

## **Multifunctional Modular Common Compact Components of Lasers (SYSTEM 2350)**

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**ABSTRACT:** Multiple Airborne and Ground based platforms will share multifunctional, common “System 2350” laser modules. Increased commonality is needed to significantly reduce development, production, and logistics costs. The platform constraints and requirements have similarities making a laser common modular concept viable. Within the very broad range of desired laser functions, a common need exists for long-range designating, Eyesafe rangefinding, and target profiling, and adding optical augmentation and MILES as required. A diode pumped ND:YAG Laser Engine and switchable OPO wavelength conversion satisfied the high end designation requirement and eyesafe ranging task. This laser engine’s assessed compact size meets the smallest of the platform space claims. An InGaAs APD array module permits profiling with the high energy, low rep rate engine output. The laser engine, receiver array, and a mix of mature and moderate risk technologies (e.g., diode laser stacks, TEC, OPO-based wavelength converters, wavelength selector, and dual wavelength receivers) form a common module B KIT. The outlined module interfaces plan for multiple combinations in an open system architecture. Conceptual laser system designs for the Apache Helicopter and the Abrams Tank platforms are presented using common modules providing both existing and new functions within the current space claim.

### **1.0 Introduction**

The “System 2350” concept builds laser systems for multiple platforms from common modules and components. Current system design practice already manages laser system complexity and maintenance by modularizing the laser system. The System 2350 seeks to further reduce development, production, and logistics cost by using more generally applicable modules. Production costs would drop if only for increased quantity. Logistics is the larger portion of the life cycle cost of most systems, and maintenance, training, and support would have more common equipment and fixtures through an open architecture. This summary details the efforts of one of three trade studies awarded under the Broad Agency Announcement.

A common modular laser system will add new laser functions within the existing laser volume and system constraints. Laser missions over the range of platforms require operational versatility and are not satisfied with one or two operational modes. If common modules are versatile enough to provide these operational features in some instances, they should succeed in increased functionality in most instances.

The starting assumption was that all laser requirements could not be satisfied with a single laser system. Study efforts concentrated on a modular, configurable, laser system that could address a great majority of platforms and missions. This goal of broad application was to be achieved while still meeting individual target systems’ space claim and functions.

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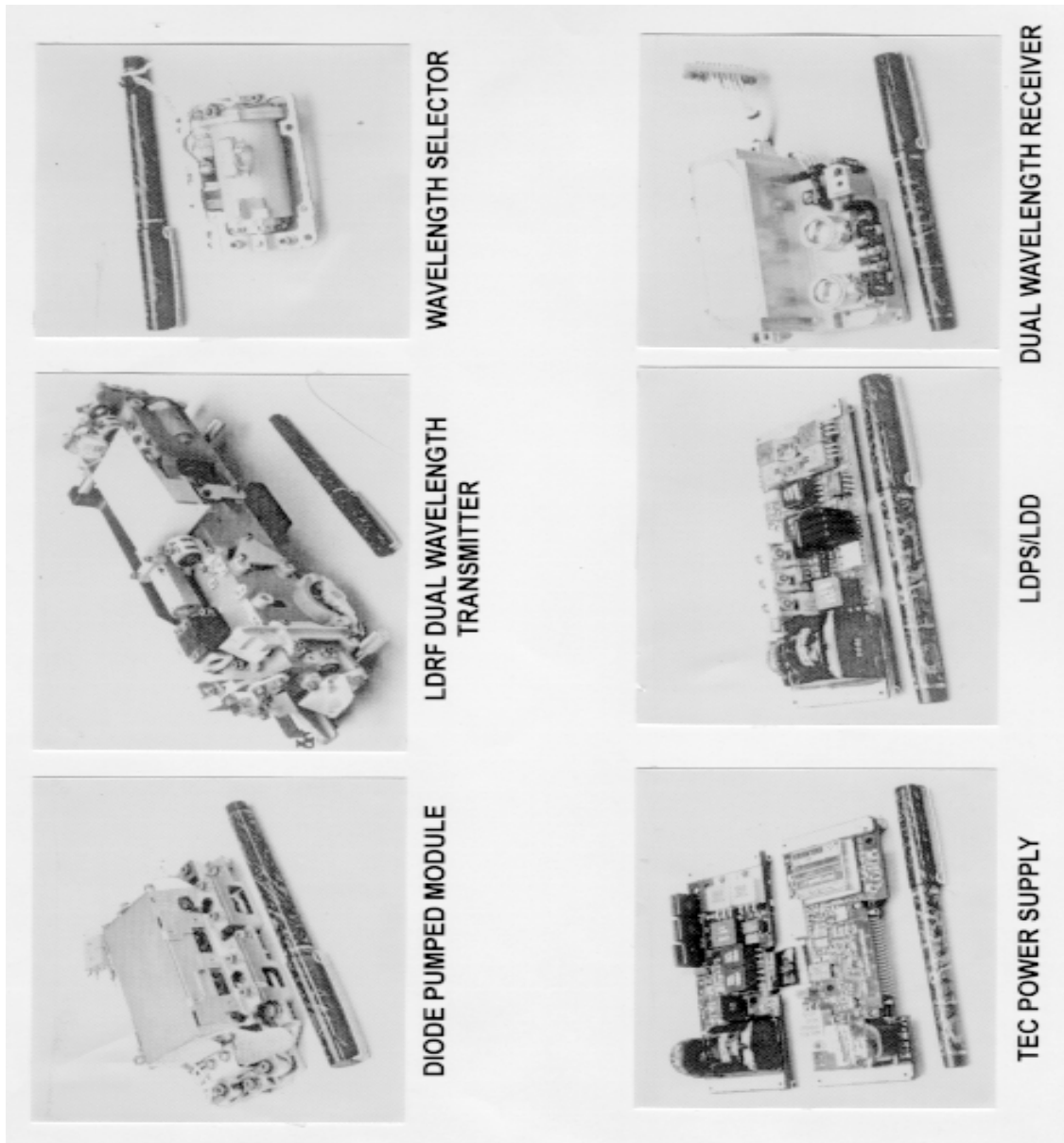
14. ABSTRACT  
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Existing multifunctional laser systems were reviewed to examine their modularity. These systems had desirable features such as diode pumping and operational flexibility consistent with a System 2350 concept. The Comanche laser is the first tactical, modular, multifunctional laser. Comanche laser modules depicted in Figure 1 served as a starting point in common module feasibility assessment.



*Figure 1 — Comanche Common Modules*

## 2.0 Multiple Applications: Laser Requirements and Priorities

An overview of platform constraints and requirements shows the similarities and differences in current laser requirements.

## 2.1 Platform Priorities

A large number of platforms were identified with laser systems or requirements for diverse functions. To set the proper relative emphasis, priorities were assigned to each platform or group of platforms in Table 1. The Integrated Product Team priorities reflected both the number of platforms and emphasized platforms with near-term requirements. The requirements and weights in Table 1 are generated by the IPT specifically for this study and are not necessarily formal performance requirements or formal priority assessments. These weights de-emphasized the rarer, special mission platforms that could unduly drive cost or risk. The high priority platforms included the airborne Apache, Comanche, and Kiowa Warrior and the Abrams, Bradley, and Future Scout ground platforms. Manportables, Unmanned Aerial and Ground Vehicles received low priority. The Land Warrior and LLDR received high priorities due to the high laser content and performance requirement similarities.

Table 1 — Updated Prioritization Table

	KW	AP	CO	UA	AB	BR	BF	FS	AA	UG	LW	TW	TL	OI	LL	Weight Total
1. Eyesafe rangefinding( to 2.5Km)											20	50	30	20		460
2. Eyesafe rangefinding (> 10Km)	20	20	20	25	29	29	24	20	30						50	1551
3. Target Marking (Out to 5Km)															50	250
4. Target Designation (> 10Km)	21	21	21		13	13	24	10	30							912
5. Eyesafe Designation (>10Km)	5	5	5													110
6. MILES training to 4Km						14	13				20			20		371
7. MILES training to 8Km	10	10	10		14			10								412
8. Pointing for NV goggles (to 2Km)											20	25	20	20		355
9. Pointing for FLIRs (to 2Km)											10	25		10		185
10. Target illumination for goggles (to 2Km)											10		15	10		155
11. Interrogation for Combat ID to 4Km											20			20		220
12. Missile countermeasure (to 5Km)																0
13. Laser profiling to 5Km	13	13	13	30	29	29	24	20	5	30						1177
14. O-EO detection greater than 6Km	21	21	21		10	10	10	20	30	30			35			1097
15. Optical countermeasure to 4Km	5	5	5		5	5	5	20								365
16. Obstacle detection and warning	5	5	5							10						140
17. Mine detection				21					5	30						168
18. Secure Communications																0
19. Biological agent detection (to 5Km)				12												36
20. Chemical agent detection (to 5Km)				12												36
Assigned Platform Weight (1-10)	6	8	8	3	8	8	3	8	3	3	8	3	3	3	5	

KW=Kiowa Warrior

BF=Bradley Fire Support Team

UA=Unmanned Aerial Vehicles

AB=Abrams

TW=Thermal Weapon Sight

BR=Bradley

CO=Comanche

AP=Apache

LW=Land Warrior

LL=LLDR

AA=Adv. Amphib. Assault Vehicle

FS=Future Scout Cavalry System

UG=Unmanned Ground Vehicles

TL=Target Locator & Observation System

OI=Objective Individual & Crew Served Weapons

## 2.2 Functional Priorities

Twenty (20) possible laser functions were identified across the major platforms. The IPT weighted the platform's needed functions for relative importance. For example, the Apache Helicopter was assigned 5 functions with weights of 27%, 34%, 13%, 20%, and 6% (for a 100% total). IPT debate and study changed some weights considerably. The Pointing function was downgraded, while initially low ranked Optical and Electro-optical Detection functions were more desirable than originally estimated.

Table 1 illustrates the combined effect of the platform weights and functional weights. The resulting weight of each laser system function is shown in the right-hand column. Although the relative importance of the platforms differs with mission and operational scenarios, the weighting by the number of respective platforms only provided small changes in the overall outcome of the weighting process. The most important and common functions across both airborne and ground platforms are the ability to perform eyesafe rangefinding and to designate targets. These core functions must be addressed. Target Profiling, Optical/Electro-Optical Detection, and MILES training were medium priority functions. This

second tier of functions is carefully considered to extend and enhance the multi-functionality of the system.

The least common functions received the lowest prioritization ratings. These functions included target marking, target pointing, night vision goggle illumination, eyesafe designation, and combat identification. Specialized functions such as infrared and electro-optical countermeasures scarcely appear among the platform functions and were very lightly weighted. The emerging technologies of obstacle and mine detection, secure communications, and chemical and biological agent detection were also rare or lightly rated even among airborne platforms. While these functions were low priority, they were not completely undesired. The System 2350 concept provides for the possibility of upgraded or new systems as threats and requirements change.

### 2.3 Operational and Interface Requirements

The operation requirements derived from the mission statements were analyzed. Clear similarities in requirements and functions across platforms made defining commonality occasionally straightforward. In some instances incremental changes in operational requirements addressed additional platform requirements and involved performance and technical trades. The analysis found a high degree of similarity for the operational requirements for the airborne platforms with high interest. Similarly for the ground vehicles, there are many common operational requirements.

In addition to operational requirements, platform interface requirements place additional constraints on the laser system. Each platform was evaluated for laser system interface requirements such as: weight, volume, power consumption, thermal management, optical exit aperture, optical transmission, etc.

## 3.0 Laser Technologies and Emerging Materials

Emerging materials and laser technologies were considered for application in common modules. Using existing laser technologies reduces risk involved with a near term System 2350 EMD, but emerging materials and technologies were considered. Moderately increased risk with incorporation of new materials in EMD would be attractive if overall system or common module performance could be enhanced. Even where risk is currently unacceptable, technologies viable for out-year development were identified. Figure 2 illustrates the study's technical evaluation flow.

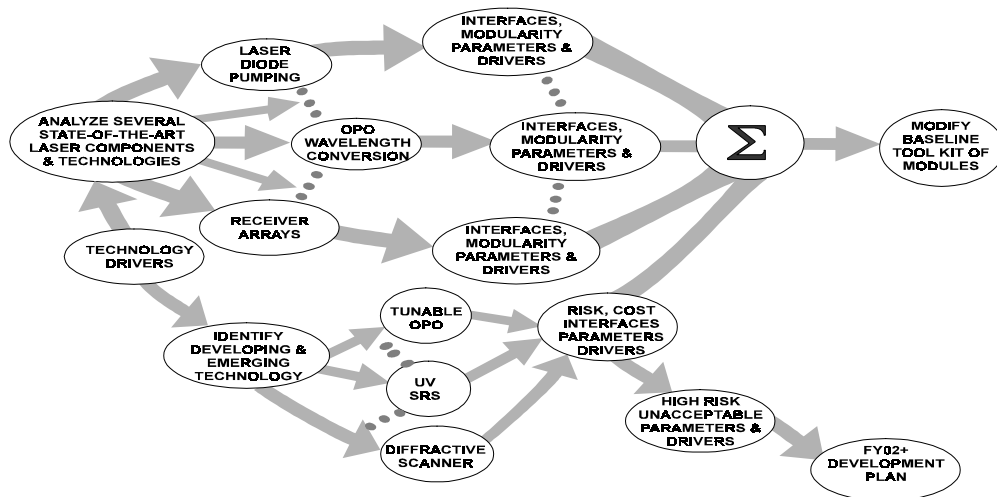


Figure 2 — Technology Drivers

### **3.1 Host Laser Crystals**

A variety of laser sources were evaluated as candidate technologies for System 2350 oscillator, amplifiers, and wavelength conversion modules. These technologies include solid state lasers of various lasing and host materials, tunable lasers, and combinations of laser source and wavelength shifters.

Materials providing output at or very near 1064nm are focused on due to the high priority placed on laser designation requiring this wavelength. The most common 1064nm lasers are Nd:YAG, and more recently Nd:YVO<sub>4</sub>, which are preferred for many applications in spite of relatively high thermal focusing. As an example, Nd:YVO<sub>4</sub> is a good choice for generation of short Q-switched pulses at high repetition rates with high average power. Its very high stimulation emission cross section (approximately six times that of Nd:YAG) facilitates short-pulse Q-switching. This performance is a good match for non-linear processes and applications such as micro machining, rangefinding, and harmonic generation. Of the less common materials, YAP is an interesting alternative with potentially better efficiency than diode pumped Nd:YAG, but is still in development and may prove to be a drop-in upgrade. This upgrade might not affect the diode pumping array.

Should the 1.064 micron designation requirement be relaxed in the future, other diode pumped lasers such as YAP (YALO) and Nd:YLF could prove attractive. The Nd:YLF medium exhibits minimal thermal focusing and has advantages for an application requiring relatively high CW TEM<sub>00</sub> output. The choice of Nd:YLF is also common for high-energy, low repetition-rate Q-switching (below 5KHz) because of an upper-state lifetime more than twice that of Nd:YAG.

### **3.2 Wavelength Agility**

Eyesafe operation, pointing for mid and far infrared imagers, and optical detection/countermeasures all require operation at wavelengths other than 1064nm. Wavelength conversion from 1064nm is a key technology for which various existing and emerging technologies were compared. Conversion can be obtained using Raman shifting of Nd:YAG laser radiation in compressed gases and solid crystals. OPO (Optical Parametric Oscillator) conversion provided the smallest estimated module size, while others provided better efficiency and tunability.

#### **3.2.1 Wavelength Conversion for Eyesafe Capabilities**

Although modules for OPO or SHG wavelength conversions could be integrated into a laser oscillator or amplifier module, more modular approaches offer improved wavelength selectability for mission flexibility. Ninety degree phase matched KTP (Potassium Titanyl Phosphate) OPO produces 1.57 $\mu$ m signal and 3.3 $\mu$ m idler wavelengths (when pumped by 1.064 $\mu$ m laser). The relatively high stability and ruggedness with this phase match offers dual wavelength selection or possibly a triple wavelength selection (e.g., 1.06 $\mu$ m, the OPO 1.57 $\mu$ m, and the idler beam at 3.3 $\mu$ m, all co-boresighted).

Thirty-five percent conversion efficiencies of Nd:YAG (at 1.064 $\mu$ m), or Nd:YLF (at 1.047 $\mu$ m) laser radiation into eyesafe region (at 1.52-1.61 $\mu$ m) are obtained today in 20mm OPO crystals even with highly multi-transverse-mode pump lasers. High beam quality OPO conversion (15mm\*mrad) has been demonstrated in a reasonable size resonator (~64mm). Short OPO resonators are compact and efficient (improved temporal matching) but result in a low brightness OPO laser output. A 30mm\*mrad beam quality has been demonstrated in a robust 32mm length cavity.

#### **3.2.2 Diversity Shifting**

Wavelength conversion methods providing more than just eyesafe laser output were considered. Of these, tuning with OPO and Solid State Raman conversion appeared most attractive. Tunable laser diodes provided insufficient peak powers for most applications, and Raman conversion with a gas medium was too bulky.

The tunable 3 to 5 micron laser radiation for remote sensing and active imaging applications with OPO crystal rotation with 17% conversion efficiency offers hundreds of nanometers tuning ranges with a single configuration. This makes the OPO a serious challenger as a tunable military laser. Of particular interest are tunable single OPO conversions and double OPO conversion.

A critically phase-matched OPO conversion from 1.064 $\mu\text{m}$  to one or two wavelengths at approximately 2.1 $\mu\text{m}$  has a high effective conversion efficiency, where the idler output and the OPO output are both used. Temperature changes affect mechanical stability with a critically phase-matched KTP crystal with minor wavelength and pointing drift. Double OPO conversion requires a crystal other than KTP due to increased bulk absorption past 3 $\mu\text{m}$ . AgGaSe<sub>2</sub> is a candidate OPO crystal in advanced development which provides significant tunable output from 7 to 12 $\mu\text{m}$ .

KTP is operationally transparent from 350nm – 3.3 $\mu\text{m}$ , has satisfactory resistance to optical damage, has good non-linear response, and is currently the material of choice for tunable conversion. Today, KTP crystal with good optical quality can be grown and cut to 60x60x30mm<sup>3</sup> and even larger dimensions.

KTA, RTA, and CTA are promising OPO materials, especially for tunable radiation in 3-5 $\mu\text{m}$  region for remote sensing and active imaging applications. They have slightly better than KTP transmission for idler wavelengths at 3-5 $\mu\text{m}$  range and may present a good competitor to the KTP crystal. Single domain KTA, RTA, CTA high quality crystals growth is still limited to relatively small dimensions, but it has potential to be improved in the next few years. At KTP crystal dimensions, these newer materials are expected to have better efficiency with a higher laser damage threshold.

Each of the above crystals can be periodically polled for a qualitatively new OPO configuration – quasi-phase matching. Further development is needed here to extend OPOs to smoothly tunable operation.

OPO conversion efficiency from a 1.06 $\mu\text{m}$  laser source to 10 $\mu\text{m}$  is nearly 0.5%. New OPO materials are expanding the practical tuning ranges of solid state materials and providing greater versatility, especially in the infrared region. Materials such as zinc germanium phosphide (ZGP) finds use in the 3—5 $\mu\text{m}$  and 8—12 $\mu\text{m}$  spectral region. A novel approach to generate high non-linear coefficients using stacks of oriented GaAs crystals is under development.

Solid state Raman conversion efficiency is high: 30% for KGW, and 60% for Ba(NO<sub>3</sub>)<sub>2</sub> and are useful for development of eyesafe LRFs. The efficiency of the Nd:KGW crystal makes it most useful inside the resonator, and Ba(NO<sub>3</sub>)<sub>2</sub> crystal outside the resonator. Ba(NO<sub>3</sub>)<sub>2</sub> Raman conversion should be a candidate for out year EMD as a high-efficiency converter module of an external pump.

### **3.3 Pumping Technologies**

Moderately high laser energy pumping technologies for the 1064nm output crystal subset were examined. Flashlamp pumping was quickly eliminated as it was not competitive in lifecycle cost trades and required liquid cavity cooling at 20 Hz pulse repetition rates.

Diode Pumped Nd:YAG Solid State Lasers offered key advantages in the designation and target profiler missions. The diode pumped lasers are more efficient, more compact, and consume lower electrical power than flashlamp-pumped lasers. The diode arrays have long operational lifetime and can be conductively or thermoelectrically cooled. There is no maintenance cost associated with liquid coolant, and reliability is improved. The diodes are coupled to the laser crystal within the diode pumping cavity with concentrating optics for better pump uniformity and efficiency. A high quality beam with lower divergence and better beam stability is produced with reduced waste heat.

Several pumping geometries were evaluated. End pumping is sufficiently limited in energy output so as to be unattractive as part of a designation source. Pump fiber coupling can achieve high laser energies but has low efficiency. Minimizing the laser head dimensions by relocating the diodes farther away from

the rod is an advantage. Side pumping a rod or slab achieves the high laser energies needed for most military applications. Pumping perpendicular to long laser axis is less efficient, with non-optimal coupling of the diode radiation into the rod or slab, but is viable due to the large crystal absorption cross-section. The high peak absorption in these bands (e.g.  $\sim 8\text{cm}^{-1}$  in 1% Nd:YAG at 808nm) allows using these arrays in a side pumping geometry transverse to the cavity axis. In this arrangement the individual laser diode emitters are not required to be coherent with each other, and pump powers can be easily scaled with multiple arrays around the outside of the rod or along its axis.

For side pumping, usually a number of linear arrays (bars) are stacked together and mounted on a heatsink, which in turn is mounted on a temperature controlled thermo-electric cooler. The laser diode output is highly divergent in the vertical dimension. The geometry of coupling is designed to ensure good diode light coupling into the laser rod. The bars are arranged to smooth out the absorbed energy profile, allowing for a circularly symmetric gain profile.

Radially symmetric pumping and cooling of the oscillator/amplifier Nd:YAG rod provide uniform gain distribution. The rear of the rod support provides a conductive heat sink for crystal. The measured near field output laser energy distribution confirms pumping and cooling uniformity. The use of the laser crystals in the form of cylindrical rods allows a uniform gain distribution across the active medium thereby improving beam uniformity and beam divergence as compared with similar diode-pumped slab lasers.

Diodes tailored to emit 807nm with bandwidths of less than 4nm FWHM can be temperature tuned to the best Neodymium absorption line. Mature, commercially available GaAlAs laser diode arrays provide viable quasi-CW output power densities. The diode arrays, inside their protective housing, are positioned close to the laser rod, directly or through the optically matched material. For such coupling, the low-order mode sizes are large enough for reasonably good laser extraction from the entire rod cross section, and the efficiency of coupling of the pump light into the rod is not very sensitive to the rod barrel finish.

A fiber-bundled-coupled diode bar pump module uses a cylindrical fiber microlens of high numerical aperture to collimate the diode bar output. The microlens is fixed to the diode bar to reduce the fast-axis divergence of the diode output. In this case, each emitting array of the collimated diode bar within the diode pump module is coupled to a multi-mode optical fiber. The optical fibers are drawn together into round bundles of 1 — 1.5mm diameter and numerical aperture of approximately 0.1 at the output. Of the light from the collimated diode bars, 85% to 90% is emitted by the bundle. The bundle is terminated with a standard fiber-optic connector that connects precisely to a laser head that can be located remotely from its power supply. Laser heads designed for this pump source are typically configured to image the output of the bundle into a laser crystal through a dichroic end or fold-mirror.

### **3.4 Detectors**

The collected applications require both highly optimized single wavelength receivers and multiple wavelength, multi-element receivers. A complex receiver addressing many needs is justified in a friendly form factor. Receiver detectors may be common across applications and platforms, and can be fiber optically remoted in several demanding missions.

Multi-element linear and array Si:APD, Ge:PIN, and InGaAs:PIN detectors have been fabricated for many years by different companies. The Si arrays are usually made using a double-diffused “reach through” structures hermetically sealed behind a glass window of a common housing. InGaAs APD arrays are under development with an 8x8 size in one case, and these developments are considered essential in

improving laser system functionality without driving average transmitter average power and system cost to an unacceptable degree. APDs improve on the sensitivity of the InGaAs:PIN with a structure requiring a 70 – 120V bias for APD gains of  $\sim 10$ . Element sizes run 85 – 200 $\mu\text{m}$  for 10 – 30 A/W sensitivity and a

5nWatt NEP at a 50MHz amplifier bandwidth. A lower risk approach constructs APD arrays with individual fiber pigtailed communications receivers. The fibers are tightly packed in a focal plane fiber chuck. The parallel receiver channels each consume approximately  $5 \times 10 \times 35 \text{mm}$  ( $0.1 \text{ in}^3$ ), but can be located within the optical bench with great flexibility and with an attractive form factor.

## 4.0 Trade Summary

Figure 3 provides a conceptual construction of a multifunctional laser system for an airborne

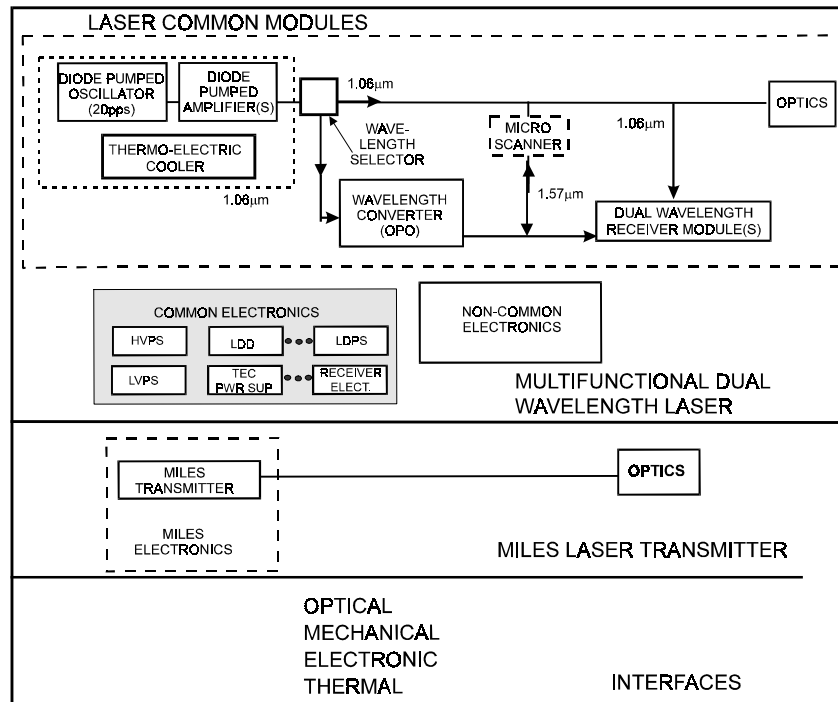


Figure 3 — System 2350 Laser Block Diagram

platform that incorporates a subset of modules (i.e., B Kit) drawn from the tool kit. Laser and electrical modules are selected as required to enable laser designation, eyesafe rangefinding, and eyesafe laser profiling. A MILES module is shown integrated into the laser system, but with a parallel optical channel. The optics, electronic interfaces, and thermal and mechanical components and interfaces could be platform-specific (i.e., A Kit). Optical/electro-optical detection can be added on to the core capabilities via the addition of a wide format scanner. This capability may use its own optical channel or will be combined with the laser rangefinder/designator/profiler optics.

### 4.1 Laser Transmitter Multi-Functionality

Mission requirements analyses for each capability are flowed down to laser system and laser subassembly parameters to define critical parameters. The flow down of requirements to the laser parameter is not independent of selected laser technology and laser system approach. The parameter flow down iteratively alternated between approach definition and performance analysis for various sets of parameters.

### 4.2 Core Functions: Rangefinding and Designating

Eyesafe rangefinding requires that there be no laser safety hazard at the system output apertures and implies a Class I or Class IIIA safety rating. These ratings are most easily achieved at wavelengths above

1.4 $\mu\text{m}$  and still provide viable rangefinding performance. Even with appropriate wavelength conversion, a Class I rating (most stringent) limits ranging performance due to an 8mJ pulse energy limit. A Class IIIA laser is also considered eyesafe, with a nominal ocular hazard distance of zero (unaided observer). A Class IIIA laser's energy output is limited to 32mJ at 1.5 $\mu\text{m}$ .

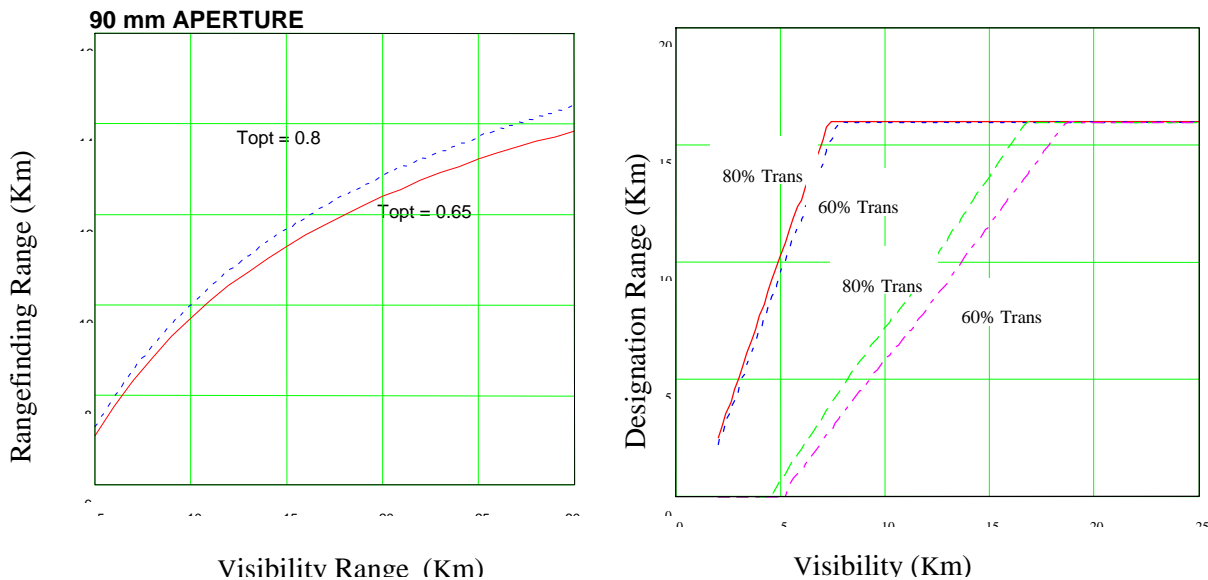
Ten-kilometer eyesafe rangefinding imposes a higher laser system demand and is considered the core rangefinding requirement. A 20mJ eyesafe rangefinder with a 90mm diameter receiver aperture diameter and a 0.3mrad divergence provides 10Km ranging in 10Km visibility. The 0.3mrad divergence is driven by the NATO target angular size at range. A 10% diffuse reflectance is assumed for this target, modestly driving energy or other parameters. 10Km ranging provides good performance in reduced visibility (smoke and dust). The rangefinder detection range is always greater than the reduced visibility range. The rival technologies are 1.06 $\mu\text{m}$  with wavelength conversion (such as OPO or Raman shifting) and direct Erbium.

Current rangefinding requirements in the M1A2 Abrams Tank are provided with an Erbium glass rangefinder. The flash lamp pumping efficiency of this rangefinder is low, and an equivalent eyesafe output can be generated with a diode pumped Nd:YAG laser engine and OPO conversion with an equivalent amount of heat dissipation. The difference is cost, reliability, and commonality. The up-front cost is much higher in rangefinding with diode pumped Nd:YAG and OPO eyesafe conversion, but the reliability is better, and upgrade possibilities through commonality arise.

As little as 70mJ Nd:YAG pumping pulse energy with suitably efficient and switchable eyesafe conversion are sufficient for full 10Km rangefinding. The limited designation capability with this energy can be extended to a full 10Km range with an additional diode pump laser amplifier.

*Figure 4 Rangefinding and Designation Performance vs. Visibility*

Laser designation is a driving requirement for the laser output energy, output wavelength 1.064 $\mu\text{m}$  and pulse repetition rate, and beam quality. The laser output energy had to be high enough to satisfy the



designation range requirement for both airborne (including a lock-on before launch requirement) and ground designation. Performance analysis resulted in a required value of 175mJ. The output wavelength

for designation of 1.064 $\mu$ m required by the existing arsenal of laser guided munitions necessitates a laser engine for designation to be Nd:YAG. Operation at 20 — 25Hz pulse repetition rates indefinitely is considered a core requirement in order to provide required Tri-service codes as well as other pulse coding schemes. This can be a problem for a laser-optimized for high rep rates, where pumping efficiency can drop if pump energy is reduced to operate continuously. The system output divergence required to maintain 90 percent of the energy, 95 percent of the time within the boundaries of the target, has to be on the order of 100 $\mu$ rad, which requires good beam quality in the order of 10mm\*mrad raw beam brightness. These core requirements affect the laser engine, diode pumping module, heatsink, and optical bench design.

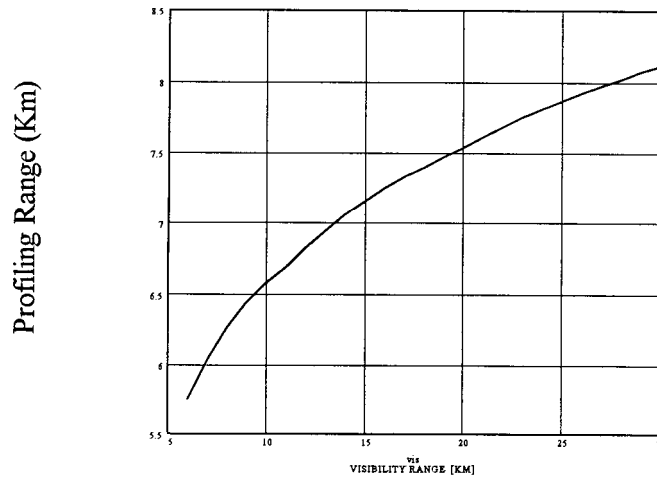
Eyesafe rangefinding is considered an essential core requirement at the system level and imposes only a conversion requirement of laser output to an eyesafe wavelength to the more stressing designator requirement. An OPO conversion module capable of generating 35mJ at 20Hz and 1.57 $\mu$ m output wavelength is the preferred method to provide this core function. The system level energy is limited below 32mJ in order to maintain a Class IIIa eye safety classification, and driven to at least 22mJ to satisfy the long-range performance requirement.

OPO eyesafe wavelength conversion has been broken out as a separate component to provide system flexibility. A modular approach is justified with rapid wavelength selection of either 1.06 $\mu$ m designation or the OPO-converted 1.57 $\mu$ m eyesafe output co-boresighted. A failsafe (eyesafe) wavelength selector common module is required and justified.

Parameter analysis and trades suggest missions can be satisfied by a common basic Nd:YAG “engine” with 175mJ at 1.06 $\mu$ m, with high beam brightness, with a switchable 1.57 $\mu$ m channel based on an OPO with 35mJ. Figure 4 provides predicted designation and rangefinding performance for this type of laser. Integrating a common modular High Power diode pumped Laser Engine, Wavelength Selector, Wavelength Converter, and CCAs into a highly compact package demonstrably provides these core functions. The core requirements of eyesafe rangefinding and laser designation have already been addressed on ELOP’s Comanche laser, the Fibertek Multi-functional System, and on Kollsman/ELOP’s SELRD for the Kiowa Warrior. In particular, the SELRD (Kiowa Upgrade) laser has a modular package that drops into all the prioritized platform space claims with minor violations. Addressing these two core requirements is considered “no risk”. Other solutions involved laser sizes complicating a common modular package definition.

### **4.3 Target Profiling**

Laser profiling can be performed with a very high rep rate (1KHz) laser system or with a 25Hz rep rate laser and a receiver detector array, and highly parallel processing. There is an increased commonality with the low rep rate, core requirements, and a detailed technical analysis focused on the later. A commonality trade favors simplifying the laser transmitter while requiring the receiver channel optics and electronics to perform a larger part of the required target profiler function. Laser profiling with a multi-element APD:InGaAs detector array and parallel receiver processing were defined to assess an associated size and processor complexity increase. A common transmitter can provide the performance necessary for eyesafe target profiling with a small receiver matrix and micro-scanning. These modified receiver technologies and scanner technologies operate well with the core designator/OPO laser parameters. The development risk of the multi-channel receiver with a focal plane fiber optic coupling is much less than the development of a brand new laser oscillator concept all the way to serial production and field support.



**Figure 5 -Profiling Range (Km) v Visibility**

A high rep rate serial target profiler would be either a separate module with its own power supplies and driving electronics (demanding additional volume on the platform), or it could be incorporated in a much more complex resonator including “three oscillators in one”. Such a concept would be very costly in development, production, and O&S. The built-in multi-functionality within such a transmitter would not allow the flexibility to reduce complexity and cost.

#### **4.4 MILES**

MILES training capability requires the addition of a laser transmitter capable of emitting 904nm laser pulses at a 3KHz repetition rate. The MILES laser transmitter optics collimates the beam to allow for simulation of the designator effective ranges. The MILES laser transmitter is comprised of a laser diode, lens element, and encoder board. The MILES laser beam of typically 1 pJ per pulse is combined as close as possible to the laser exit aperture to simplify beam combining.

It is estimated that the MILES laser transmitter can be packaged within 5 in.<sup>3</sup> and therefore, can be added to the core capabilities with minimal volume impact. As adding MILES involves no increase in average power, the power and heat dissipation assessment remains low on most platforms and moderate on the MIA2 and Bradley.

#### **4.5 E/e&o-Optical Defection**

Including EOD along with the designator and rangefinder requirements addresses approximately 60% of all laser systems platform requirements. EOD drives:

- laser beam divergence control requirements (-20mrad)
- wavelength selection (agile tuning or 2.0pm operation desirable)
- scanning (approximately 20 times the divergence)
- receiver technology, laser cooling, and laser pulse repetition rate

A higher degree of detection success requires laser output within the operating band of the target sensor. EOD to the ranges and fields of regard require a very high rep rate. The needed high rep rate laser output was considered to involve a second laser resonator and had an unacceptable volume impact on most of the critical platforms. Limited EOD operation was analyzed with reduced FOVs but effectively providing the needed functionality with a common laser transmitter.

Operation at 1064nm and 1540nm was presumed in this analysis and provides EOD of visual and near infrared optical sensors. Analysis indicated that PRF rates and energy levels for designation and

rangefinding were adequate for EOD within a limited FOV. Operation with the natural idler output at 3.3 microns offers EOD possibilities for Mid and Long IR augmentation.

OEO detection is a feasible additional capability to both airborne and ground vehicles to be added during out year upgrades.

## 5.0 Common Module “B Kit”

Twelve common modules are justified as part of a “B Kit” of laser modules. Performance specifications, packaging, and other interface requirements were defined for each of these modules. A “tailored-to-platform” laser system can be cost effectively constructed utilizing selected B Kit modules.

The strawman module set defined has drawn from the robust and mature diode pumped Nd:YAG resonators with eyesafe OPO wavelength conversion and added low to moderate risk improvements providing increased on-the-fly wavelength selection and smoother operational mode changes. The new modules are in most cases smaller but do not sacrifice stiffness and ruggedness. Each module has interfaces for multiple combinations and great system tailoring flexibility. Table 2 summarizes critical parameter flowdown to each module. The laser Engine Module includes a Diode Pump Module and Wavelength Converter/Selector.

Table 2 — B KIT Modules and Critical Parameters

B KIT Module	Critical Parameter	Weight	Size (mm)	Power(W)
Nd:YAG Laser Engine	175mJ output at 1064nm	780g	260x70x87	290 max
Diode Pump Module	TEC cooled	400g	74x55x21	290 max
Wavelength Converter/Selector	25 — 32mJ at 1.57 μm ~1μJ at 1.06μm	63g	69x46x41	4.2 max
Receiver Module	Single Element, Dual Wavelength	80g	68x28x37	5
Receiver Array Module	multi-channel receiver electronics	360g	20x59x70	0.2 max
Laser Diode Driver	80A @92% efficiency	12 g	164x60x28	8.7 max
Energy Storage Module	Electrolytic Storage Caps	310g	146x63x41	2
Pockels Driver	3000V @ 300μA	110g	71x55x15	2.5
Energy Sense Assy	Output energy monitor	20g	40x35x20	0.3
MILES Module	1μJ @ 904nm, 3KHz	42g	25x51x13	1.0

A common diode pump module includes a diode pumped oscillator and a diode pumped amplifier; both pumped with the same type of diode bars and located on a Thermo-Electric Cooler (TEC) is proposed. This DPM module is mounted on a heat exchanger (A Kit module) and connected the optical bench of the common 175mJ laser transmitter. Thus, commonality is achieved on multiple levels: components (diodes, TEC, etc.), module (DPM, WL converter, etc.), and the laser transmitter optical bench “super-module”.

Four of these modules are highlighted. The resulting trade flow down performance and Interface Specifications are shown.

### 5.1 Diode Pumped Nd:YAG 175 mJ Common Laser Engine

A highly compact common high energy 175mJ diode pumped Nd:YAG Laser Engine and OPO based wavelength conversion provide a wide range of upgrade utility; The high output meets the high end mission energy requirements and the compact size was driven to meet the smallest space claims. The weight, size, and efficiency performance trades and analysis based on a mature pump geometry suggest a low to moderate production risk. The common module laser engine interface specification could allow detailed geometry within the unit, but would at a minimum require using particular diode stack modules.

The Common laser engine will likely be used as a drop-in common module, but itself is an integrated subassembly of other common modules (a “super-module”). To provide a more open architecture, several interfaces within the laser engine are defined to simplify future upgrades and improvements. The diode stack interface is one of these.

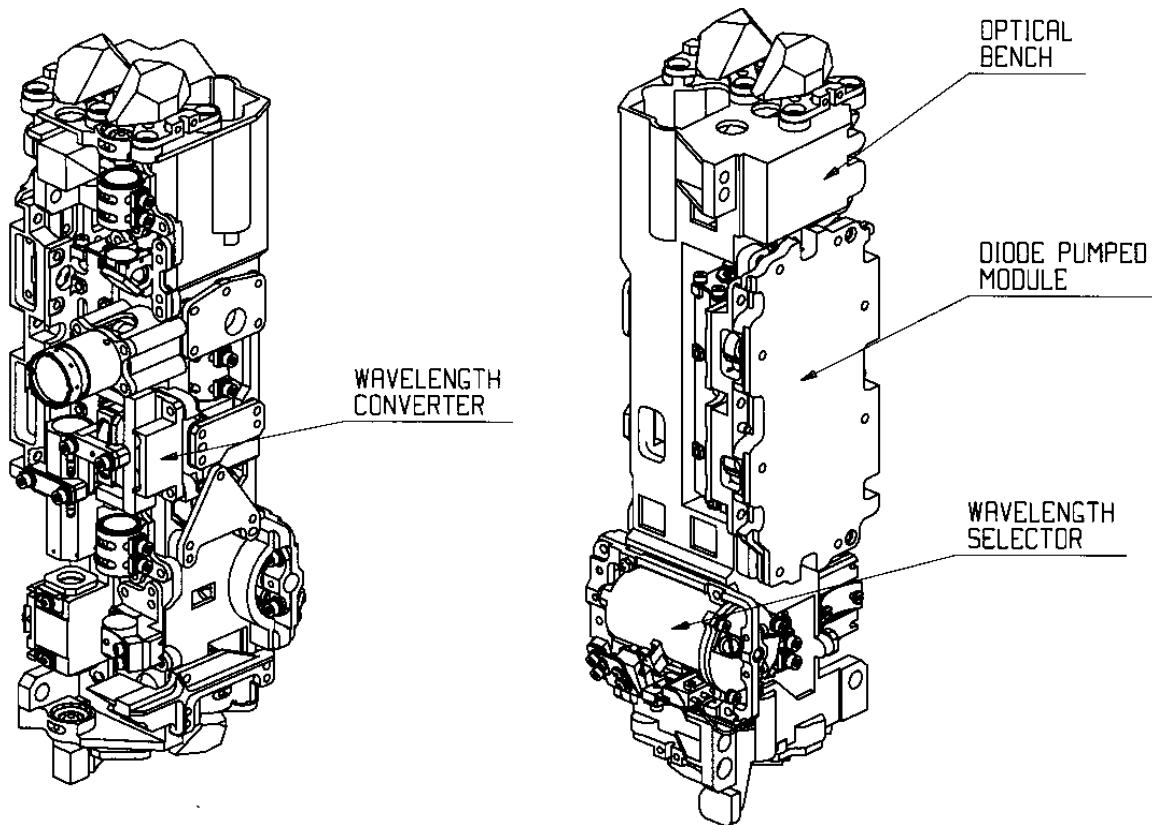


Figure 6 — Common 175mJ Nd:YAG Laser Engine

Table 3 — Common Nd:YAG Laser Engine Specifications

Output Energy @ 1.06 $\mu$ m	175mJ	Beam Quality	9mm*mrad
Pulse width	20 $\pm$ 5ns	Raw Beam Divergence	1.5mrad
Pumping efficiency	41%	Cooling	TEC & Air Fins Heat Exchanger
Eyesafe Output Energy	35mJ @ 1.57 $\mu$ m	Beam Quality	33mm*mrad
Pulse width	12 $\pm$ 5ns	Operating Temperature	-32°C to +56°C
Size (mm)	260x70x87	Weight	780g
Input Electrical Power	Diodes 120W	TEC 170W max.	

### 5.2 Diode Pump Module

The diode pump module integrates the pumping diode stacks, Nd:YAG rods, and thermo-electric cooler at a low level of assembly. This module provides thermal, mechanical, and optical interface controls and is highlighted due to the critical role diodes play in overall system cost. Internal details of the oscillator and amplifier geometry provide for flexibility in the number of stacks and the output laser energy. Size, weight, and electrical current constraints are based on mature designs and deemed low risk.

Diode Pump Module: Interface Specification Summary			
Optical Pump Efficiency	41%	Q-switched Output Energy	175 mJ@ 1.06 $\mu$ m
Laser Diode Current	80A max.	Diode Temperature Regulation	$\pm$ 5 degC
Operating Temperature	-32°C to +56°C	Shock	40G/18ms & 100G/2ms
Size (mm)	74x55x21	Weight	400g

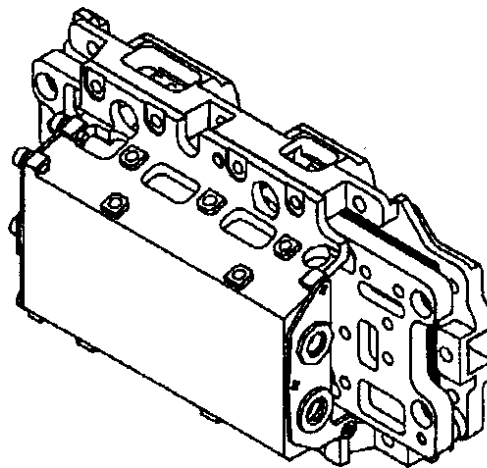
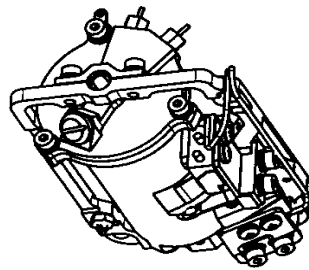


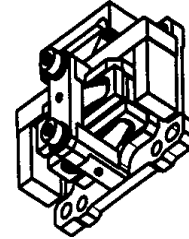
Figure 7 Diode Pump Module

### 5.3 Wavelength Converter Module/ Wavelength Selector Module

Dynamically selecting wavelength (e.g. from 1.06 $\mu$ m designation to 1.57 $\mu$ m eyesafe rangefinding



Wavelength Selector



Wavelength Converter

Figure 8 — Common Wavelength Converter/Selector

and target profiling) is commonly required at the operational level. The adopted module size is consistent with proven wavelength switches diverting into OPO chain with the required boresight accuracy. This technology has been implemented as required in a practical engineering design, and is considered as a low-risk, existing technology.

Table 4 — Wavelength Converter/Selector Specification

Switching Time	Less than 1 sec
All solid state	KTP Crystal: active material
1.06/1.57 $\mu$ m Conversion Efficiency	20%
Output Beam Brightness	33mm*mrad
Maturity	In serial production for various LRFs
Beam size at output	Same as for 1.06 $\mu$ m
Residual 1.06 $\mu$ m energy	1 $\mu$ J/pulse
Temperature Stabilization	$\pm 40^{\circ}$ C
Voltage/Current	28VDC/0.150 Amp Max (at no load)
Laser Safety Failsafe	Micro-Switch Protection
Size	69x46x41mm
Weight	TBD
Power Consumption	4.2W max

## 6.0 Conceptual Outlines and “A Kit” for the Apache and Abrams

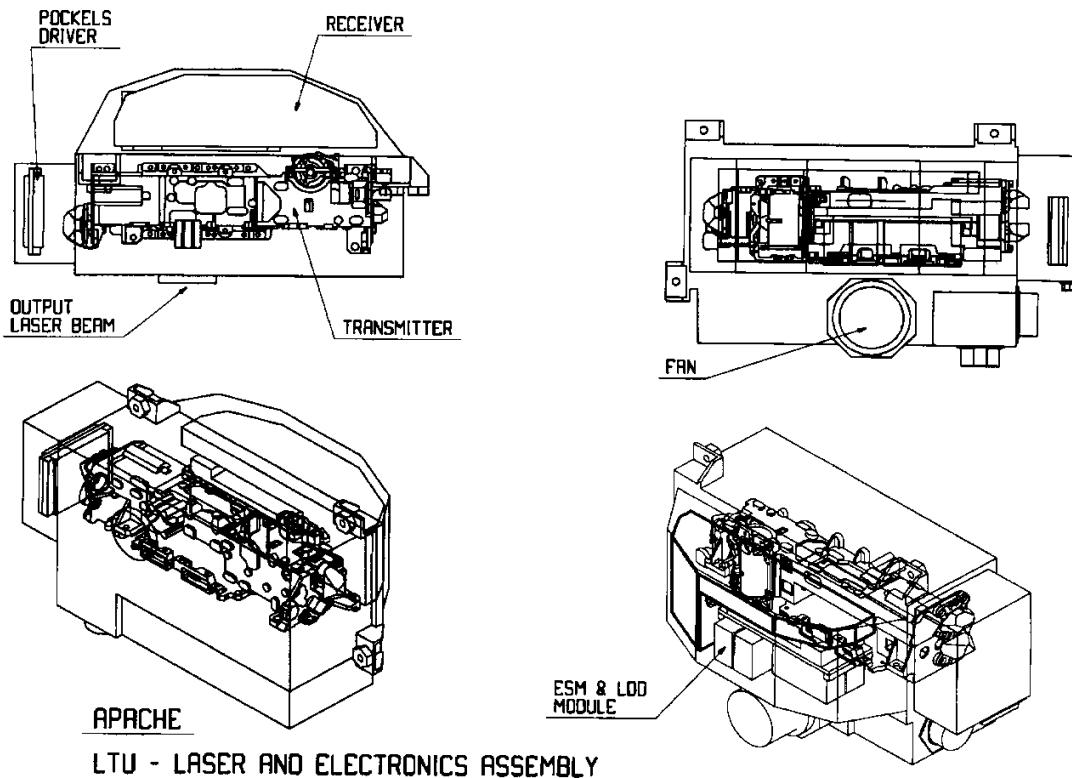
The conceptual design goal was to implement the core capabilities of eyesafe laser rangefinding and laser designating and add capabilities of MILES training simulation and laser target profiling. The volume constraints of the current laser system are met providing a form fit for a function upgrade to these

systems. The conceptual design also served to better define A Kit modules and to provide the baseline for cost estimates. This concept was tested for two IPT selected platforms (Apache and M1A2) in order to demonstrate the feasibility of constructing a practical multi-functional laser based on the selected B Kit modules.

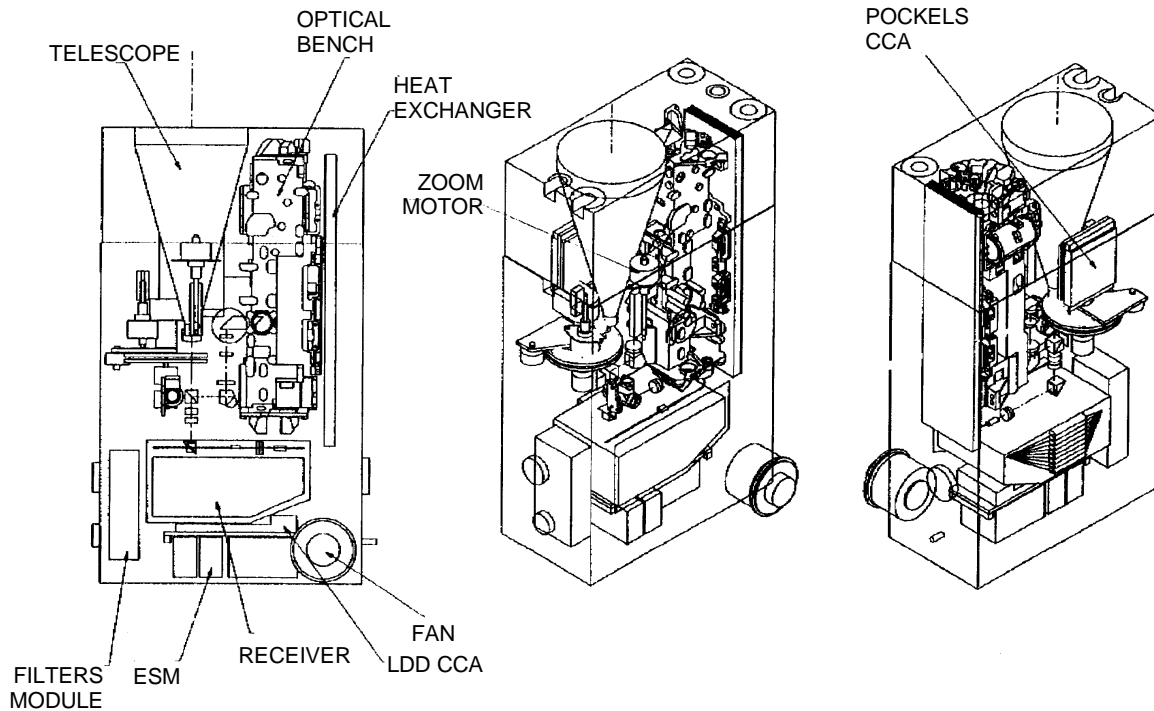
The HTI system design concept seeks to provide modularity of the system structure and design, common optics, and low system power with diode pump technology. Central to this modularity concept is a Diode Pumped Laser (DPL) optical bench in a compact and versatile form factor. The DPL laser bench integrates mounting features for flexible coupling of a pre-beam expander telescope, wavelength converter, and wavelength selector for maximum boresight stability and for an operable subassembly. The remaining modules are grouped and compartmentalized around this major module to efficiently use the available space.

A common optical channel is a basic element of the design approach. A highly common optical channel design reduced volume and weight to meet the tightest airborne weight budget. This common optical channel is folded with refractive elements with zoom operation and compensations at multiple wavelengths. Dual passband coating requirements at 1.06 and 1.57 microns also provide adequate transmission at 905nm for MILES. The refractive design is more forgiving, lower cost, and allows for continuous zoom operation.

(Figure 9 System 2350 Apache Multifunctional Laser) and (Figure 10 System 2350 M1A2 Multifunctional Laser) show the two conceptual layouts with the above common design features and the common module configurations shaping to fit within the space claim. The Apache electronics are divided between a close proximity electrical compartment within the LTU and a remote LEU.



*Figure 9 System 2350 Apache Multifunctional Laser*



*Figure 10 System 2350 M1A2 Multifunctional Laser*

The Abrams LTU is packaged within the dimensions of the existing M1A2 laser rangefinder housing and is integrated into the gunners primary sight unit. The dimensions of the main housing are approximately 394.5x223.5x109.5mm (HxLxW). The internal space is divided into laser, optical, and a close proximity electronics compartment. A logic interface and power supply cards would be a portion of the “A” Kit and fit within a VME slot outside the LTU.

## **7.0 Cost and Risk Evaluation Highlights**

\$20K/system in life cycle savings is projected with common modular systems on several platforms. Reduced development costs at the module and B Kit level, reduced recurring productions costs due to greater quantities, and reduced logistics costs are all significant. Based on our analysis of the non-recurring cost benefits of using a common B Kit module across six (6) platforms, a savings in excess of \$30M can be achieved. Additional savings can be realized with reduced training and support duplication.

The basic laser optical bench and electronics/components for the B Kit Core Capability are already under development as part of the Comanche Program and the SELRD development for the OH-58D Kiowa Warrior. The design teams for the Comanche, SELRD, and System 2350 have been in continuous contact throughout this study activity specifically for the purpose of keeping the common module base as wide as possible. Non-Core Capabilities such as the profiler modules will be developed under a separate program(s).

### **7.1 Life Cycle Cost Analysis**

The Army’s Value Engineering Group in AMCOM recently concluded for the OH-58D Kiowa Warrior that a Diode Pumped-based laser will generate significant Operation & Support (O&S) savings over the existing Flash lamp Pumped laser largely due to its improved reliability. A Diode Pumped laser is expected to have a MTBF in excess of 5,000 hours with its conductive cooling and solid state design.

This represents an order of magnitude improvement over existing flash lamp pumped lasers. Table 5 provides

the results of the LCC Analysis performed for the Kiowa Warrior and Apache. The increased laser reliability significantly improves fielded system MBTF. Another source of O&S savings is generated by the eyesafe rangefinding and training capabilities inherent in the multi-functional design of the SELRD. This eliminates the need for the Army to procure eyesafe training lasers.

Table 5 — LCC Cost Analysis Summary

	Kiowa	Apache
Total Net Benefits (20 Years ,Constant 1997 Dollars)	\$296,737,858	\$180,582,838
Total Investment (Recurring Production)	\$73,827,241	\$113,435,777
Payback	4.8 Years	6.6 Years

## 7.2 Production Cost Analysis

Recurring production costs savings were evaluated based on directed IPT assumptions for platform, quantities, and production rates. Even using a relatively conservative learning curve for production of B Kit modules will generate savings of more than \$22M when quantities are increased from 1,000 to 4,000 at a 200-unit/year rate. The reduction of laser diode stack costs stems from the increased quantities of the common components and will contribute an additional \$50M in savings with a diode cost/Watt decrease by \$2. The use of common laser modules and B Kit units could realistically save the U.S. Army over \$100M over the next 10-15 years as the aging lasers in the Kiowa Warrior and Apache are upgraded and new systems such as the Comanche and Future Scout enter into service.

## 7.3 Performance Risk

Conceptual designs for two platforms combining the basic functions of tactical designation with switchable eyesafe rangefinding and training modes were examined and found to have a low performance risk. CAD packaging trials showed reasonable fits into the allocated Apache and M1A2 platform space claims. Thermal and power management, decontamination requirements, and the respective vehicles' environmental requirements, were considered in the risk assessment. Similarities to existing programs reduce the risk associated with the A and B Kit integration.

The schedule risk associated with the basic Core Capability is low. However, there is some moderate risk associated with packaging the Target Profiler and the MILES components. The B Kit presented in this study is comprised of the multi-channel receiver PCBs (SMT-based) and fiber-optic bundles. Although the technology is mature enough to merit a low-risk classification, there is risk associated with the volume that is available for these elements in the LTUs of the Apache and the M1A2. If during the EMD phase it is determined impractical to implement the desired packaging (as envisioned in the presented conceptual design), and a hybrid electronics solution is required to enable both the Target Profiling (TP) and the MILES in the Apache platform, additional risk will be incurred on the program schedule.

This set, comprised of the zoom telescope and receiver optics, is based on proven engineering design, and therefore considered a low risk, provided the appropriate allocation in the EMD resources.

## 8.0 Conclusion

The study outlined a method to establish an open architecture with low risk growth path based on a high-level common diode pumped laser transmitter. The study also demonstrated the feasibility and cost

effectiveness of multi-functional lasers based on such a common transmitter, as well as on other B Kit modules.

Kollsman/ELOP currently provides a robust and demonstrated tactical Diode Pumped Laser for the Comanche Program and a Switchable Eyesafe Laser Rangefinder/Designator to upgrade the Kiowa Warrior Laser. A variant of this laser is shown to be realistically extendable and provides near-term capabilities for MILES training and Target Profiling. This study's emphasis on multi-functional operation and broad platform compatibility outlines a realistic program reducing the size and power of existing engineered hardware to meet prioritized platform constraints. The common modular transmitter and other common modules would be natural outgrowths proceeding to a low unit cost, large-scale acquisition in support of the U.S. Army's HTI for Tactical Laser Program.

The efforts and contributions of Robert Fong-Tom, Steve Minigh, and Mike Quinlan (Kollsman) and Jerry Garfinkel, Uri Almi, Avi Ganan, and Michael Gordon (ELOP) are acknowledged and thanked.