LOAN DOCUMENT

PHOTOGRAPH THIS SHEET

DTIC ACCESSION NUMBER

LEVEL

0

INVENTORY

A High Energy Laser System Design

DOCUMENT IDENTIFICATION

H A N D L E W I T H C A R E

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

DISTRIBUTION STATEMENT

ACCESSION FOR	
NTIS GRA&I	☒
DTIC TRAC	☐
UNANNOUNCED	☐
JUSTIFICATION	
BY	
DISTRIBUTION/	
AVAILABILITY CODES	
DISTRIBUTION	AVAILABILITY AND/OR SPECIAL
A-1	

DISTRIBUTION STAMP

DATE ACCESSIONED

DTIC QUALITY INSPECTED 4

DATE RETURNED

19990621 088

DATE RECEIVED IN DTIC

REGISTERED OR CERTIFIED NUMBER

PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-FDAC

A HIGH ENERGY LASER SYSTEM DESIGN AND PERFORMANCE EVALUATION TOOL

Steve Doerr, Senior Member, Principal Engineer, SAIC, Albuquerque NM
Russell Vernon, Business Area Manager, SAIC, Jupiter FL
Donald Link, Senior Scientist, SAIC, Jupiter FL

Abstract

Recent developments, primarily in solid state lasers and compact power supplies, make the application of an electrically powered high energy laser (HEL) as a tactical weapon feasible in the near term. Cost/performance design tradeoffs are needed to maximize the benefit of such a weapon. The Atmospheric Compensation Simulation code emulates the entire HEL system and allows designers to evaluate and optimize performance prior to hardware commitment. Simulation results indicate that the inclusion of an adaptive optics subsystem, to compensate for atmospheric effects, on a tactical HEL weapon system significantly improves system performance thereby decreasing required power or increasing lethal range or target set.

1.0 Introduction

The era of laser weapons is almost upon us. The Tactical High Energy Laser (THEL), a joint US-Israeli program, is soon to become operational, followed by the Airborne Laser (ABL) in 2006, and the Space-Based Laser (SBL) in the 2010 timeframe. In addition, there are many other directed energy projects under development such as infrared countermeasures, active imaging, lidar, and ladar that have many of the same requirements and design challenges.

There are a myriad of problems that must be resolved to create an effective HEL weapon system including generation of sufficient laser power, removal of waste heat, accurate target acquisition, tracking, and pointing (ATP), weapon integration, command and control, etc. A major problem that has to be overcome with all ground and airborne laser weapons is the atmospheric effects on the beam. Light propagating through the atmosphere is not only absorbed and scattered by various molecules and aerosols, the beam is also distorted by pre-existing and laser-induced temperature fluctuations causing wavefront aberrations and scintillation (random intensity variations) that can dramatically decrease the effectiveness of the weapon.

Pioneering work at the USAF Starfire Optical Range in adaptive optics[1] provided a means to mitigate the influence of the atmosphere. The basic idea is to measure the atmosphere-induced distortion and subsequently impose the conjugate on the outgoing beam such that it arrives at the target nearly diffraction-limited. While fairly simple in concept, the actual mechanics of accomplishing the task are non-trivial. The high costs of the adaptive optic (AO) components, wavefront sensors, deformable mirrors, array processors, etc., encourages modeling to analyze requirements, minimize risks, and evaluate and optimize performance prior to hardware commitment.

This paper addresses the design and performance evaluation of a notional tactical HEL. The particular example chosen is 500kW laser system applicable as a mobile point defense weapon. Comparisons are presented that show the performance advantages of a system that incorporates AO over a similar system that does not attempt to compensate for atmospheric distortions.

2.0 Weapon System Design

There are many factors that drive HEL system design including mission, operational constraints, power availability, and those mentioned previously. This paper focuses on the optical subsystem design. Two major elements of the optical subsystem are discussed in detail - the laser source and the AO portion of the beam train.

The primary metric for determining laser weapon effectiveness is irradiance (W/cm^2) on target. For example, a beam with sufficient irradiance and a diameter greater than the 'critical crack length' is required to cause a catastrophic kill of a thrusting missile.[2] Other targets have different kill mechanisms. Power on target is a function of laser power, optical system losses, and atmospheric transmission. Beam diameter is a function of the optical system, beam spreading, and range.

2.1 Laser Selection

There are specific spectral regions or atmospheric "windows," see Figure 1, where transmission through the atmosphere approaches 100% and laser systems are typically designed to take advantage of these. There is still the requirement to generate sufficient power and much effort has gone into developing lasers that emit at wavelengths within these windows. Most current weapon concepts take advantage of the energy available through chemical reactions.[3] Examples of nominal system parameters are provided in Table 1 for several current MW-class weapon systems under development.

Table 1. Nominal system parameters of Megawatt class weapons.

Weapon System	Laser Description*	Wavelength (μm)
THEL	Chemical - DF	3.8
GBL	Chemical - DF	3.8
ABL	Chemical - COIL	1.3
SBL	Chemical - HF	2.7

* DF – Deuterium Fluoride
COIL – Chemical Oxygen-Iodine Laser
HF – Hydrogen Fluoride

Advances in diode lasers and efficient coupling with solid-state gain media has led to the creation of reliable diode-pumped solid-state lasers making a electrically powered HEL feasible in the near-term. The technology has progressed to where kW-class solid-state lasers have been demonstrated.[4,5] Despite the literally hundreds of materials that have been demonstrated to lase, there are only a few that can be reasonably considered for an HEL since most have poor efficiency, poor spectroscopic properties, poor thermo-mechanical properties, and are difficult to grow into crystals of sufficient size and purity. The standard for many years has been, and still is, the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser with a fundamental wavelength λ=1.063μm.

Other laser candidates include Yb:YAG and, in the future, banks of phased-matched fiber optic ampifiers.[6] Yb:YAG (λ=1.03μm) has better storage capacity than Nd:YAG, lower thermal load, and has a wide absorption peak centered at 943nm that is suitable for InGaAs diode laser pumping[7] and could readily serve as the source for our concept.

Being conservative, our design assumes that 5MW of electrical power are available and that the Nd:YAG laser has a wall plug efficiency of 10% resulting in a HEL output of 500kW.

2.2 Optical System

The primary purpose of the beam train is to transmit the laser energy towards the target. Many functions are typically done to the beam to optimize this task including pulse shaping, magnification, and pointing. Another task that can be accomplished is wavefront control to remove optical system aberrations and/or to impose the conjugate of atmospheric-induced distortions. This last task is the focus of this paper as, as will be shown, atmospheric distortion severely affects the performance of ground and airborne HEL systems.

The goal is to put a beam with a specified, or at least known, size onto a specified location on the target with minimum power loss. Physical optics limits the smallest spot that a laser can focus, the diffraction limit, to $\delta=2.44R\lambda/D$ where λ is the wavelength, R is the range, and D is the diameter of the limiting aperture. Most, 63%, of the power is actually contained within a diameter roughly half the diffraction limit diameter. Atmospheric induced refraction causes beam spreading and pointing error reducing the weapon system effectiveness. Also, signal dropouts caused by scintillation decrease tracker and wavefront sensor performance. The AO subsystem mitigates these effects by minimizing beam spreading.

In addition to spreading the beam, the atmosphere adds a dynamic tilt to the beam causing the laser to wander on the target. Platform vibrations introduce additional beam wander. Beam wander reduces the accumulated flux on the target and thus also reduces weapon system effectiveness. The tracking system attempts to correct for jitter and for target motion. The AO subsystem improves tracking performance by reducing image blurring on the tracker detector plane.

3.0 Atmospheric Compensation Simulation Code Description

The SAIC developed Atmospheric Compensation Simulation (ACS) code emulates the entire HEL system from the laser resonator to the target, including laser phase and intensity variations, beamtrain aberrations and hardware limitations, active illuminator and target reflection effects, and atmospheric effects.[8] ACS is currently being used to simulate the complex optics systems found in the ABL, SBL, GBL, THEL, and other programs. The influences of controllable features such as the number of subapertures in the wavefront sensor, actuator latency, control system bandwidth, and target tracking algorithm on target irradiance are modeled and, through optimization, have led to large improvements in expected system performance. The effects of uncontrollable variables such as target and platform motion, wind, atmospheric turbulence, thermal blooming, etc. can also be assessed to evaluate system performance over a wide range of conditions.

ACS is a flexible, time-domain wave-optics code that uses Fourier Transform theory to propagate wavefronts through the beam train and the atmosphere. ACS includes digital controls (of any order) and 3rd-order analog responses to accurately simulate electro-mechanical response effects of servos and AO actuators. Adverse hardware effects such as detector noise, misalignment, gain variation, quantization, etc. are modeled as well. The atmosphere is simulated as a series of two-dimensional phase screens scaled by the turbulence power spectral density. The line of sight of the wavefronts relative to the phase screens changes at each time step (typically .1-2 ms) to simulate the effects of wind and target and platform motion.

Performance measurements include short and long term on-axis and peak Strehl ratios, peak and centroid jitter, farfield spot width, near-field phase statistics, scintillation, power-in-a-bucket, and strip power.

Code validation has been accomplished by comparison with theory, other simulations, and data from experiments conducted at several test facilities.

4.0 HEL System Example

ACS was used to calculate the performance of the notional HEL system shown in Figure 2. The basic system consists of a 500 kW Nd:YAG HEL, four 15W 1.5μm probe lasers (for tracking and atmospheric effects sensing), and a 30cm ceolostat. The adaptive optics system consists of a 10x10 Hartmann-Fried wavefront sensor with 4x4 pixels per subaperture and a deformable mirror with 121 actuators and a 400Hz servo bandwidth. Target acquisition would be accomplished via an IR imager.

Operationally, the four probe beams would illuminate the target, having been cued by the acquisition subsystem, and the reflected radiation would be used for fine tracking, via the target tracker, for atmospheric effects monitoring, via the wavefront sensor, and for HEL pointing, via the boresight sensor. The phase compensation is induced via the target loop deformable mirror. The fast steering mirror, controlled by the imaging tracker, allows precise tracking despite image jitter. The HEL would fire either for a prescribed time or until commanded to shut off by a signal from the kill assessment subsystem.

The target, shown in Figure 3, is a notional cruise missile. The calculation simulates a missile flying at 250m/s at 150m altitude with a 3m/s crosswind. All of the images shown in the figure are computer generated.

5.0 Results

The optical system shown in Figure 2 has been optimized via a complicated process that is outlined in Figure 4, but whose details are beyond the scope of this paper. The process and the multiple interrelationships of the many variables are described in Ref. 9. Tracking bandwidth, number of subapertures in the wavefront sensor and actuators in the deformable mirror, and other elements of the optical system were varied and their effects on system performance assessed to optimize the design.

An indication of both the complexity and the power of ACS is indicated by the top-down performance allocation/error budget shown in Figure 5. These are the basic optical requirements that are needed to specify hardware components. For example, the bottom left two boxes indicate that requirements for the deformable mirror include a 12-bit resolution encoder and an actuator stroke of 100μm to achieve the performance predicted.

Two head-on tracking images (1x1m view) of the target, a diffraction-limited image and an atmospheric degraded image with AO (closed loop), are shown in Figure 6. The images are "taken" at a range of 6km using the 1.5μm illumination lasers through a WSMR August atmosphere with a visibility of 23km. The poor quality of the image on the right indicates the difficulty in determining precise target aimpoint and the need for sophisticated tracking algorithms. The images at 12km are unrecognizable.

The images in Figure 7 (10x10cm view) show irradiance patterns of the HEL, diffraction-limited, open loop, and closed loop, on the nose of the target (as indicated by the overlay line) at 12km. The images show that, prior to closing the adaptive optics loop (middle image), much of the HEL energy is dispersed away from the aimpoint decreasing the effectiveness of the weapon. The maximum irradiance for the closed loop, compensated beam (right image) is 15 times greater than the uncompensated case resulting in dramatically better system performance.

Necessary dwell times and system lethality to targets of interest can be assessed from this spatial irradiance data. Input power and/or system complexity and cost could then be reduced should the lethality analysis indicate overkill.

6.0 Summary and Conclusions

Advances in power supplies, diode and solid-state lasers, and adaptive optics make it feasible to consider an electric HEL as the source of a tactical weapon system. The ACS code has been shown to accurately model complex optical systems, atmospheric propagation, and target interaction and thus can be used for design and for performance optimization/evaluation prior to hardware commitment.

The simulation presented indicates that an AO system would improve the irradiance on target by a factor of fifteen and would reduce jitter by at least a factor of five substantially increasing weapon system effectiveness (range, target set, and number of targets engaged). Alternatively, the input power required could be decreased below the 5MW suggested and still result in a formidable weapon. The bottom line is that the concept could be a lethal point defense weapon against a wide variety of targets.

References

1. Fugate, R., "Laser Beacon Adaptive Optics," Optics and Photonics News, Vol. 4, No. 6, June 1993.

2. Beraun, J., et.al., "Airborne Laser Lethality Test Series," PL-TR-96-1051, June 1996.

3. Handbook of Chemical Lasers, Gross, R.W.F. and Bott, J.F., Wiley, New York, 1976.

4. St. Pierre, R.J., et.al., "Diode Array Pumped Kilowatt Laser," SPIE Vol. 3264, Jan 1998.

5. Sumida, D.S., et.al., "High power Yb:YAG Rod Oscillators and Amplifiers," SPIE Vol. 3265, Jan 1998.

6. Reichel, V., et.al., "High-Power Single-Mode Nd-doped Fiber Laser," SPIE Vol. 3265, Jan 1998.

7. Cunningham, R., "New Solid-State Laser Materials," Lasers and Optronics, Dec 1996.

8. Link, D., "Comparison of the Effect of Near-Field and Distributed Atmospheric Turbulence on the Performance of an Adaptive Optics System," SPIE Proc. Vol. 2120, Jan. 1994.

9. Vernon, R.G., et.al., "How to Cost-Effectively Specify Adaptive Optics and Tracker Performance," OSA Engineering "How-To" Program, Sept. 1992.

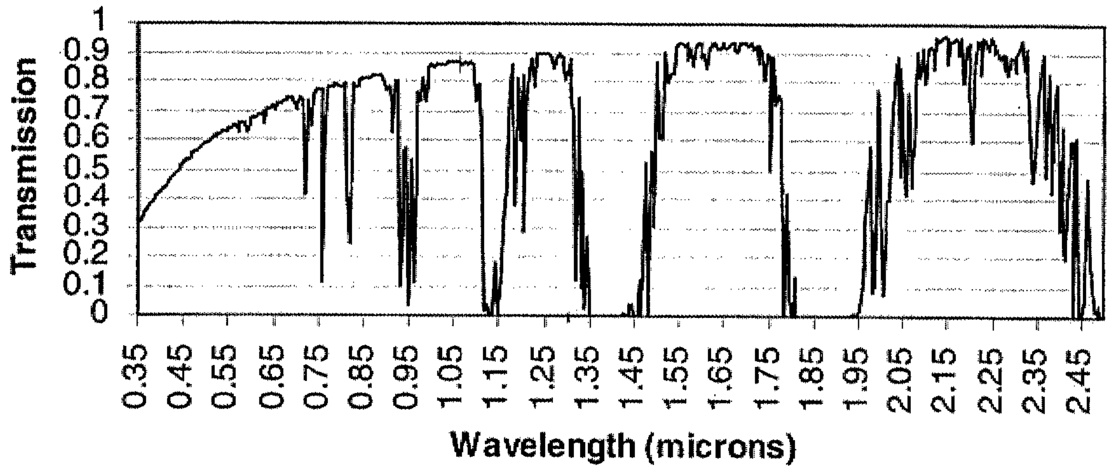

Figure 1. Atmospheric transmission as a function of wavelength.

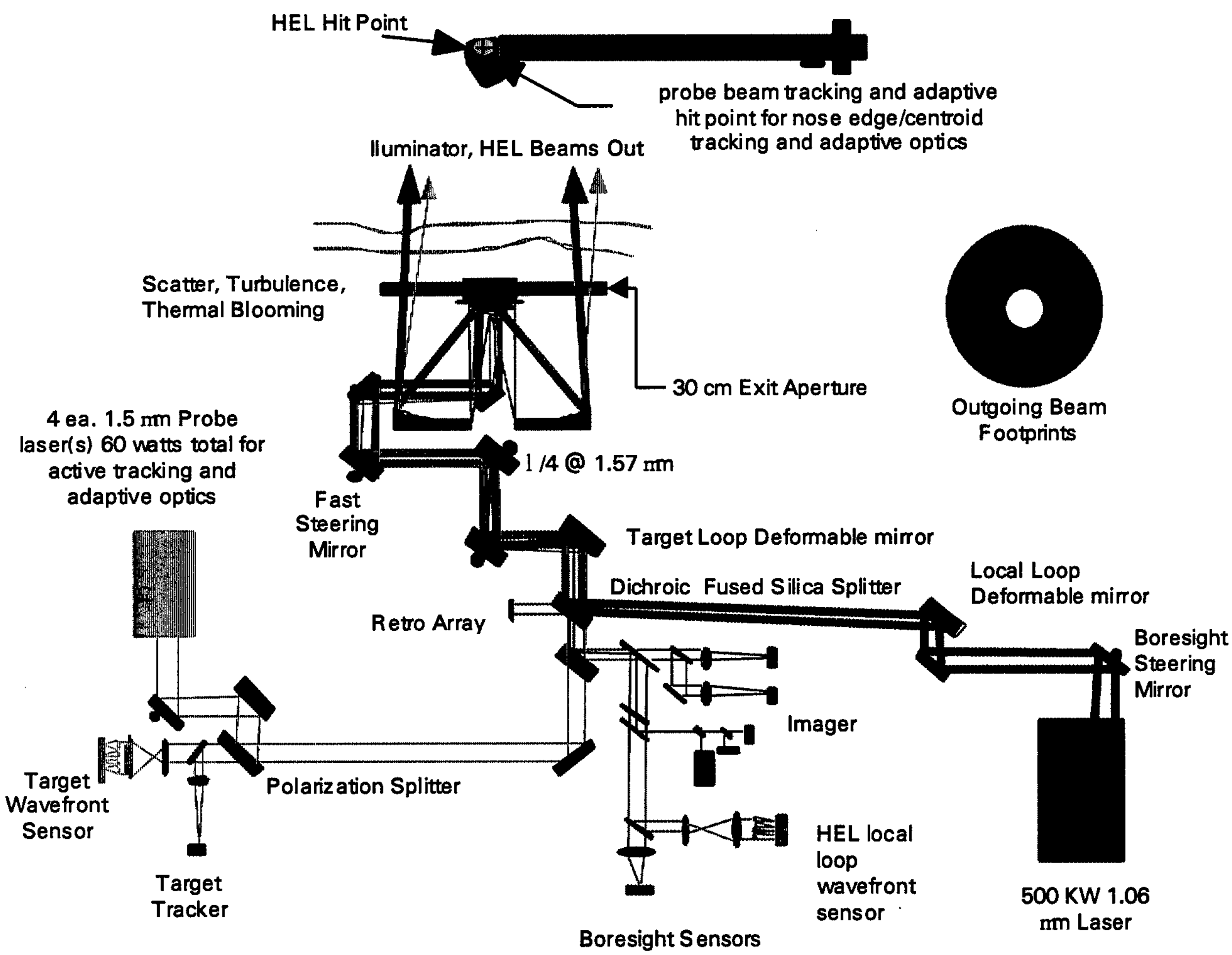

Figure 2. HEL system schematic

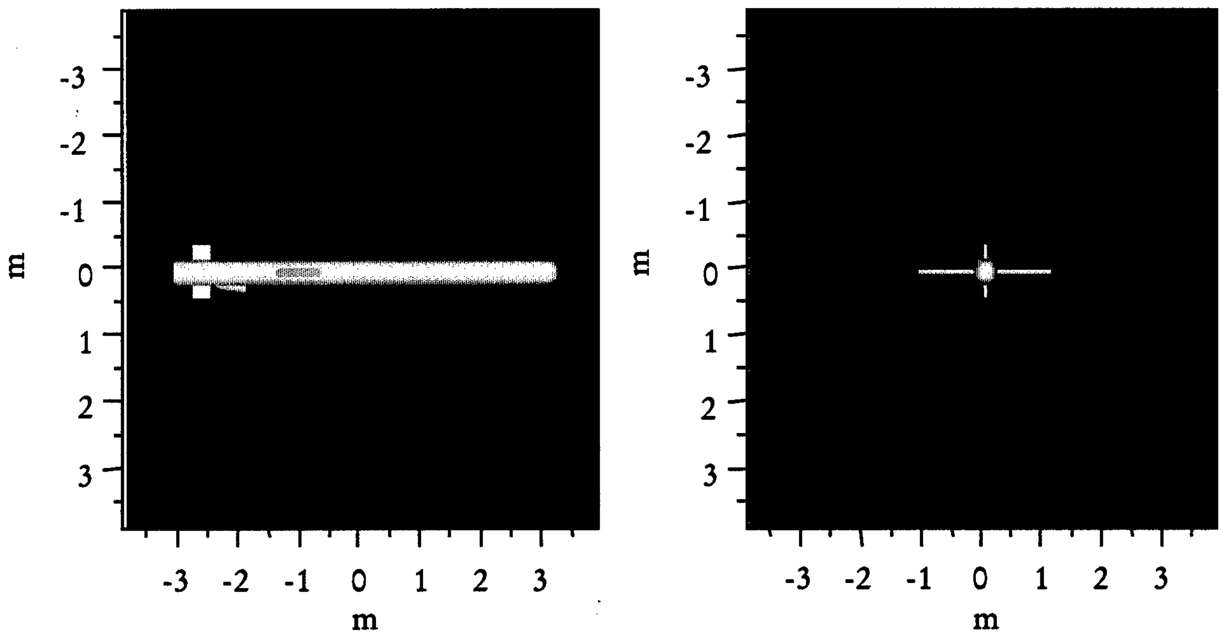

Figure 3. Notional target

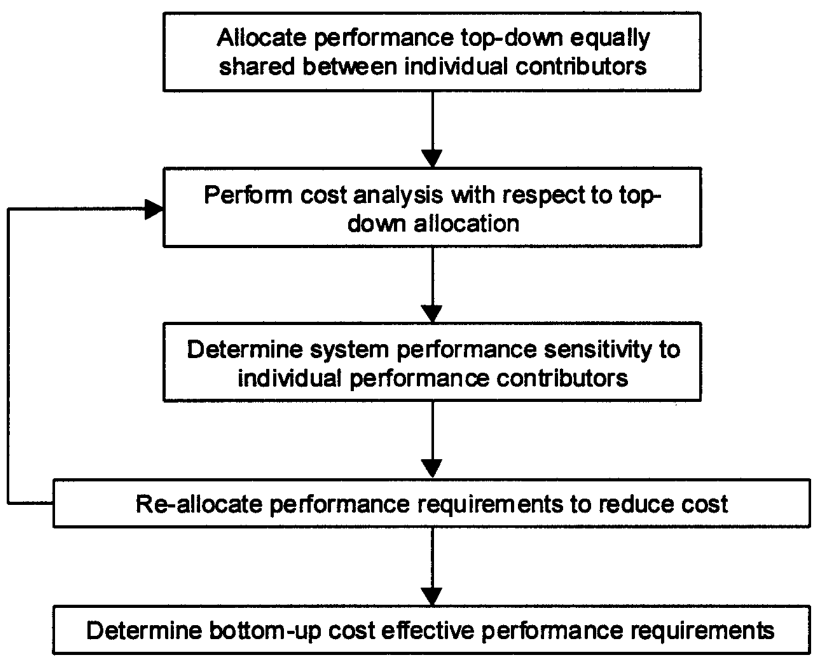

Figure 4. Optimization process overview

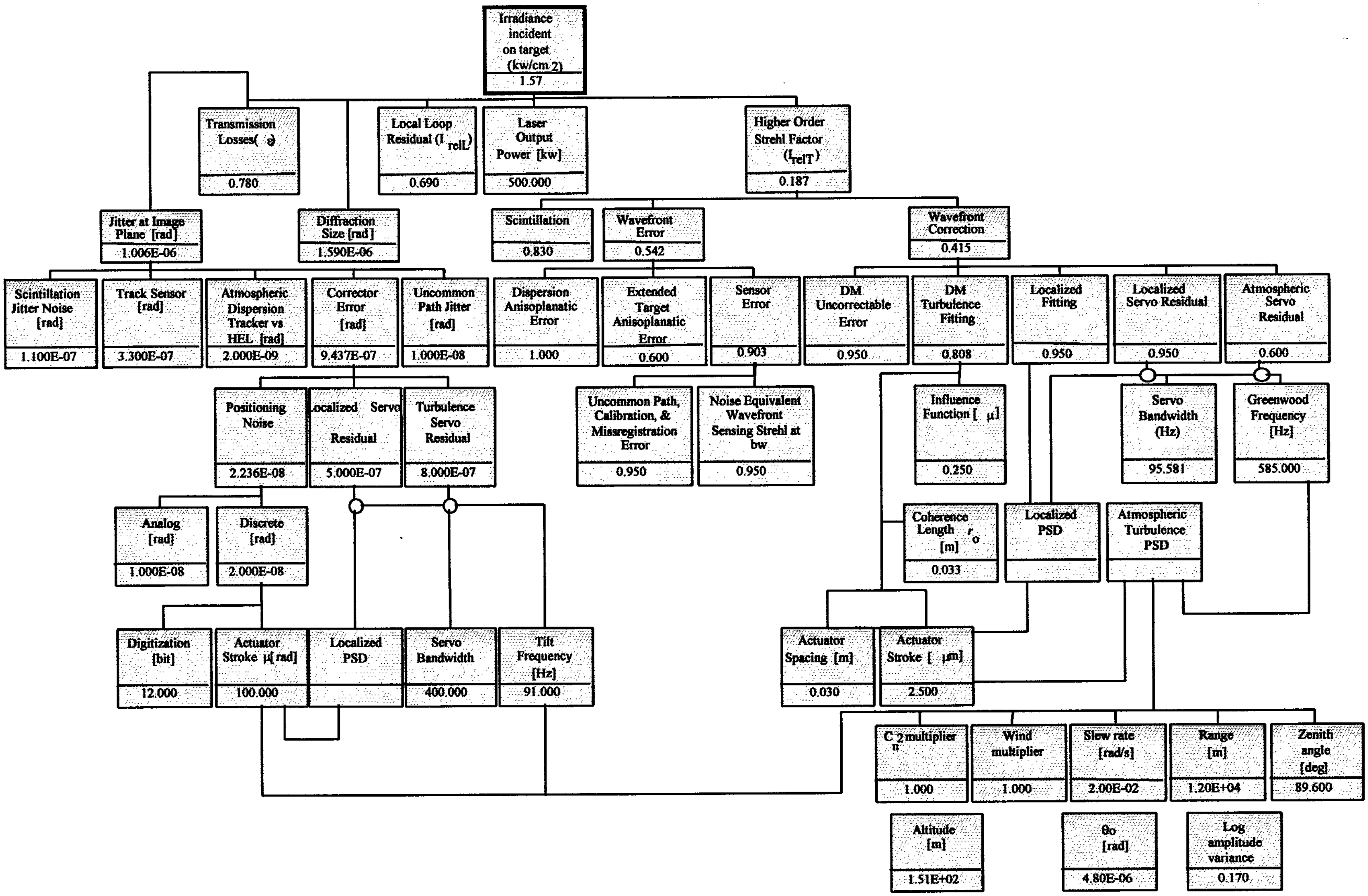

Figure 5. Performance allocation/error budget

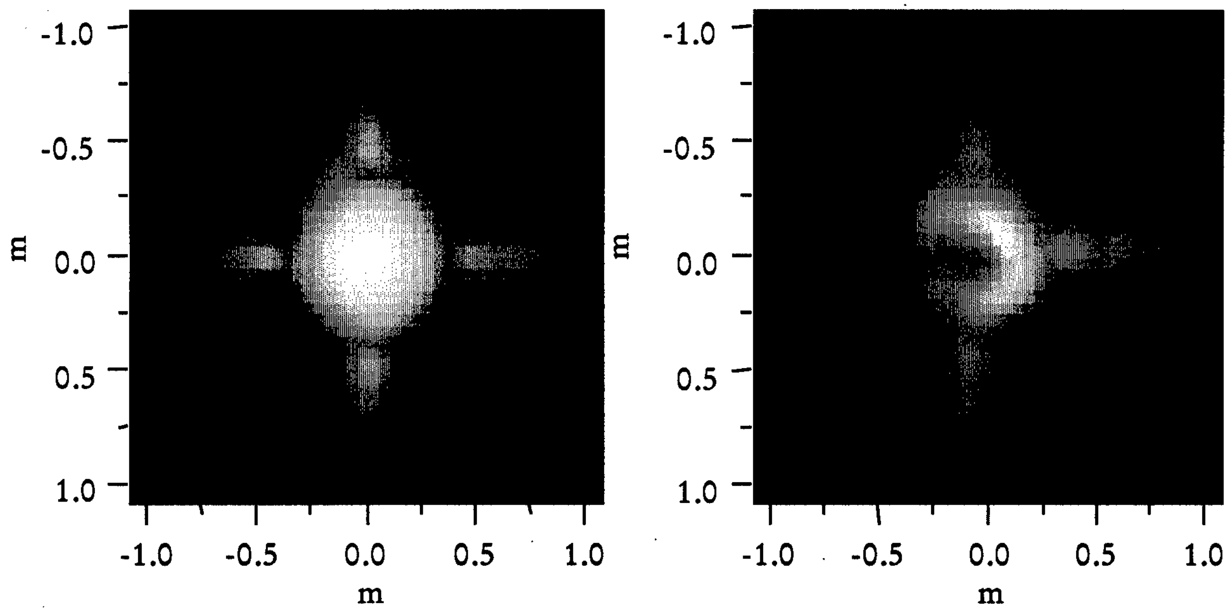

Figure 6. Target head-on tracking images at 6 km

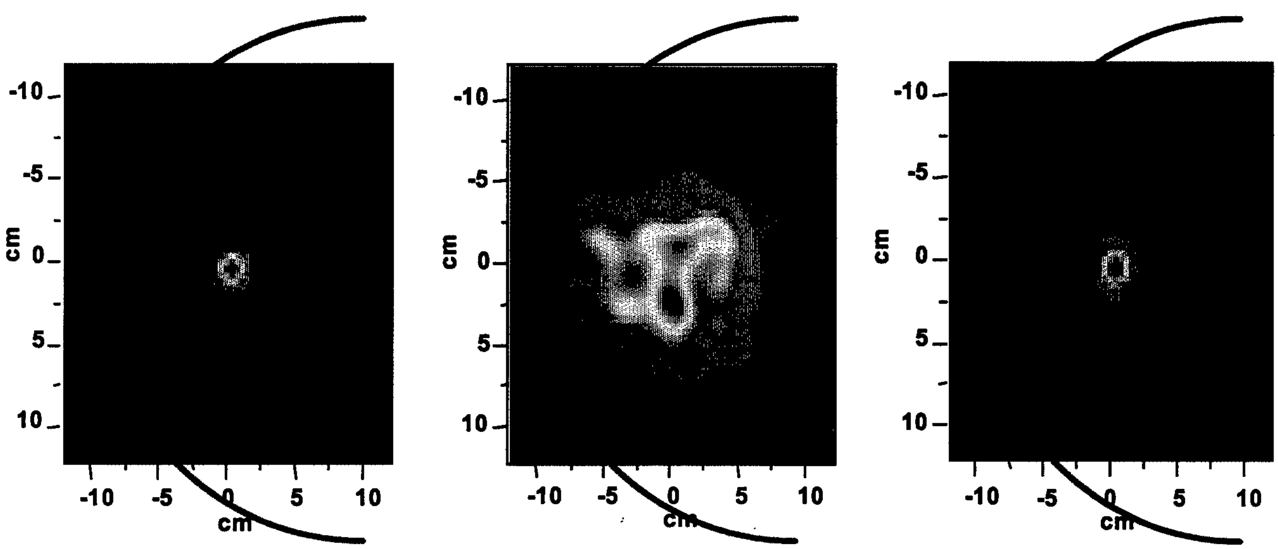

Figure 7. HEL irradiance pattern on the target nose

Title of Document: A High Energy Laser System Design and Performance Evaluation Tool

PLEASE CHECK THE APPROPRIATE BLOCK BELOW:

o A Copies are being forwarded. Indicate whether Statement A, B, C, D, E, F, or X applies.

o DISTRIBUTION STATEMENT A
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED

o DISTRIBUTION STATEMENT B:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES ONLY: (Indicate Reason and Date). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office)

o DISTRIBUTION STATEMENT C:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND THEIR CONTRACTORS: (Indicate Reason and Date). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office).

o DISTRIBUTION STATEMENT D:
DISTRIBUTION AUTHORIZED TO DoD AND U.S. DoD CONTRACTORS ONLY: (Indicate Reason and Date). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office).

o DISTRIBUTION STATEMENT E:
DISTRIBUTION AUTHORIZED TO DoD COMPONENTS ONLY: (Indicate Reason and Date). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office).

o DISTRIBUTION STATEMENT F:
FURTHER DISSEMINATION ONLY AS DIRECTED BY (Indicate Controlling DoD Office and Date) or HI ONER DoD AUTHORITY.

o DISTRIBUTION STATEMENT X:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND PRIVATE INDIVIDUALS OR ENTERPRISES ELIGIBLE TO OBTAIN EXPORT-CONTROLLED TECHNICAL DATA IN ACCORDANCE WITH DoD DIRECTIVE 523025, WITHHOLDING OF UNCLASSIFIED TECHNICAL DATA FROM PUBLIC DISCLOSURE. 6 Nov 1984 (Indicate date of determination). CONTROLLING DoD OFFICE IS (Indicate Controlling DoD Office).

o This document was previously forwarded to DTIC on ______________ (date) and the AD number is ______________.

o In accordance with provisions of DoD instructions the document requested is not supplied because:

o It will be published at a later date. (Enter approximate date, if known).

o Other. (Give Reason)

DoD Directive 5230.24, "Distribution Statements on Technical Documents," 18 Mar 87, contains seven distribution statements, as described briefly above. Technical Documents must be assigned distribution statements.

Elise Heitmeyer
Print or Type Name

703-288-5308
Telephone Number

Elise Heitmeyer
Authorized Signature/Date