Tactical High Energy Laser

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ABSTRACT

The Nautilus Project was started in 1995 as a joint US-Israel feasibility study for using laser systems to defend against short-range artillery rockets. It has now matured into a successful laser weapon demonstration program – the Tactical High Energy Laser (THEL) Advanced Concept Technology Demonstration (ACTD) Program. By now the THEL Demonstrator has engaged and destroyed a large number of artillery rockets in mid-flight in an extended series of demonstration tests at the US Army's White Sands Missile Range in New Mexico. The THEL ACTD hardware and development process are described in this paper, as well as the major test results. The paper also describes the operational concept for a deployed THEL weapon system and some possible growth paths for the THEL ACTD Program.

BACKGROUND

On February 9, 1996, the Mid-Infrared Advanced Chemical Laser (MIRACL) and the Sea Lite Beam Director (SLBD) were used to shoot down a short-range artillery rocket at the US Army's High Energy Laser Systems Test Facility (HELSTF) in White Sands Missile Range, New Mexico (see Figs. 1 and 2). This was the culmination of the Nautilus Project; a joint US-Israel project designed to demonstrate the feasibility of shooting down artillery rockets with high power lasers. It was also a key and enabling event for the further development of ground-based laser weapon systems for air-defense applications. TRW was the prime contractor on Nautilus. It was supported by a number of Israeli subcontractors, including RAFAEL, IAI-MBT, Tadiran and El Op. The US Army Space and Missile Defense Command (SMDC) managed this program jointly with the Israel Ministry of Defence Directorate of Defence Research & Development (DDR&D). SMDC was the executing agent, and the period of performance was May 1995 to February 1996.

MIRACL is a TRW-built, large-scale, facility-based laser test bed installed at HELSTF in the early 80's. It was used in numerous laser lethality demonstrations and shootdowns, including a series of laser lethality testing under the Nautilus Project that concluded with the artillery rocket shootdown in Feb. 96. Following the Nautilus testing and shootdown demonstration, the US and Israel agreed to move beyond testing with the existing facility-based MIRACL and SLBD, and to build instead a more compact, stand-alone and transportable Tactical High Energy Laser Technology Demonstrator specifically designed to destroy artillery rockets in mid-flight. Project offices were established both in Israel (DDR&D) and in the US (SMDC), and a contract was awarded to TRW in July of 1996 for the design, fabrication, integration and testing of the THEL Demonstrator. Once again TRW solicited the support of several Israeli companies and some US companies as well. All members of the TRW THEL Team are identified in Table 1. This team started with just a concept, and in four years produced a complete stand-alone weapon demonstrator that by now shot down more than twenty artillery rockets.

The THEL program is a direct outgrowth of more than 30 years of research and development on high-energy chemical lasers in the US. It is the forerunner of still more powerful and more capable US chemical laser weapons development programs, such as the Airborne Laser, designed to provide defense against short to medium range Theater Ballistic Missiles, and the Space Based Laser, that will be capable of destroying hostile ballistic missiles in their boost phase, anywhere around the globe.

OPERATIONAL CONCEPT AND REQUIREMENTS

One near-term mission for ground-based tactical laser weapon systems is the defense of civilian and military populations and high-value assets against short-range artillery rockets. An artist's rendition of a THEL weapon system similar to the THEL Demonstrator and deployed in an air defense role is shown in Fig. 3. A typical rocket engagement scenario is depicted in Fig. 4, showing how this weapon would defend a town against a rocket attack: A radar system detects the launched rockets, establishes coarse tracks, and classifies the rockets as legitimate targets for a THEL engagement. It then hands over a designated target to an optical tracker. The optical tracker generates a fine track and selects a laser aimpoint on the target. Once the target comes within range, the high power beam is turned on and the target is destroyed in mid-flight.

The key THEL ACTD requirement was to demonstrate that a stand-alone, transportable and fieldable laser weapon system could engage and destroy artillery rockets in mid-air under typical short-range rocket attack scenarios. Attack scenarios specified included both single and multiple rocket launches out of an extended threat zone. These scenarios were replicated at the US Army's White Sands Missile Range and THEL ACTD has successfully engaged and destroyed both single and multiple rockets launched in these scenarios.

SYSTEM DESCRIPTION

THEL ACTD is comprised of three subsystems: 1) the Command, Control, Communications and Intelligence (C3I) Subsystem, 2) the Laser Subsystem (LS), and 3) the Pointer Tracker Subsystem (PTS). The THEL ACTD radar, used for search, acquisition and fire control, is part of the C3I subsystem. A layout of the THEL system with photographs of its three subsystems is shown in Fig. 5. A brief description of each subsystem is presented below.

Command, Control, Communications and Intelligence Subsystem

The C3I Subsystem controls all Radar Assembly and LS and PTS operations. It manages the complete engagement, searching the extended threat zone, detecting and classifying the aerial targets within its range, radiating and destroying the designated targets, and providing kill assessment as well. Once THEL is ready for operation, it takes only two people to man the C3I and to run the entire THEL system: a commander and a gunner. The C3I is designed to operate in three modes: (a) A fully automatic mode, where no human intervention is required, other than a visual target identification by the commander. The commander or gunner can only intervene to stop fire or skip a target in this automatic mode. (b) A semi-automatic mode, where all functions are performed automatically, except that the commander must manually authorize firing by pressing a fire button. And (c) A manual mode, where the commander both designates the target to be engaged and issues the fire command.

The C3I is comprised of four assemblies. The Fire Control Radar (FCR) continuously searches the threat zone and detects, acquires and classifies all flying objects that come within its range. It then sends flight-object state-vectors and other measurement data to the Radar Communications Assembly.

The Radar Communications Assembly (RCA) controls the radar and reports the radar-tracked objects and their state-vectors to the Tactical Command Assembly.

The Tactical Command Assembly (TCA) sets up the subsystem (C3I) configuration and provides initialization parameters for the FCR and for the Fire Control Assembly (FCA). In addition, it selects the targets to be engaged, provides the engagement parameters for the FCA, and determines the threat engagement priorities. It also collects system status data and monitors the laser and pointer-tracker subsystems and the other C3I assemblies (RCA and FCA).

The Fire Control Assembly (FCA) receives selected threat targets from the TCA and interfaces with and controls the Laser Subsystem and the Pointer Tracker Subsystem during target acquisition and engagement. It also provides the commander and gunner with target data and engagement status, including kill-assessment and other target information during the engagement, such as a direct video feed from the PTS and track lock or loss data.

Laser Subsystem

THEL uses a Deuterium-Fluoride (DF) laser. NF3 and C2H4 are first reacted in multiple, side-by-side, high-pressure combustion chambers using an oxidizer (NF3) rich mixture that generates free F atoms. After ignition the combustion-generated F atoms, mixed with combustion by-products and a He diluent, flow into the laser cavity. A mixture of He and deuterium is also injected into the laser cavity, and DF is generated in an excited state as deuterium reacts with the free F atoms. The laser cavity is now ready to produce a laser beam. A negative branch unstable resonator is used to enhance the stimulated emission of radiation in the cavity and to extract a continuous-wave collimated laser beam from the cavity.

The Laser Subsystem is made up of four assemblies: the Fluid Supply Assembly (FSA), the Gain Generator Assembly (GGA), the Pressure Recovery Assembly (PRA), and the Laser Optics Assembly (LOA).

The Fluid Supply Assembly provides all reactants and other fluids necessary for laser operation. The gases used to generate the lasing action are NF3, C2H4, He and D2. In addition, the FSA supplies both the cooling water needed to operate the laser and the hydrogen peroxide (H2O2) needed to run the PRA. The FSA is comprised of high-pressure tanks, tubing, regulators, fast turn-on/turn-off fire valves, flow control valves, and relief valves and sensors needed to monitor and control the various fluids and flow circuits, and to maintain a safe operating environment. The THEL FSA was proven to be very successful in precisely metering and turning on and off large flow rates under very high pressure in a fraction of a second. THEL ACTD has thus demonstrated, for the first time, the rapid turn-on and turn-off flow controls needed for laser weapon systems using chemical lasers.

The GGA is comprised of 44 individual NF3 and C2H4 combustion chambers, each about 1” wide, each feeding an expansion nozzle that leads into the laser cavity. Thin cavity injection blades that feed a mixture of D2 and He into the laser cavity span these nozzles. All the gas and water feed tubes and manifolds that are closely coupled to the laser cavity are part of the GGA. The GGA also includes an F2 gas generator (F2GG) that is needed to ignite the NF3 and C2H4 mixture, since this mixture is not hypergolic at normal (room) temperature. This F2GG is a new development, specifically designed for the THEL laser and, as demonstrated on this program, proven to be a very effective and dependable DF laser igniter.

A Pressure Recovery Assembly is needed since the laser cavity operates at sub-atmospheric pressure, typically around 20 torr, but the laser gases flowing through the cavity must still be exhausted to the atmosphere. The first element of the PRA is a passive diffuser, which recovers the kinetic energy from the super sonic laser cavity flow and increases the pressure of this gas stream to about 200 torr. The next element is a heat exchanger that reduces the gas temperature and increases its density, thus reducing the gas volume that needs to be exhausted to the atmosphere. The last element is an H2O2-driven ejector pump. Seventy percent H2O2 is catalytically decomposed to generate the high temperature and high-pressure ejector driver fluid (steam + oxygen) that produces the pumping effect. This ejector pump raises the laser gas pressure from about 200 torr to slightly above atmospheric pressure and exhausts the gas to the atmosphere.

Finally, the Laser Optical Assembly is used to extract the laser beam from the laser cavity and to shape it before it enters the PTS. The LOA includes all laser mirrors and their supports, the laser optical bench, the instrumentation that checks and records the optical bench alignment relative to the laser cavity, the vacuum enclosures needed to house all LOA optical elements, and the isolation valves that separate the LOA from the laser cavity.

All high-power THEL optics, including both the LS and PTS optics, were produced with Very Low Absorption (VLA) optical coatings, which drastically reduce the laser absorption and the heating of these elements, and eliminate the need to actively cool them. This is the first time a complete high-energy laser system was built without a single water-cooled mirror. THEL has thus demonstrated that VLA coatings are reliable and ready for high-energy laser applications, allowing a very significant simplification in the design of laser weapon systems by eliminating the need for water-cooled high-power optics.

Pointer Tracker Subsystem

The PTS acquires the designated target from the FCR and transmits the LS-generated laser beam to the target, while also pointing and focusing the beam on the target. The PTS tracks the target with sufficient precision to place the focused laser beam on the desired aim point, and keeps the beam there until the target is destroyed. The PTS also provides visual target tracking information to the THEL commander and gunner for the final target verification and manual intervention, if required.

The PTS is comprised of five assemblies: the Beam Director Assembly (BDA), the Beam Alignment and Stabilization Assembly (BASA), the Off Axis Tracker (OAT), the Shared Aperture Tracker (SAT), and the PTS Controller (PTSC).

The BDA accepts the laser beam generated in the LS, which is roughly 10 cm in diameter, and expands it by a factor of 7 in order to improve beam focusing and intensity on-target. The BDA slews to follow the threat target and allows the BASA to point the focused laser beam onto the selected aim-point on the target. The BDA can track and point anywhere in the sky with hemispherical coverage, thus turning THEL into a true stand-alone weapon that can address any threat that comes within range. It does so by utilizing a 3-gimbal pointing system. A close-up view of the BDA is shown here Fig. 6.

The PTS performs the target acquisition in a two-step process: once the C3I generates a target state vector, the PTSC commands the BDA to slew to the target and the OAT acquires the target. The OAT is a wide field of view, low resolution IR tracker. The OAT steers the BDA to maintain the target in the center of its FOV, where the Shared Aperture Tracker (SAT) can also see it. The SAT is a near-IR, narrow field of view high-resolution tracker. When the SAT acquires the target, it takes over the target tracking function from the OAT, selects the aim point on the target, and points the laser beam to the selected aim point.

DEVELOPMENT PROCESS

Once the decision was made to build a laser weapon demonstrator that could engage short-range artillery rockets, there was strong motivation both in the customer community and on the part of the THEL Contractor Team to complete this demonstration in the shortest possible time. A plan was developed to minimize the time required to build the demonstrator while keeping the cost and schedule risks under check. A number of important decisions were made early in the program to support a rapid development schedule. These were (a) Use of existing, both contractor-developed and commercial, “off the shelf” hardware and software, when available and feasible. (b) Making sure each subsystem has clearly defined and simple interfaces with the other subsystems, and then breaking up each subsystem into well-defined, stand-alone assemblies, also with clean and simple interfaces, that could be developed in parallel. (c) Early definition and tight control of all interfaces. (d) Extensive use of simulators to facilitate parallel development of assemblies and subsystems. (e) Empowering the subsystem and assembly managers to forge ahead with their respective elements, without waiting for other system elements to come along in parallel. And (f) Concurrent design and fabrication, to the maximum extent possible, for components and assemblies that could be defined early in the development process and that were not likely to change.

This strategy has worked extremely well. The TRW-led THEL Team succeeded in moving very quickly from preliminary to final design and from component fabrication and acquisition to subsystem and system integration and test. As one assembly or subsystem design was completed, a critical design audit (CDA) was held for that element. These CDAs were spread over a four-month period, between February and June of 1997. Many major components were already in fabrication while the CDAs were still being held. Brashear started the fabrication of the BDA in October

1996 and delivered it to TRW in December of 1997. Similarly, RAFAEL started the fabrication of the FSA and PRA in February 97 and delivered them to TRW at the end of 1997. TRW had the bulk of its laser hardware (the GGA and LOA) built by February 1998, a short nine months after the end of the CDA.

The C3I Subsystem was the first subsystem to be fabricated, integrated and tested. Since most of the C3I components and assemblies originated in Israel, this subsystem was integrated and first checked out there. The assembly and checkout of the RCA, TCA and FCA, and their integration into the C3I shelter, occurred at the IAI MBT facility in Yahud, Israel. The radar (FCR) was built, integrated and checked-out at the IAI ELTA facility in Ashdod. All C3I assemblies were then integrated and field-tested against live rockets flying typical threat trajectories in early 1998 at the Israel Air Force Test Range in Palmachim. The C3I shelter, with the RCA, TCA and FCA integrated into it, was then shipped to the TRW Space Park Facility in Redondo Beach, California, for interface checkouts with the LS and PTS, which were assembled at that time at TRW. Upon the successful completion of these interface tests, the integrated C3I shelter and the FCR were both delivered to HELSTF, at the US Army's White Sands Missile Range, in late 1998, for the final validation of the C3I performance. Once again the C3I was tested against flying rockets at its new installation and its performance re-verified.

In the meantime, the PTS was assembled and tested at TRW's Space Park Facility. The BDA arrived there in December of 1997 and the other PTS assemblies were ready in early 1998. The final assembly and checkout of the PTS was then started. This took a little over a year. At the end of this period, all alignment and performance tests that could be conducted from inside a building were complete. These tests included pointing and tracking tests against a stationary rocket warhead located on a rooftop some distance away from the PTS building.

The GGA and the LOA were first integrated in the same building where the PTS was located, and then shipped to the TRW Capistrano Test Site (CTS) to be integrated with the PRA and FSA, which were delivered there by RAFAEL. The laser integration and checkout at CTS also took about one year, from mid 1998 to mid 1999. The laser subsystem was ready in June of 1999, with "first light" generated on June 26, 1999. There was further optimization work on the laser power output that lasted through September 1999. By the fall of 1999, both the LS and the PTS were ready to be moved to the US Army's laser test range at HELSTF.

The PTS was moved first, in September 99, followed by the laser in October 99. Several months were spent on re-integrating and reactivating these subsystems, first individually and then as a completely integrated system, together with the C3I. During that period the PTS repeated its testing against static targets at various ranges, and started testing against flying targets as well. The PTS achieved all its test objectives in the spring of 2000, including successful tracking of single rockets and rocket salvos with both the OAT and the SAC.

The LS was first reactivated at HELSTF in late December 1999, at which time a laser beam was extracted from the laser subsystem for the first time. Until moving to HELSTF, all lasing tests were close-coupled into a calorimeter. An extensive series of laser beam characterization tests was then performed. Laser beam shape, size and intensity distribution were measured, and some indirect assessments were made of the laser's beam quality and beam stability. Once it was determined that the beam characteristics were consistent with the test requirements, the final LS to PTS beam alignment could start. The first lasing through the PTS occurred on April 11, 2000, when the laser beam was propagated and focused through the PTS to a distant stationary test target. These static tests demonstrated excellent beam pointing and focusing performance, and the system was declared ready for its first live-fire test against a dynamic aerial target.

SHOOT-DOWN TESTS

The first shootdown of a flying rocket by THEL ACTD occurred on June 6, 2000, a scant four years after the start of the program. This would be remarkable enough for any weapon demonstration program, but was even more so for this fundamentally new type of weapon.

Many additional rocket intercepts have occurred since then, both against single rockets and against salvos of multiple rockets. A collection of THEL rocket intercepts is shown in Fig. 7. These tests mapped out the performance of the THEL ACTD system over a wide range of engagement parameters and demonstrated that the system met its essential requirements. Parameters of major interest, which were systematically explored in these field tests, include the engagement range, the aspect angle between the rocket axis and the laser beam, the elevation angle of the engagement, the target slew rate, and other engagement parameters important for an operational system. Through these tests, a comprehensive performance map was developed for this demonstrator. This performance map will be invaluable if a decision is made to design and build the Next Generation THEL, which could be a prototype for a fully operational THEL weapon system. Furthermore, with the THEL ACTD system now out in the field for more than two years, much critical data has been collected on system environmental compatibility, reliability, availability, and maintainability in the harsh HELSTF desert environment. This data too will be of great value both for the continued operation and testing of THEL at HELSTF, and for the Next Generation THEL system, if a decision is made to develop such a system.

WHAT'S NEXT?

Both the US and Israel recognize the critical role which THEL-like tactical laser weapon systems can play in defending civilian and military populations and assets. The US Joint Theater Air and Missile Defense Mission Needs Statement (JTAMD MNS), approved by the Joint Requirements Oversight Council on 7 July 99, states, "Current joint air and missile defense measures do not adequately protect friendly forces from the very short range missiles, rockets, mortars, and artillery threat." Laser weapon systems are excellent candidates to fill this mission need, and the THEL ACTD is a clear pathfinder for such systems. Last year the US and the Israel governments have made a decision to proceed with a joint study that will define a Next Generation THEL system, a system that will be a militarized, mobile and operational, tactical ground-based laser weapon system for defense of high value assets against aerial attacks. A decision for the joint development of such a system could be made later on, depending on the outcome of this design study and subject to other considerations as well.

TRW has proposed several concepts for the Next Generation THEL weapon system. An artist's rendition of one such concept is shown in Fig. 8C. It is expected that the Next Generation THEL will be a mobile laser weapon system on a truck. Initially, fuel would be provided only from auxiliary trucks that can have a very large magazine for extended engagements and laser run times. Later, in addition to the auxiliary fuel trucks, a smaller amount of laser fuel could be mounted also on the laser truck itself, for more limited operations and engagements. Similarly, the C3I functions may be initially provided by sensors and other hardware mounted on a separate C3I truck. Later this hardware may also be compacted and transferred to the laser truck. As presently envisioned, the Next Generation THEL should not depend on new inventions or new technologies. It will, however, require significant re-engineering and re-design to transform the THEL hardware into a more compact and mobile system. The TRW concept for such a Mobile THEL would still use a DF laser and a beam director that is quite similar to the one currently used in THEL ACTD, including similar on and off-axis optical trackers.

Beyond the Next Generation Mobile THEL, TRW has considered two parallel development paths. One is to further reduce the size of Mobile THEL so that it could be placed on a single, possibly armored, vehicle. An artist's conception of such an "Objective THEL" fighting vehicle is shown here in Fig. 8D. This system should be able to move with the troops, provide first-line battlefield protection against a variety of air threats, and possibly be able to "shoot-on-the-move." Significant technology advances will be required to move from the Mobile THEL described above to this Objective THEL. Another path (not shown in Fig. 8) is to package a laser weapon system, that is much like the Mobile THEL, on an airborne platform to extend its operational range and effectiveness. Both of these options could offer very capable and revolutionary air defense weapon systems. It should be noted, however, that no significant engineering effort was expended to date in defining these two concepts, and they are mentioned here only to indicate where the THEL ACTD pathfinder may take us in the future.

Company/Location	**THEL/ACTD Role**
TRW Redondo Beach, California, USA	• Prime Contractor • Systems Engineering and Design • Tactical Command Assembly • Laser Gain Generator and Optics Assemblies • Pointer Tracker Subsystem Controller • Subsystem and System Integration and Test
Ball Aerospace & Technologies Co. Boulder, Colorado, USA	• Beam Stabilization and Sensors, and Pointer Tracker Subsystem and System Integration and Test Support
Brashear LP Pittsburgh, Pennsylvania, USA	• Beam Director Assembly, and Pointer Tracker Subsystem and System Integration and Test Support
Electro-Optic Industries, Ltd. Rehovot, Israel	• Systems Engineering and Design Support for the Pointer Tracker Subsystem
Israel Aircraft Industries, Ltd. **MBT Systems & Space Technology** Yahud Industrial Zone, Israel **ELTA Electronics Industries, Ltd.** Ashdod, Israel	• Fire Control Assembly and Off Axis Tracker • C3I Engineering and Integration and Test Support • Fire Control Radar and System Integration and Test Support
RAFAEL Haifa, Israel	• Fluid Supply Assembly • Pressure Recovery Assembly • Laser Engineering and Laser Integration and Test Support
Tadiran Holon, Israel	• Radar Communications Assembly and C3I Integration and Test Support

Table 1. The TRW THEL Team

Figure 1. The MIRACL and SLBD Installation at HELSTF used for the 1996 Nautilus Rocket Shootdown

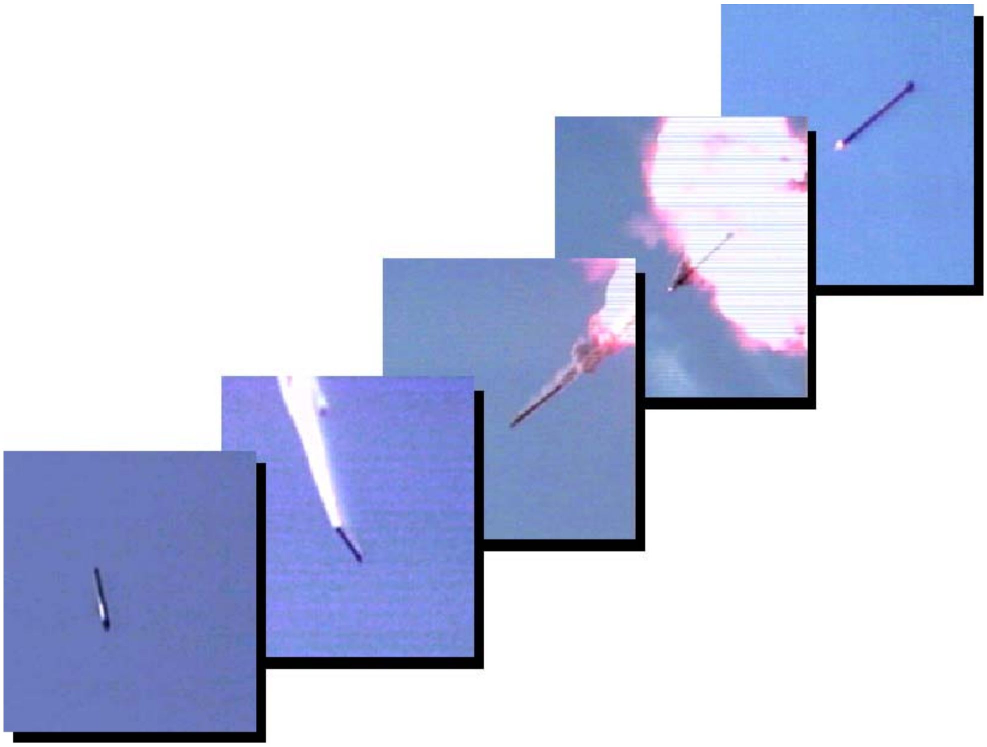

Figure 2. Nautilus Demonstration of a Single Rocket Shootdown, Feb. 9, 1996

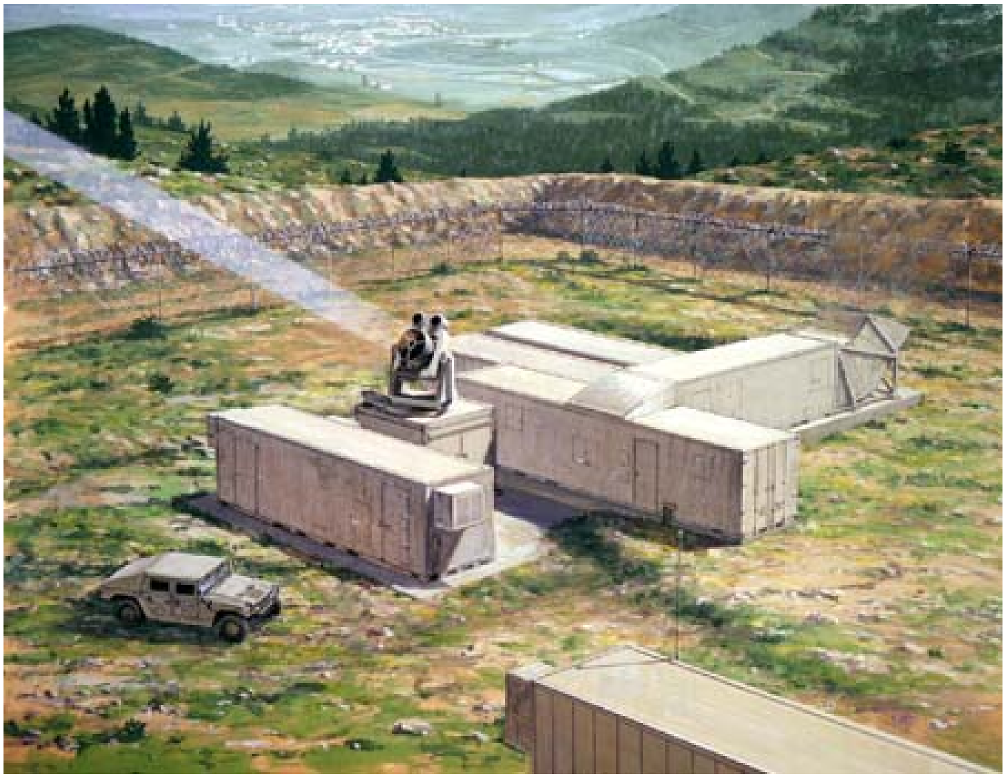

Figure 3. Artist’s Concept of a Deployed THEL Weapon System

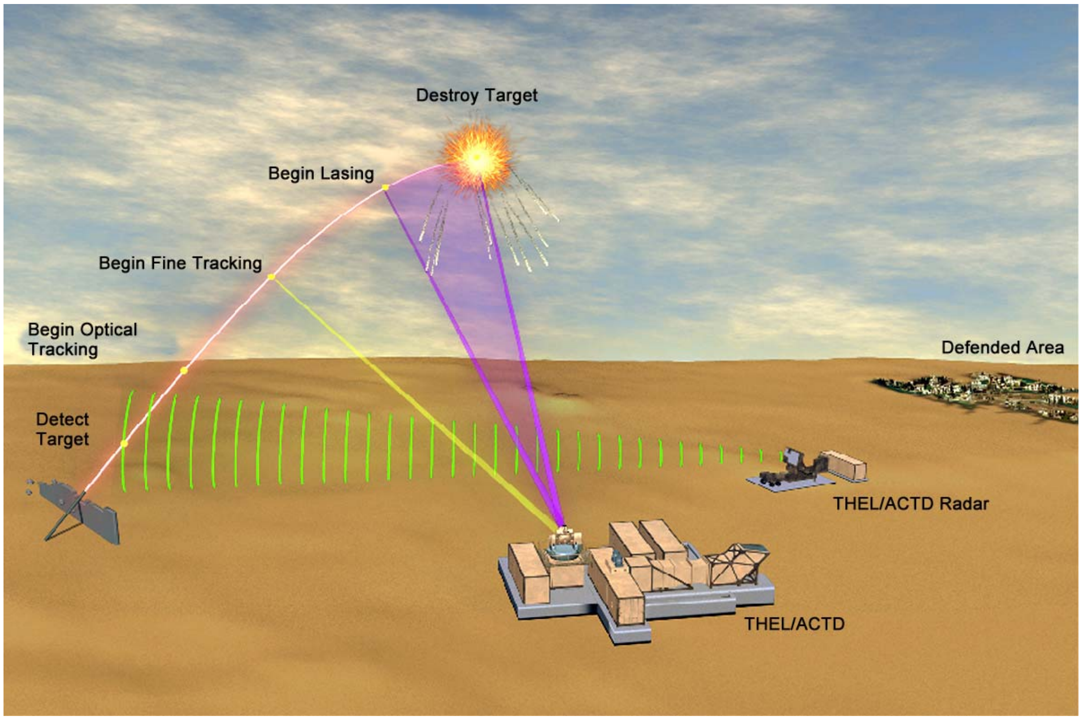

Figure 4. Typical THEL Engagement Scenario

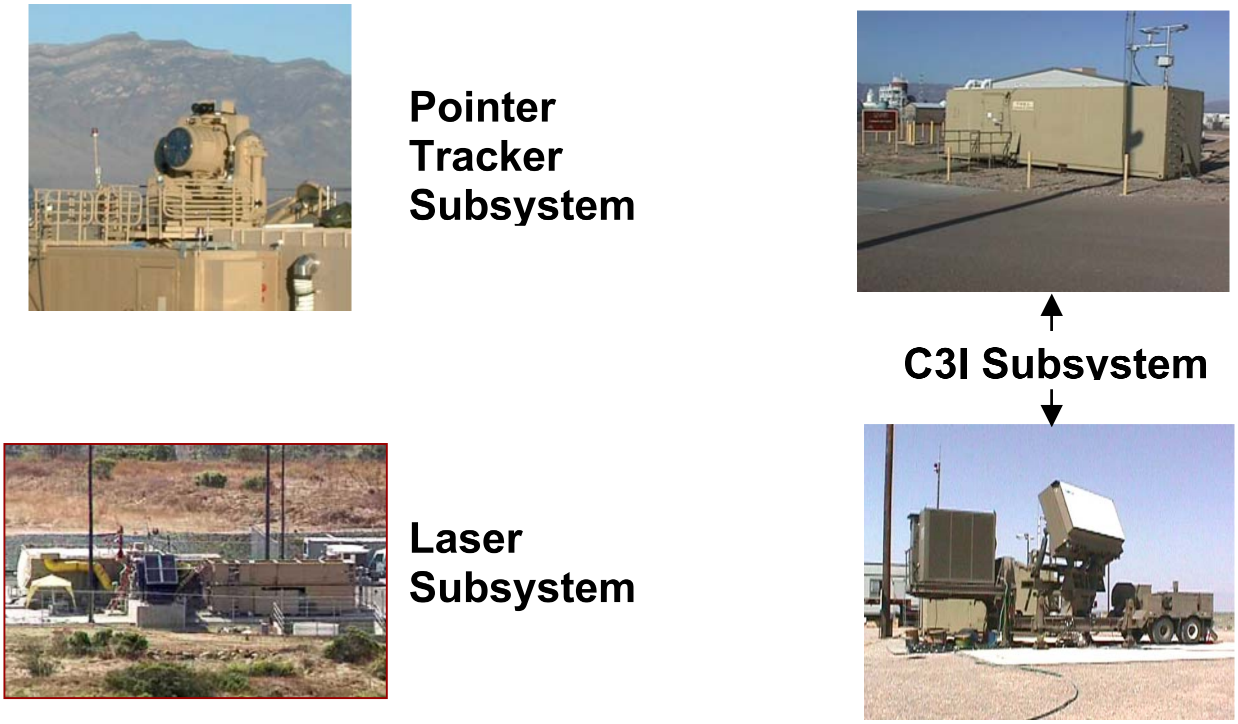

Figure 5. THEL ACTD

Figure 6. PTS Beam Director Assembly

Figure 7. Photo Gallery of THEL ACTD Shootdowns

A. MIRACL & SLBD at HELSTF

B. THEL ACTD

D. Future (Objective) THEL

C. Next Generation (Mobile) THEL

Figure 8. Possible THEL Development Path