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Endoatmospheric LEAP

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Mr. Mike Cantrell
U.S. Army Strategic Defense Command
Huntsville, AL

MAJ Thurston VanHorn
Strategic Defense Initiative Organization
Washington, D.C.

Mr. Andrew Muras
MEVATEC Corporation
Huntsville, AL

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Mike Cantrell
US Army Strategic Defense Command
Huntsville, AL

MAJ Thurston VanHorn
Strategic Defense Initiative Organization
Washington, D.C.

Andrew D. Muras
MEVATEC Corporation
Huntsville, AL

Abstract

The Strategic Defense Initiative (SDI) envisions the use of multiple tiers of non-nuclear weapons to provide an umbrella of protection from ballistic missiles. Operational engagement constraints typically require a high velocity interceptor in order to achieve reasonable protective coverage, and with an endoatmospheric intercept, this results in severe aerodynamic, aerothermal, and structural environments for the acquisition and homing phase of the intercept. The ENDO LEAP vehicle program is in the process of developing an interceptor which can operate successfully in this severe environment.

The objective of the ENDO LEAP vehicle program is to design, develop, integrate and test vehicle technologies compatible with affordable lightweight interceptors to perform high and low endo atmospheric defense against ballistic missiles. These technologies will be developed and tested in state-of-the-art testing facilities, such as the Large Energy National Shock Tunnel (LENS). Innovative simulations, ground tests and flight tests will be used to help validate the designs.

Introduction

The objective of the ENDO LEAP program is to design and develop vehicle technologies compatible with affordable lightweight interceptors to perform high and low endoatmospheric defense against ballistic missiles (both strategic and theater). The goal of the ENDO LEAP program is to produce an integrated vehicle with a mass of 10 to 17 kilograms. In order to accomplish this goal, the program will exploit emerging technologies in the areas of advanced seeker heads and component designs. Lightweight seekers and other components will be combined with interceptor integration technology to develop high performance test vehicles.

The ENDO LEAP program shall be accomplished in three phases. Phase I consists of preliminary designs of lightweight vehicle concepts for performing high and low endoatmospheric intercepts, and detailed designs of associated seeker head technologies. Phase II consists of detailed vehicle designs, and fabrication and test of critical seeker head concepts. Phase III consists of fabrication and test of the vehicle components, integration of the vehicle components, and integrated vehicle technology demonstrations via ground and flight testing. It is planned to perform downselects at the conclusions of Phases I and II. The developed integrated technologies can later be applied to selected follow-on SDI system elements (e.g., E2I, THAAD).

There are three competing contractors currently developing vehicle designs, at least one of which will be selected to fabricate and test an ENDO LEAP Vehicle. The three prime contractors are: General Electric, Lockheed Missiles and Space Co. and McDonnell Douglas Space Systems Co. Figure 1 shows a schedule of the ENDO LEAP Program.

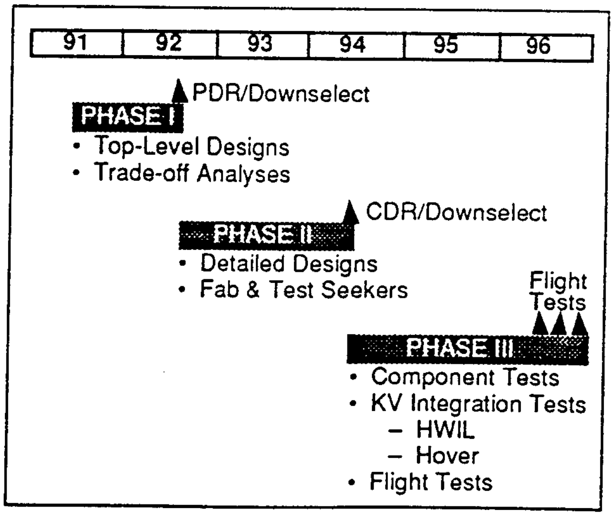


Figure 1. ENDO LEAP Schedule

ENDO LEAP Design Requirements

The ENDO LEAP program has few specified requirements for the vehicles. Only top level performance requirements were provided in order to allow the the contractors maximum latitude in performing trades to select their own baseline design. In addition, future SDI operational system requirements will not drive ENDO LEAP vehicle designs since the primary intent of the program is to develop and demonstrate lightweight seekers and other technologies that can later be applied to selected endoatmospheric systems.

The ENDO LEAP vehicle should have a mass of between 10 and 17 kilograms, not including a protective shroud. The ground and flight test vehicles may have additional mass required for instrumentation, encryption and telemetry. A ballistic coefficient greater than or equal to 5000 kg/m**2 is required for the vehicle, including any protective shroud.

The ENDO LEAP trajectories and engagement battlespace determine many of the design requirements. Figure 2 shows typical endo missions.

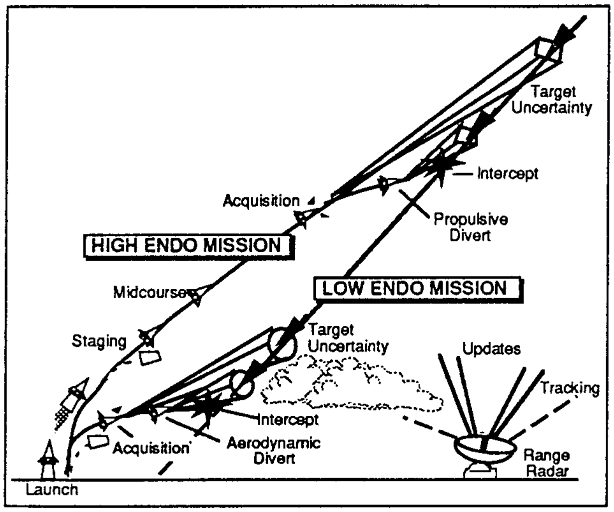


Figure 2.
Representative ENDO LEAP Engagements

As shown in the figure, a ground-based range operations radar is assumed to acquire, track and transmit target state vectors to the ENDO LEAP vehicle. The radar track error for target altitudes above 50 km is assumed to be 50m (1 sigma) and below 50 km to be 25 km (1 sigma). The interceptor then flies to a midcourse basket and releases the vehicle. The fire control system tracks only the target; it does not track the interceptor or the vehicle. However, if desired the range support radar can provide vehicle location updates for the lofted trajectory mission (see Figure 3). After the ENDO LEAP vehicle is released from the booster, it continues to receive target state vector updates from the flight test operations radar at a rate of up to 20 Hz. The vehicle subsequently flies to its target acquisition point, acquires the target autonomously with either an electro-optical (EO), radio frequency (RF) or dual-mode seeker, and initiates terminal homing.

The ENDO LEAP vehicle is expected to operate at the design points shown in Figure 3. These points are specified for the environment at target acquisition. Lower vehicle speeds at intercept are acceptable.

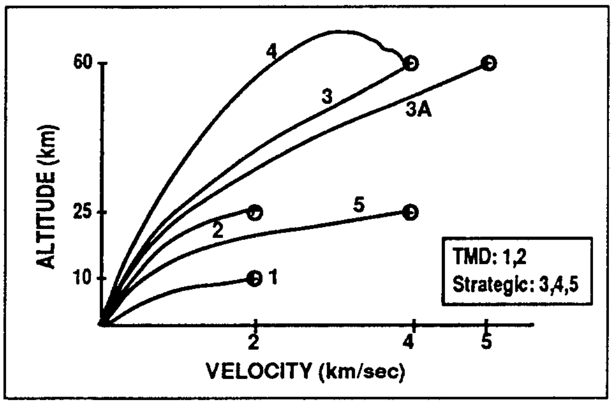


Figure 3. Desired Design Points

Hit-to-kill (HTK) is required for the ENDO LEAP program. It is also required that a single navigation system, located in the ENDO LEAP vehicle, be used for guidance throughout the flight. For the purposes of design of the divert and attitude control system, it is assumed that 300 m/sec is required for midcourse maneuvers and 300 m/sec for terminal maneuvers, with at least 15 G's for vehicle end-game. The divert velocity may be supplied aerodynamically and/or propulsively. The vehicle shall be capable of implementing the midcourse maneuvers, in whole or in parts, at any time after booster separation. Figure 4 shows an example of the engagement geometries expected for defense against both tactical ballistic missiles (TBMs) and re-entry vehicles (RVs).

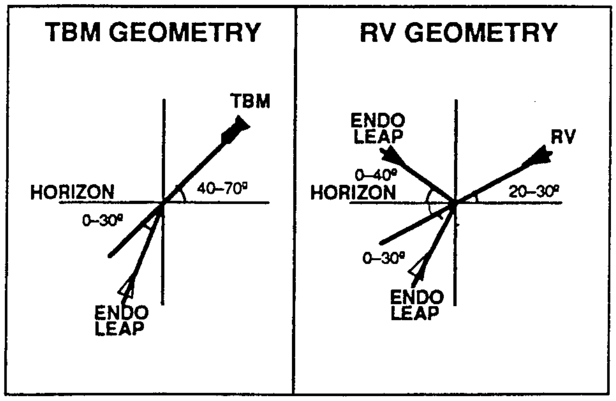


Figure 4. Engagement Geometries

Critical Issues

During the process of concept design and evaluation, issues arise about the proposed concept for which there is no credible answer. Those issues which absolutely must be answered prior to moving into the next program phase are usually classified as critical issues. The ENDO LEAP program has several critical issues which must be resolved before designs are considered feasible. Following is a brief description of some of ENDO LEAP's critical issues.

Aero-Optics/Aerothermal Environment

Hypersonic endoatmospheric operation presents significant issues for the use of EO seekers for end game guidance. Aero-optical (AO) effects, which are usually defined as boresight error (BSE), blur and jitter, are not expected to be as serious for an RF seeker. Figure 5 presents a top level description of the hypersonic flowfields surrounding a missile forebody and the effects on the target point spread function.

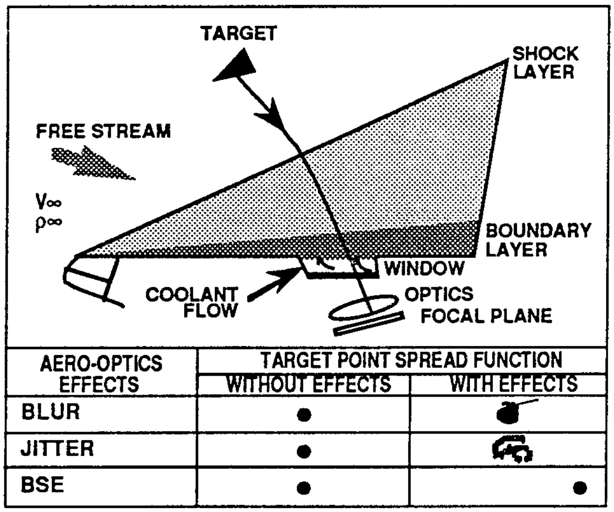


Figure 5. Aero-Optical Effects

The missile conical shock layer is the primary contributor to bore-sight error (BSE), or shift in the location of the signal on the focal plane array (FPA). The shock wave produces a rapid change in density and it is this density variation which is the cause of BSE (index of refraction gradients are proportional to the density gradients). BSEs usually range from 1 to 10 milliradians at lower altitudes and must be compensated in the guidance scheme to achieve HTK performance, since seeker track accuracy requirements are typically < 100 microradians.

Blur and jitter effects are predominantly caused by the turbulent boundary layers, with rapidly changing density variations, near the missile body. The problem of calculating image degradations for seekers operating through turbulent boundary layers is extremely complex. Turbulence occurs when fluid flow becomes unstable and is characterized by vortices or swirls of the fluid media. Time dependent turbulence is not well understood and is difficult to calculate, or to experimentally measure. The velocity distributions within the turbulent swirls have proportional temperature and density distributions. It is these density distributions, and resultant index of refraction changes, which tend to distort the wavefront. The net effect is to spread the energy in the point spread function (decrease the Strehl Ratio) and to produce high frequency jitter.

Aerothermal (AT) issues are caused by the high temperatures associated with hypersonic flight and are coupled with the AO problem. AT effects include: window distortion due to thermal expansion, window self-emission caused by temperature rise, reduced structural integrity due to severe thermal environments and ablation. AT effects will also influence RF designs. Increases in forebody temperature will cause changes in aperture dielectric properties and mechanical distortions (aperture or antenna). In addition, plasma may cause attenuation, angle of arrival variations, signal fluctuations and noise temperature increases. Typical methods of countering these effects include trajectory shaping to lower heating rates and cooling techniques to lower aperture temperatures (but with the negative effect of increasing AO effects). ENDO LEAP has been investigating other methods of countering these AT issues, including various window materials, forebody shapes and aperture sizes and locations.

Miniaturized Vehicle

One of the goals of the ENDO LEAP program is to examine innovative means of lowering the size and weight of hypersonic endoatmospheric interceptors. Low weight interceptors are of particular interest in the current environment of the SDI since more emphasis is being placed on transportable/mobile systems, particularly for Theater Missile Defense (TMD) applications. Therefore a substantial number of trades are being performed to ensure that the lowest weight components and materials are used for the vehicle.

The heaviest components of an endoatmospheric vehicle are the divert/attitude control system (DACS) and the seeker. Figure 6 shows a percentage weight breakout of components for a typical ENDO LEAP vehicle. Since the DACS and seeker account for over sixty percent of the total vehicle weight, it makes sense to first try and optimize these two components. Therefore vehicle designs will be examining the minimum weight configurations that satisfy the design requirements and are compatible with geometry/packaging constraints. Technologies that might satisfy these constraints include solid state devices, Z-plane electronics and lightweight composite materials. However, a careful assessment of component risk will need to be performed, as many technologies offer the potential for substantial weight savings but may not be a viable alternative when schedule, cost and risk constraints are examined.

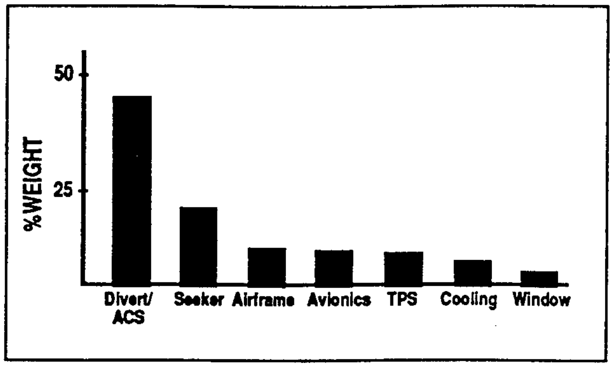


Figure 6. Typical ENDO LEAP Vehicle Weight Breakdown

Large Seeker Field of Regard

SDI endoatmospheric interceptors are unique from other missile systems and exoatmospheric interceptors in that they require very large fields of regard (FOR). (The field of regard is defined as the total area that can be viewed, or swept, by the seeker.) The reason for this is seen from the target/interceptor trajectories, and associated crossing angles, as shown in Figure 4. Typical crossing angles for point-defense TMD intercepts will be on the order of zero to fifteen degrees, while strategic crossing angles will be from thirty to sixty degrees. A good approximation is that the half angle FOR is equal to the maximum crossing angle that is expected in the engagements. These crossing angles are the primary drivers in determining seeker FOR requirements.

Large FORs are typically obtained by scanning the seeker FOV (e.g., with a scanning mirror). However, this requires a large window, with associated large amounts of coolant, and a scanning mechanism. This often accounts for a significant portion of the weight of the seeker system. Non-scanning systems are currently not used because of limitations on the size of the FPA and the size of individual pixels (resolution) required for a staring system. Therefore, innovative ideas to overcome these limitations will be required. Potential concepts being investigated for ENDO LEAP include: selectable multiple apertures, panoramic lenses, fiber-optic fish eyes and holographic/binary optics.

Hit-to-Kill

In order to achieve lightweight ENDO LEAP vehicles, warheads cannot be used to help damage the target. Therefore, hit-to-kill (HTK) is required. Hypersonic endoatmospheric HTK is a difficult task and has yet to be proven viable through flight testing. However, extensive simulation and ground testing has shown that a direct hit is feasible. ENDO LEAP will attempt to validate HTK through a series of flight tests from White Sands Missile Range (WSMR) and U.S. Army Kwajalein Atoll (USAKA).

There are a substantial number of phenomena associated with hypersonic homing that are not well understood, especially those pertaining to AO and AT effects. Analyses and six degree-of-freedom (6DOF) simulations will be performed on vehicle concepts to understand the effects of various errors on miss distance. This is a complicated and time-consuming task as error sources are not additive and are often not well understood. Figure 7 shows a typical error budget allocation for a generic ENDO LEAP interceptor. Probabilities of hit associated with such an interceptor will typically be 0.7 to 0.9.

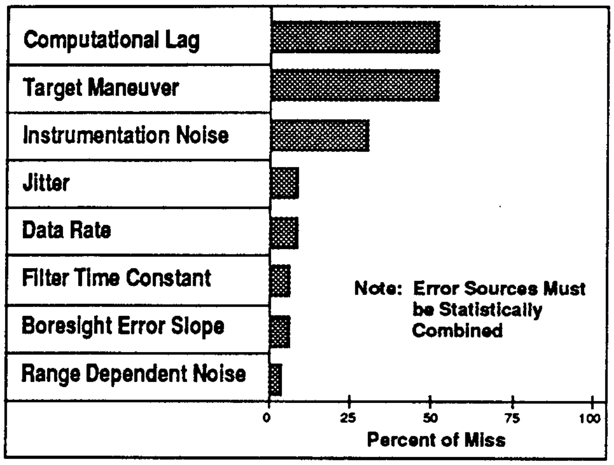


Figure 7. Error Budget Calculation

Target Aim Point Selection

SDI endoatmospheric interceptors have typically not been required to perform aim point selection. However, ENDO LEAP dictates that this requirement be addressed. The ENDO LEAP vehicle is much smaller than typical endo interceptors and so has a smaller area to project onto the target. Therefore, in order to achieve a lethal kill (i.e., vehicle projected area impact the target warhead) it is necessary for the vehicle to more accurately choose an impact point on the target vehicle. In addition, for TMD applications the ENDO LEAP vehicle will be required to defend against targets that do not separate from their booster. This will require the vehicle to choose an impact point on the payload itself and not just impact the booster motor casing. This requirement for aimpoint selection will drive designs in terms of lower miss distances, lower component error budgets and additional aimpoint algorithms.

Design Approaches

There are a variety of technology choices for use on the ENDO LEAP vehicle. Following is a description of some of the design issues for the vehicle components.

Requirements Flowdown

ENDO LEAP vehicle concepts must be derived from both system level and technical requirements. This derivation/flowdown process translates threat characteristics, design/technical constraints and program objectives into interceptor requirements through a logical sequence of decisions. This process is often iterative as optimum decisions are refined at each level. It begins with top level parametric analyses and trades that model gross effects in order to characterize the fundamental interceptor requirements (e.g., velocities, coverage, battlespace, handover, etc.). These top level requirements are then decomposed, through functional analysis, into specific component requirements. Figure 8 is an example of an initial interceptor functional analysis breakout in which requirements are progressively allocated to interceptor subsystems and components.

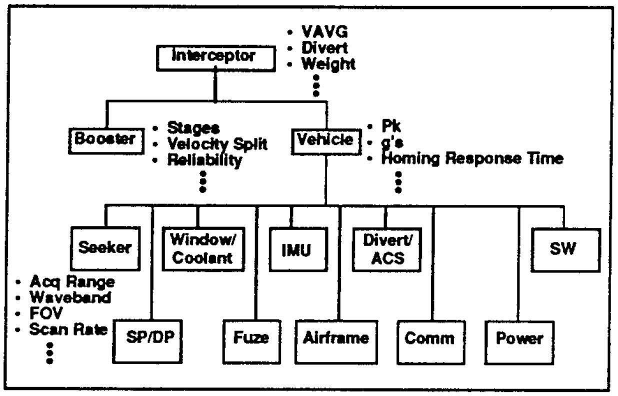


Figure 8. Requirements Allocation

Vehicle Configuration

Figure 9 illustrates a generic ENDO LEAP vehicle configuration and is not intended to be an actual design solution. The basis components that require packaging are shown. AN IR seeker system is depicted; however, the vehicle could also incorporate a RF or dual-mode seeker. An aerodynamic control approach is shown for the low endoatmospheric regime and a divert thrust system for lateral displacements in the high endoatmospheric regime.

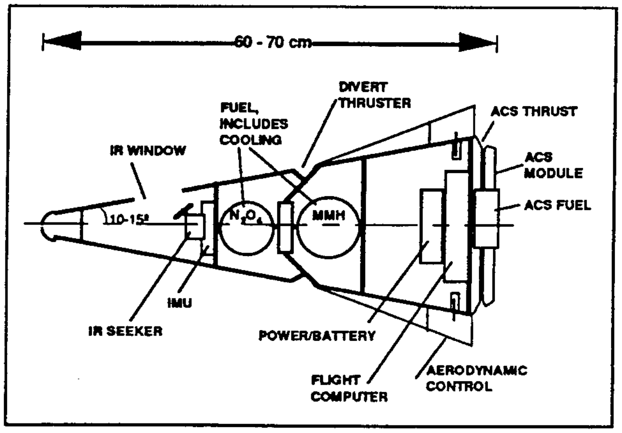


Figure 9. Generic ENDO LEAP Configuration

Seeker

The Seeker is the most critical component in the ENDO LEAP vehicle since its basic function is to gather data on the target (position, intensity, etc.) and provide inputs to the vehicle's guidance, navigation and control (GN&C) system. The broad flight environment shown in Figure 3 dictates the need for two types of seekers: RF for all-weather operation at low altitudes and EO for high altitude operation where longer acquisition ranges are required. Design trades are being performed on whether two types of vehicles are required, with two types of seekers, or whether a combined dual-mode vehicle (RF and EO) is feasible. The seeker risk areas which are being addressed are shown in Figure 10.

EO	RF
• AO Refraction Effects	• Power/Weight
• Window Design/Thermal Changes	• Aperture/Radome Design
• FOR and Angular Measurement Accuracy	• AT Plasma Environment
• FPA Configuration	• Signal Processing Volume/Weight

Figure 10. Seeker Areas of Concern

The two primary drivers of seeker requirements are the threat signature (magnitude and wavelength as a function of altitude) and the vehicle operations (trajectory, dynamics, GN&C). These two parameters help define the type and design of the seeker. Two requirements which also help define the seeker, and which are flowed down in the functional analysis process, are the data rates and the angular measurement accuracies required to achieve HTK. Typical data rates are > 100 hertz and accuracies are < 100 microradians. Other requirements that will be defined include FOR (derived from engagement angles and angle of attack profiles), FOV, acquisition range, waveband and FPA type.

Electro-Optical

High altitude engagements lead to the use of passive infrared (IR) seekers since targets produce little visible or ultraviolet signatures in the upper atmosphere/exoatmosphere. Such passive seekers can usually be made small and lightweight since they do not require active transmission (as opposed to RF and lasers) and are also able to achieve high resolution/pointing accuracy necessary for HTK operation. Mass and volume savings will result from the use of strapdown seekers with no moving parts. However, strapdown seekers are complicated by the large FOR requirements and the high angular measurement accuracy (AMA) requirements. With non-strapdown/scanning seekers, it is easier to obtain required FOR and AMA, but the mechanical scanning devices increase seeker size and weight.

Hypersonic operation also presents significant performance issues for IR sensors. The shock and boundary layers distort incoming target signals, produce background radiance and elevate window temperatures (which increases background radiance). Therefore it is important to develop a seeker and aperture design that mitigates these effects. The aperture window is one of the more important features of the total seeker design. Window materials are carefully selected based on high temperature operation, thermal shock resistance, producibility and spectral transmission. Typical materials include sapphire, diamond, ALON, yttria and spinel. Window materials usually require some sort of technique to help mitigate thermal effects. Mitigation techniques range from the use of uncooled windows (trajectory shaping and minimizing exposure time) to active cooling. Active cooling is the most popular technique, but injecting coolant iinto the airstream is a major contributor to AO effects and has a large impact on vehicle size and weight (because of coolant storage and injection hardware). An example of one of the tradeoffs in using active cooling is shown in Figure 11.

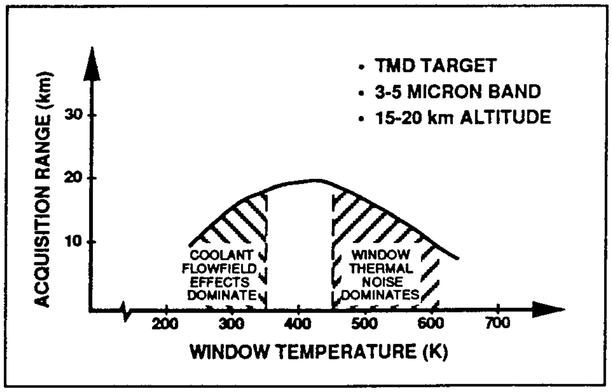


Figure 11. Window Operating Temperature

It is also important to determine the proper wavelength of IR operation, and match this to the detector type and the window. Waveband selection is based on the target signature, atmospheric transmission, seeker sensitivity and angular pointing accuracy. Industry-standard models used to help determine waveband operation include LOWTRAN and SIRRM (Standard Infrared Radiation Model). Typical operating wavelengths for endoatmospheric vehicles are in the 3 to 5 micron band. Other design tradeoffs to be performed for the IR seeker include: instantaneous FOV (IFOV) - driven by resolution and pointing accuracy requirements, size of the FPA - determined by the FOV and the IFOV, and aperture size - driven by frame rate.

Radar Frequency

The low altitude intercepts (<15 km) require an RF seeker system because of potential clouds, fog and rain. One of the major challenges with RF systems is to provide the required pointing accuracy over the entire FOR. In addition, the small ENDO LEAP vehicle size limits the antenna size and associated gain, thus increasing power requirements.

Millimeter wave (MMW) is the frequency of choice for ENDO LEAP since lower frequencies do not achieve antenna beam widths small enough for the required line-of-sight (LOS) accuracies. Higher frequencies are not considered since the technology is too immature. Practical MMW frequencies, based on atmospheric propagation windows, include Ku (17Ghz), Ka (35Ghz) and W (95 Ghz) bands. Figure 12 shows a tradeoff for the various MMW bands in which W band is shown as a preferred frequency based on its smaller aperture requirements. However, the technology base for W band is not as mature as for Ka and Ku bands and therefore poses a higher risk. MMW systems will typically have less of an acquisition range versus EO systems. However, this is not a detriment in the lower altitudes since target velocities have slowed down considerably in the dense portion of the atmosphere.

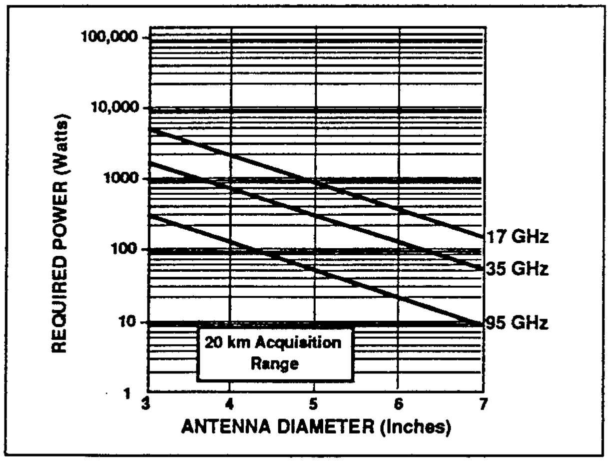


Figure 12. MMW Power Requirements

There are number of design tradeoffs facing the MMW seeker designer. A major trade is between the use of mechanically or electronically steered arrays. Mechanical arrays can be made simple, rugged and relatively heavy but can achieve accurate angle measurements. Electrically steered arrays have the ability the track multiple targets in complex environments and have a higher growth potential, but are usually more costly. ENDO LEAP will probably also require the use of solid state technology for the transmitter. While tube technology is mature and generally available, it is relatively heavy and has little growth potential. Solid state technology has the advantage of being smaller and lighter and offers more potential for technology growth, but is much less mature. A final major trade is in the aperture concepts in which both radomes and conformal arrays, cooled and uncooled, are being examined to determine which is best suited to ENDO LEAP goals. In the tradeoffs mentioned above it is evident how cost, risk and performance evaluations will play a major role in determining the proper technology for ENDO LEAP.

Dual-Mode

Dual-Mode systems (RF and EO) are attractive in that they offer the possibility of covering the entire battlespace with a single vehicle. EO would be optimized for long range acquisition at high altitudes and RF for low altitude operation in clouds and rain. Previous approaches have relied on separate apertures for the EO and RF systems, which have increased the problems of packaging, accurate LOS measurement, and scene/target classification. However, advances in window and aperture technologies have made dual-mode a feasible, but high risk approach.

Laser

Active lasers have also been discussed for ENDO LEAP seeker applications. Lasers are attractive in that they provide accurate range, range rate and angle measurements useful for GN&C. However, power requirements for lasers are high (varies with range to the fourth power), the optical system is complex and slewing a narrow beam rapidly across large FORs is difficult.

Divert/Attitude Control System

The divert and attitude control system (DACS) account for a significant portion of the total vehicle weight (see Figure 6). Therefore the design process call for a vigorous pursuit of technology advances in this area. One of the major design drivers for the DACS include the impact on end game miss distance due to propulsion response time and the minimum impulse bit. In addition, the seeker will also have a major impact on control requirements (e.g., homing time versus maximum lateral acceleration, maneuver response time versus angular noise error, etc.).

A divert thrust propulsion system with a high thrust level and total impulse is required for high altitude intercepts. At low altitudes aerodynamic maneuvering can be accomplished with fins, flaps, jet reaction control, etc. Four typical approaches to controlling the vehicle during end-game maneuvers are shown in Figure 13. Blended control systems will also need to be addressed to determine the most effective used of divert and aero controls in the transition region (25 to 40 kilometers). Attitude thrusters will be required to maintain precise vehicle orientations. Attitude thrusters are generally sized by the low endo force requirements and may have too large an impulse for high endo control. However, by decreasing the static margin and using fast valves, the high and low endoatmospheric requirements can be fulfilled with common thruster sizes.

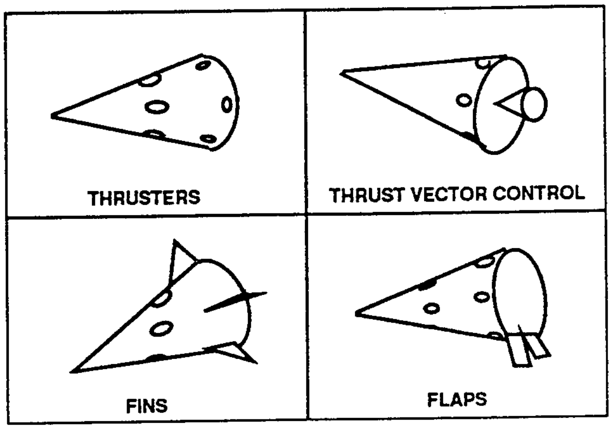


Figure 13. Typical ENDO LEAP Maneuvering Schemes

Both liquid and solid propulsion systems are viable candidates for the divert thruster system. Liquid systems are generally used because of their capability for start/stop control. However, it will be difficult for today's liquid systems to achieve mass fractions above approximately 0.3. Solid systems can be a viable contender (mass fractions up to 0.6) if mission or end-game maneuvers can be met with a throttleable or pulse system. Solid systems also have the potential of being easily packaged, low cost and low weight. Figure 14 shows typical motor weights for an ENDO LEAP-sized vehicle.

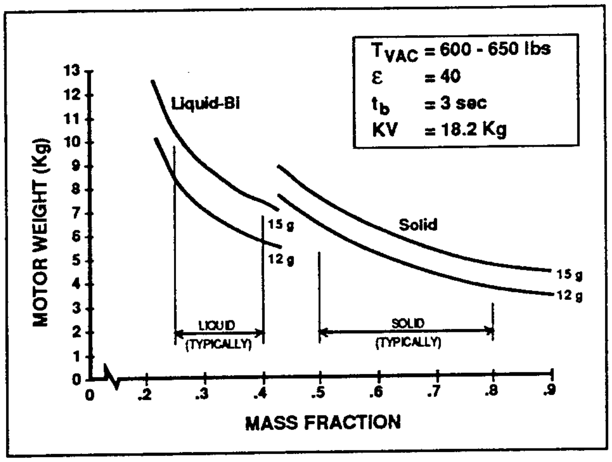


Figure 14. Typical Divert Propulsion System

Airframe/Structure

Airframe and structure concepts must satisfy the requirements for maneuvering, environmental survival and ballistic coefficient. In addition, the configuration must be compatible with the seeker concept, control system and internal packaging. The airframe and structure will be designed to survive the flight environmental loads, including shock, vibration, acceleration and aerothermal heating. The portions of the trajectory which drive these load requirements include flyout, staging, shroud ejection and homing maneuvers.

The airframe shape will be driven by seeker and aerodynamic requirements (look angles, aperture type, and aerothermal loads). Parametric analyses are performed to optimize geometry, minimize size and weight and satisfy performance requirements. A variety of cone shapes are being investigated. Sharp cones have low drag coefficients, but induce stronger shocks and associated temperature rises on the body. Blunt cones tend to lower temperatures on the body, but have higher drag and tend to be unstable in hypersonic flight. Bi- and tri-conic shapes are often used to add stability, but again tend to increase drag. Figures 15 and 16 show examples of tradeoffs associated with various cone angles and nose radii.

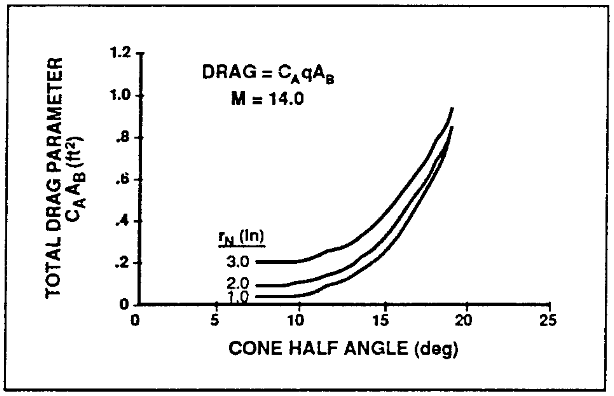


Figure 15. Drag Parameter Variation with Cone Angle

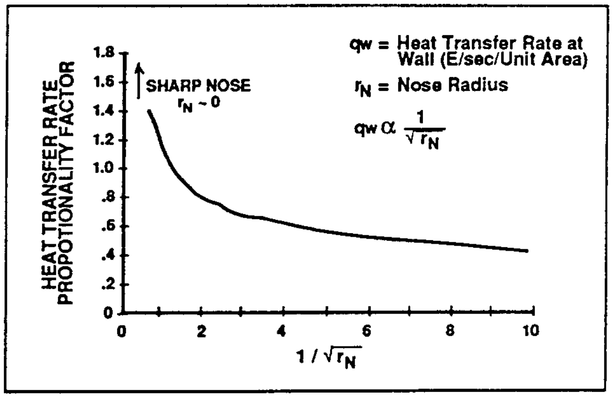


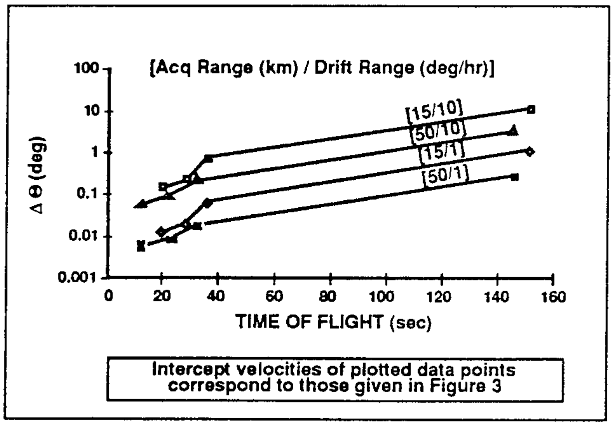
Figure 16. Heat Transfer Rate Proportional to Nose Radius

Material selection will emphasize minimum weight, but will also be based on specific strength, thermal capability, fabrication cost and availability. Structural materials under consideration include conventional materials such as aluminum, as well as composites such as metal matrix and graphite epoxies.

Inertial Measurement Unit

The inertial measurement unit (IMU) will be located on the ENDO LEAP vehicle and is used to determine vehicle position and attitude. In addition to navigation, the IMU provides information which allows vehicle body motion to be uncoupled from seeker measurements IMU technologies which are being considered include: ring laser gyros, fiber optics and solid state.

Trajectory and end-game analyses are used to help define IMU performance requirements. For example, figure 17 shows how vehicle time-of-flight affects drift rate requirements for example trajectories. It is shown that the longest time-of-flight (trajectory 4 in Figure 3) requires the best IMU performance. Other requirements which must be defined include size, weight, power, initial azimuth alignment and IMU-to-seeker alignment. Of these, the most critical is the initial (prelaunch) azimuth alignment.



Intercept velocities of plotted data points correspond to those given in Figure 3

Figure 17. IMU Drift Rate Error Analysis

Software and Processing

The data processor for ENDO LEAP will support the navigation, guidance, autopilot and other vehicle on-board functions. The purpose of the data processor is to: execute object and track processing algorithms and GN&C functions; communicate with the IMU and signal processor; perform telemetry processing; control DACS valve functions; and control real-time task sequencing and execution. Performance requirements are developed in terms of throughput, memory size (global and local), and message traffic. The seeker and GN&C algorithms will be the primary drivers on performance requirements (e.g., IR seeker processing is driven by the number of detectors and the frame rate). All system software developed for processing functions will follow DOD-STD-2167A guidelines.

Power and Electronics

The power and electronic requirements are derived from ENDO LEAP vehicle operational characteristics, and include the avionics, electrical wiring and battery. The power and conditioning for complex interceptor systems often occupy a large percentage of the electronic system weight and volume. The design of the power sources and conditioning is mainly driven by the vehicle seeker and propulsion system.s The power source is sized primarily on the duration of the trajectory (flyout navigation) and the end-game homing (seeker operation and DACS valve demands). In addition, extra energy will be required to support instrumentation, telemetry and range safety functions during flight testing. A variety of batteries are being examined to fulfill ENDO LEAP power requirements. Selection will be based on high energy density, reliability, shelf life, cost and safety. Electronic packaging techniques, such as wafer scale integration, surface mount assembly and ceramic hybrids, will also be evaluated to minimize size and power consumption.

Design Verification/Validation

One of the primary purposes of any vehicle development program is to resolve critical issues and show that requirements can be met with feasible design solutions. Critical issues are first defined and then used to help derive a development and test approach. The selection of an approach by which to resolve issues is an important step in the critical issue resolution process. The resolution criteria must be quantifiable, realistic, and serve as a central indicator of how well overall program objectives will be met. It is important to attempt, within available resources, partial or complete early resolution of issues since concepts and requirements may be highly dependent on them. Development paths to resolve issues can include analysis, simulation, ground tests and flight tests. Facilities which will be used in the ENDO LEAP program to resolve critical issues include: Kinetic Energy Weapon Digital Emulation Center (KDEC), USA Strategic Defense Command; Kinetic Kill Vehicle Hardware-in-the-Loop Simulator (KHILS), USAF Armament Test Laboratory; Long Wavelength Infrared Environmental Threat Simulator (LETS), Wind Tunnels, Arcjets, and Ballistic Range, Arnold Engineering and Development Center; National Hover Test Facility (NHTF), USAF Astronautics Laboratory; and Aero-Optical Evaluation Center (AOEC), Calspan/University of buffalo Research Center. The following sections will discuss the use of various techniques for critical resolution.

Simulation

Simulations are used to predict hardware performance and provide data for resolving critical issues. High fidelity six-degree-of-freedom (6DOF) guidance simulations are being developed for the flyout and end-game homing phases of the ENDO LEAP vehicle to accurately model vehicle dynamics and interactions. Such models are necessary to analyze the complex, and coupled, interactions between the various vehicle components and also to evaluate candidate vehicle and seeker/aperture concepts. Sensitivity analyses can be performed to rapidly determine the effects of potential design alterations (e.g., aerodynamic shape, center of gravity shifting, control schemes, etc.). The simulations will be modified and upgraded as the baseline vehicles mature and as ground test results become available. These models will also be used for the development and confirmation of hardware-in-the-loop simulations and to provide range safety trajectory analyses for flight tests.

The flyout simulations will be driven by the required design points shown in Figure 3. Various attitude, acceleration, velocity and position data will be defined for each of the trajectories. End-game models will be high fidelity in order to accurately model component performance. Models may be modular in order to allow evaluation of a variety of components. End-game simulations will include seeker accuracy (both EO and RF), autopilot error, vehicle response, control error band target spiral motion and effects of asymmetrical ablation.

Ground Tests

The ENDO LEAP ground test program will attempt to demonstrate that the vehicles meet the design requirements and minimize the risks associated with flight testing. The ground test program will begin with component testing and culminate with integrated vehicle testing.

Seeker Head Tests

ENDO LEAP vehicle seeker heads will be tested in the AOEC or other government facilities (e.g., Naval Surface Weapons Center, Arnold Engineering Development Center). These tests will help address a variety of AO and AT issues, including: seeker line-of-sight stabilization, signal attenuation, bow shock irradiance, aperture cooling effectiveness, and simulated flight environmental effects. The tests will also be used to assist in validating 6DOF, computational fluid dynamics codes and wave optics codes. The AOEC facility will provide the instrumentation required to help measure these effects, including holographic interferometry to provide wavefront distortion data at the seeker aperture. Figure 18 shows the AOEC test facility set-up for vehicle seeker head testing.

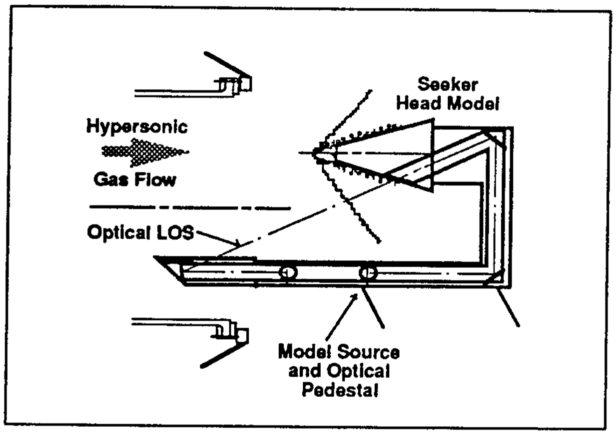


Figure 18. AOEC Testing

Hardware-in-the-Loop

Hardware-in-the-loop (HWIL) testing is being performed to implement closed-loop characterization of ENDO LEAP components. In addition, HWIL verifies flight hardware interface compatibility and performance, verification and validation of flight software and verification of sensor/avionics performance. Next to flight testing, HWIL represents the most realistic evaluation of integrated hardware/software performance.

HWIL facilities are typically designed to concentrate efforts on the seeker, signal processing, and GN&C components. Figure 19 shows a generic HWIL configuration. The seeker, processing and IMU components will typically be mounted on the motion table, while a scene generation system will provide target signature for each sensor to be evaluated. Both RF and EO seekers systems will be evaluated for ENDO LEAP, thus requiring two different HWIL facilities. Results will then be compared with the 6DOF simulation predictions.

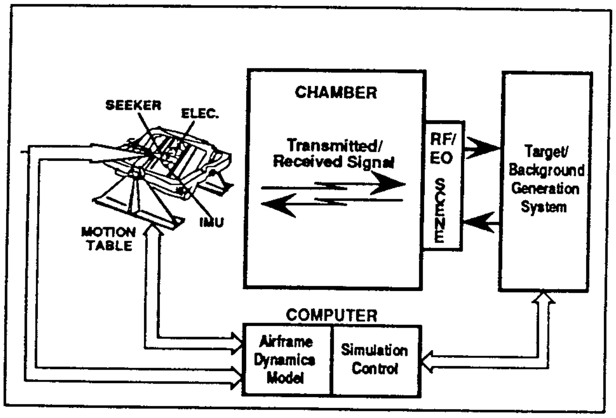


Figure 19. Generic HWIL Diagram

Hover Testing

The purpose of hover testing is to demonstrate stabilized free flight. Although this type of testing is typically used for space engagement scenarios, the high endo mission can also be tested. The hover test will simulate a high altitude intercept with a near-head-on engagement. Aerodynamic effects will not be simulated, but such effects are not expected to be stressing at high altitudes. Vehicle body dynamic responses will be evaluated under DACS thrusting. Results from the hover tests will be used to help validate 6DOF simulation models.

Flight Tests

The final testing phase of any missile system usually involves actual flight tests against simulated target vehicles. The ENDO LEAP flight tests will demonstrate that the vehicle meets all requirements, including those which can not be verified during simulation and ground testing. Figure 20 shows a generic ENDO LEAP test scenario.

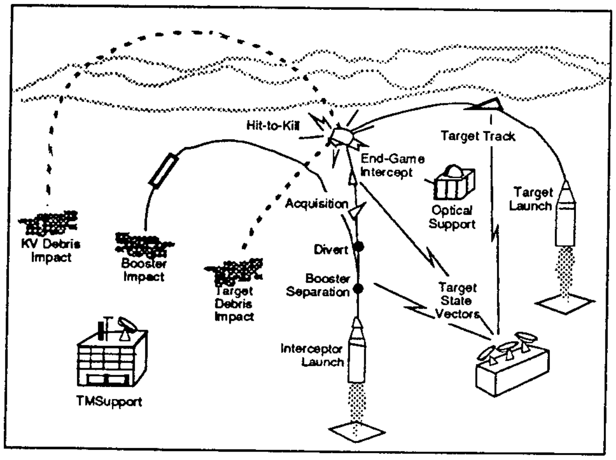


Figure 20.
ENDO LEAP Flight Test Scenario

Various flight test ranges will be evaluated to determine their merit to support the test program. Ranges will be evaluated based on their ability to support ENDO LEAP design point intercepts, telemetry and tracking capabilities, cost and schedule availability. CONUS-based ranges (e.g., WSMR) should be sufficient for TMD engagement scenarios, while off-CONUS sites (e.g., USAKA) are probably better suited for strategic engagements. Data from these flight tests will be used as a final validation/verification tool to demonstrate the feasibility of the ENDO LEAP vehicle designs.

Conclusion

The ENDO LEAP program is proceeding along the path towards developing extremely light hypersonic vehicles for SDI applications. The vehicle designs will be based on requirements to counter strategic and theater ballistic missiles. Hardware will be extensively simulated and tested in state-of-the-art facilities across the country. ENDO LEAP will validate the feasibility of performing high velocity intercepts within the atmosphere and for the basis for future SDI endoatmospheric vehhicles.