for Skin - MPE_{sk}*** (see [16]: Table 7, page 48)

$MPE_{SK} = 1.1\, C_A\, t^{0.25} = 1.1 \cdot 5 \cdot (10^{-3})^{.25} = 0.98$ J/cm^2 with $C_A = 5$ (see [16]: Table 6, page 47)

2. ***Maximal Permissible Exposure for Eye - MPE_E*** (see [16]: Tables 5(a,b) page 45-46)

a. Small Source (table 5a) – $MPE_{E\text{-}SS}$

b. Extended Source (table 5b) – $MPE_{E\text{-}ES}$

$MPE_{E\text{-}SS} = 9.0\, C_C\, t^{0.75} \times 10^{-3} = 9.0 \cdot 1 \cdot (10^{-3})^{0.75} \times 10^{-3} = 5 \times 10^{-5}$ J/cm^2

$MPE_{E\text{-}ES} = 9.0\, C_C\, C_E\, t^{0.75} \times 10^{-3} = 9.0\, (10^{-3})^{0.75} \times 10^{-3} = 5 \times 10^{-5}$ J/cm^2

with $C_C = 1.0$; $C_E = 1$ $C_A = 5$ (see [16]: Table 6, page 47)

3. ***Nominal Ocular Hazard Distance – NOHD*** (see [16]: Eq. B51, page 104)

$$\text{NOHD} = \frac{1}{\phi}\sqrt{\frac{1.27Q}{MPE} - a^2} = \frac{1}{10}\sqrt{\frac{1.27\times 0.5}{5\times 10^{-5}} - 20^2} \approx 110 \text{ m}$$

$\phi = 10^{-2}$ rad - laser beam divergence
Q = 0.5 J - maximal output energy
a = 20 cm - laser beam diameter

4. ***Protective Eyewear and MHOD estimation***

$$D = \log\frac{H}{MPE} = \log\frac{1.6\times 10^{-5}\, J\cdot cm^{-2}}{5\times 10^{-5}\ J\cdot cm^{-2}}$$

where radiant exposure is $H = \frac{\rho_\lambda Q\cos\theta}{\pi r^2} = \frac{1\cdot 0.5\, J\cdot 1}{3.14\cdot (100cm)^2} = 1.6\times 10^{-5}\, J\cdot cm^{-2}$

$\rho_\lambda = 1$ reflection from the surface
r = 100 cm – distance from the diffuse surface
Q = 0.5 J – pulse energy
$\theta = 0$ – angle of observation

In our analysis we considered the beam reflected of the surface and not scattered. In this case

The exposure $H = \frac{1.27\, Q}{a^2} = \frac{1.27\cdot 0.5\, J}{(20cm)^2} = 1.59\times 10^{-3}\, J\cdot cm^{-2}$

And this results in the value for D defined as

$$D = \log\frac{H}{MPE} = \log\frac{1.59\times 10^{-3}\, J\cdot cm^{-2}}{5\times 10^{-5}\ J\cdot cm^{-2}} = 1.5$$

The KGGL-05 optical goggles (with optical density OD > 6) from Kentek were used during this test since MetroLaser already acquired this type of goggles for other activity and they satisfy well the estimated safety requirements.

2.7. Conclusion to Hazard Analysis

The analysis indicates that the ALTS, though not eye safe inside the laser unit and along the beam path to the target, can be clearly marked for preventing any hazardous effects on the personnel involved in the test. The ALTS module is well-shielded with only one channel to transmit laser energy outside. This output port is made of the computer controlled gimbal mirror installed on a main tracking platform.

The ALTS module Nominal Hazard Zone (NHZ) has been established as enclosed within a solid angle of 2×10^{-4} strad along the tracking trajectory with the tip of the apex at the target. The NHZ describes the area within which the level of direct, reflected, or scattered radiation during operation exceeds the applicable Maximum Permissible Exposure (MPE). Exposure levels beyond the boundary of the NHZ are below the applicable MPE. Maximum Permissible Exposure is the level of laser radiation to which a person may be exposed without hazardous effects or adverse biological changes in the eye or skin. Personnel are required to wear laser protective eyewear if they are located in the NHZ when the laser is operating.

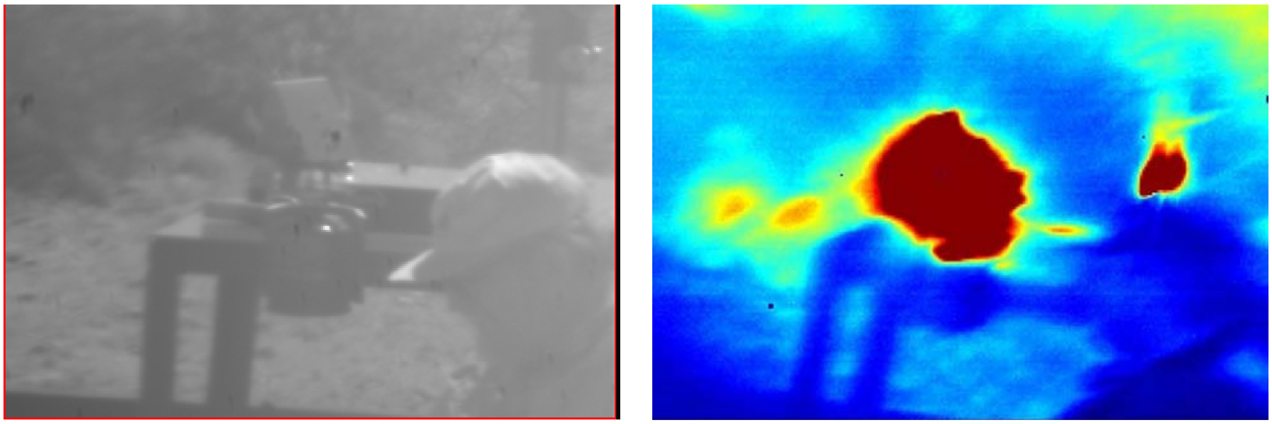
In addition to an active laser tracking sensing channel, the capabilities of the ALTS are enhanced by a PC-controlled passive VNIR and MWIR sensors. All sensors operate through a sheared optical train and, therefore, the operator of the ALTS can constantly observe the target on the monitor once it is within the FOV of the system.

Based on the performed Test Hazard Analysis, significant impacts on the human environment are unlikely to take place, and no further environmental documentation is needed.

3. TEST EXECUTION AND RESULTS

Once all safety and technical requirements were satisfied and ALTS was successfully deployed we initiated the test activity. For that, we started with the target positioned at the short-range spot about 320 m downhill of the ALTS site.

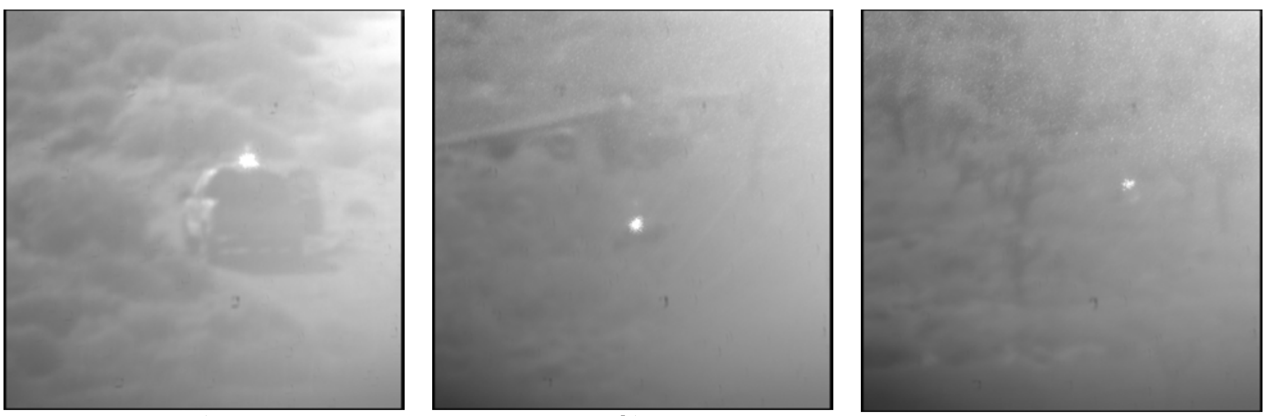
After locating the target through the optical train by using visible and infrared sensors we were able to get the images of the location with relatively good resolution as shown in Figure 5, we then initiated the laser module getting a reliable oscillation in the channels. Operation at this position served to prove satisfactory initial alignment of the system after its relocation from the MetroLaser facilities to the test location. Prior to this relocation comparable range of operation was covered during the in-house tests.



a) b)

Figure 5. Visible and IR images of the target sets at short distance

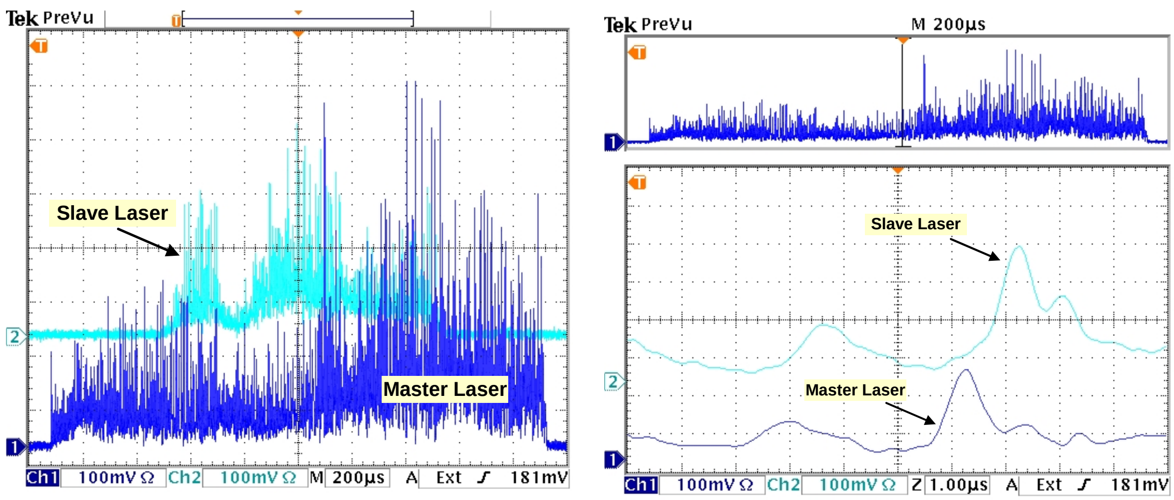
After this initial testing the target was sequential moved further along the testing path. Figure 6 illustrates images of the target with lasing spot from it at the locations with incremental distances to it. It is clearly seen from this figure that the image quality strongly degrades as the target distance increases, mostly due to strong atmospheric turbulence effects.



a) b) c)

Figure 6. ALTS images with lasing spot at the range: a) 1.5 km; b) 3.5 km; c) 6.38 km

A typical trace of laser oscillation in both legs of the ALTS is shown in Figure 7 (a) for the target distanced at 1.5 km. It is obvious from this figure that the master laser leads the oscillation process and the target coupled slave cavity starts with certain delay time. This delay time is defined by the losses in the cavity and the pump rate. Since with increase in the ALTS-target distance the losses increase too the initiation of the slave leg lasing starts with time-delay. Figure 7(b) illustrates a high-resolution the fragment these two traces. It is visible from this fragment that although slave and master traces are identical, there is a time-delay between them. This time delay is due to difference in arrival time of the pulses from these two cavities to the relevant detector. Because the travel time of the matched pulses differs accordingly to the disparity of the length of both cavities, the traces of the pulses are shifted too. In the case of the representative trace shown in Figure 7 such dissimilarity is equal to 1.5 km what corresponds to the delay time about 1.0 μsec on a round trip.



a) b)

Figure 7. Lasing traces of the of Slave and Master cavities at ALTS-target distance 1.5 km.

Further upgrades of the ALTS capabilities require the following:

- High-speed electronics and processing board for an increased spatial (especially longitudinal) resolution of tracking operations;
- Programmable random frequency tunable, agile laser. Such laser will serve as a local oscillator for heterodyne detection. This will enable retrieval of a normal component of target velocity and its variations.
- Algorithm and software that are required to control the gimbaled mirror for steadfast tracking performance.

4. CONCLUSIONS

In conclusion, this paper outlines the procedure needed for deployment and field-testing of active laser tracking system at realistic environment. This deployment required finding a proper test location, estimation of hazard zone, finding an optimal position between the ALTS and the target. Finally after system was fully deployed the critical experiments on locking the laser module to target was performed at different distances right up to maximal range about 6.4 km. Despite strong atmospheric turbulence along the tracking path, the system allowed for a sustainable oscillation, demonstrating the lasing of a longest cavity known so far from the open literature. All performed experiments proved the proposed concept of active laser tracking system that is based on the fundamental principle of optical phase conjugation for compensating the intra-cavity aberrations.

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