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Lightweight Exo-Atmospheric Projectile (LEAP) Space Flight Test, June 1992, Performance Validation

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LIGHTWEIGHT EXO-ATMOSPHERIC PROJECTILE (LEAP) SPACE FLIGHT TEST, JUNE 1992, PERFORMANCE VALIDATION

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Abstract

The Army Lightweight Exo-Atmospheric Projectile (LEAP) program achieved a significant milestone in execution of the LEAP 2 Space Flight Test on June 19, 1992 at White Sands Missile Range. The primary objective of the LEAP 2 Flight Test was to demonstrate hit to kill intercept performance against a non-boosting target. Although intercept of the target was precluded by degraded test conditions, the data from this space test successfully validated the performance of the kill vehicle in a space environment. All test objectives were achieved except the intercept. The kill vehicle tracker, guidance, electronics, propulsion, inertial sensors, battery, and telemetry worked as predicted. Data from the space test has been used to validate kill vehicle simulation models.

I. Overview

The LEAP program is a technology component and integration validation program sponsored by the Strategic Defense Initiative Organization (SDIO). SDIO has developed various lightweight interceptor technology components which are now integrated into kill vehicles. The LEAP program has progressed from extensive ground testing to space testing of these exo-atmospheric kill vehicles. LEAP 2 was the designation for the first space test to verify the performance of the fully integrated interceptor developed by the Army.

The LEAP 2 Space Flight Test was preceded by a rigorous ground test program which validated hardware and software in the fully integrated kill vehicle. System level testing at Hughes Missile Systems Company included software evaluation, dynamic testing on a motion isolation table and air bearing tests. In 1991, the Army LEAP was tested in a strapdown configuration at Phillips Laboratory, Edwards Air Force Base. The strapdown test was followed by a successful free flight Hover Test on June 18, 1991 at the same facility. Data from these ground tests was used to validate both the kill vehicle hardware and performance simulations.

The LEAP 2 mission scenario was constructed to demonstrate all subsystems of the kill vehicle. In the test, the kill vehicle autonomously tracked and diverted to intercept a non-boosting target. The Space Test validated all performance margins including image jitter, thermal management, center of mass migration, pressure control, fuel consumption, and alignments between seeker, inertial sensors and thrusters. This paper discusses the successful resolution of numerous technology integration challenges and presents comparisons of predicted kill vehicle performance to actual flight.

The Army LEAP program is managed for SDIO by the U. S. Army Space and Strategic Defense Command in Huntsville, Alabama, which provides contract administration and technical direction for development and test of the kill vehicle. The prime contractor for the Army LEAP is Hughes Missile Systems Company in Canoga Park, California. The Kaiser-Marquardt Company, Van Nuys, California is subcontractor for the propulsion system.

II. LEAP 2 Kill Vehicle Overview

The Army LEAP program has successfully addressed and solved the complex challenges of integrating the subsystems necessary for a light weight autonomous kill vehicle. The Army/Hughes LEAP kill vehicle is the smallest of the SDIO developed interceptors, weighing less than 13 pounds. The kill vehicle is approximately 6 inches in diameter and 16 inches long. The seeker includes a 5.7 inch aperture beryllium primary mirror, a flat secondary mirror and germanium refractive elements. The sensor is a 128 by 128 Mercury Cadmium Telluride staring focal plane array encompassing the 3 to 5 micrometer spectral band. The Electronics Unit is a high density, double sided 5.6 inch diameter card with an 80386 computer. The computer operates at 20 MHz and provides 4 MIPS processing capability. The propulsion system is a liquid hypergolic system which uses hydrazine (N_2H_4) and nitrogen tetroxide (N_2O_4) to operate four divert thrusters and decomposed hydrazine to operate eight attitude control thrusters. The Army/Hughes LEAP Kill Vehicle is shown in Figure 1.

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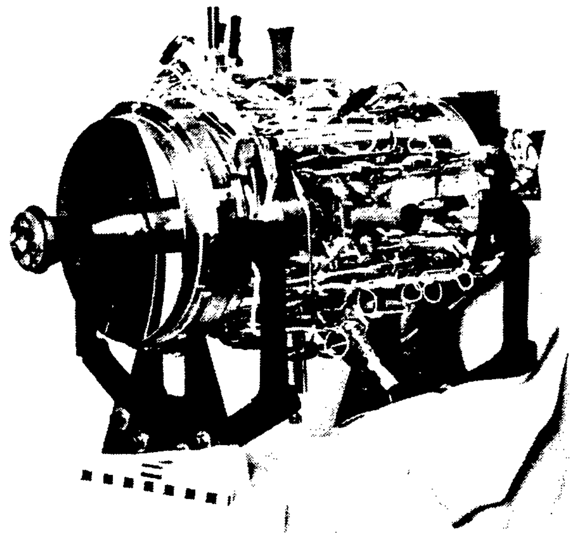

Figure 1. Army Lightweight Exo-Atmospheric Projectile

III. LEAP 2 Space Test

The LEAP 2 space test was designed to demonstrate the Army LEAP integrated technology components by performing a free flight space intercept of a target similar to a reentry vehicle. The space test trajectory is illustrated in Figure 2.

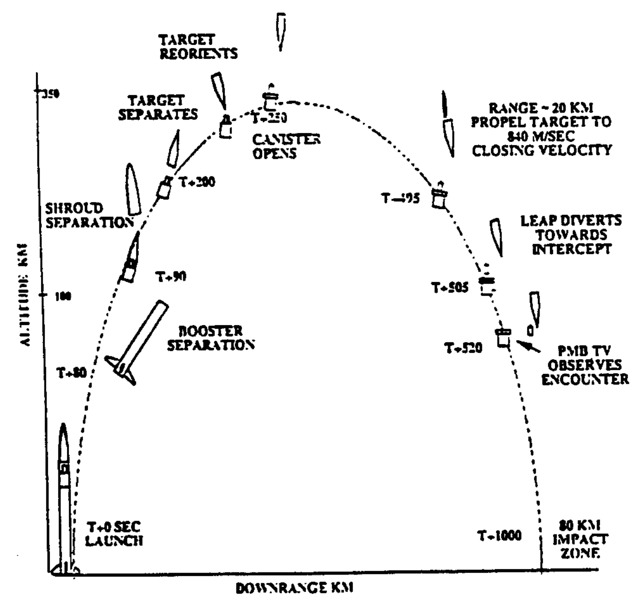

Figure 2. LEAP 2 Trajectory

Mission Objectives

With respect to the kill vehicle performance, there were four objectives established as criteria for success of the LEAP 2 mission.

1) Demonstrate an intercept of a post-boost (non-thrusting) target at moderate closing velocity.
2) Demonstrate sensor acquisition and discrimination of a post-boost target against a space background.
3) Demonstrate LEAP terminal guidance algorithm performance.
4) Demonstrate propulsion and control system response to guidance and control commands.

Objectives 2, 3, and 4 were successfully achieved during the mission.

Mission Overview

The launch vehicle chosen for the LEAP 2 flight was a Minuteman 1 (MMI), Stage II (M56) solid rocket booster. A Payload Module Bus (PMB) provided guidance during the boost phase and served as a stable platform from which to launch the kill vehicle. The target was launched from the same booster as the kill vehicle. The target was pneumatically separated after the rocket motor boost phase and used cold gas nitrogen expulsion to achieve a separation distance of approximately 20 kilometers from the PMB. A modified Viper solid motor was ignited on the target to provide an approximate closing velocity of 800 meters per second.

The kill vehicle operated autonomously of the PMB, receiving only power and initialization commands. The kill vehicle locked onto the target prior to ejection from the PMB, then was ejected and diverted to the target intercept point. Prior to ejection, the kill vehicle should have received fire control information from the PMB which contained the target's velocity and range at acquisition. This information is used to initialize the Kalman guidance filter. Due to a failure of the target's telemetry system, the fire control message was not relayed to the kill vehicle. The lack of fire control information coupled with degraded target performance resulted in a failure of the kill vehicle to achieve an intercept.

Kill Vehicle Support Hardware

Kill vehicle support hardware for the LEAP 2 launch included a Canister, Cryogenic Gas Storage (CGS) system, and an Electrical Interface Unit (EIU). The Canister provided environmental protection and a precision machined ejection platform. The CGS provided 30 minutes of Argon gas for cooling the sensor's focal plane array after booster launch. The EIU conditioned + 28 V battery power from the PMB into the regulated power forms required by the kill vehicle. The EIU also buffered discrete commands and conditioned serial interface data to the kill vehicle from the PMB.

LEAP 2 Timeline

With the exception of target closing velocity and transmission of the target range and velocity, all timeline events occurred at nominal times. The Aries booster received the ignition command at T = 0, lifted off the launch pad and burned for 62.7 seconds. At T + 64 seconds, the V-band cutter was initiated and the aerodynamic shroud was removed from the target. The booster separated from the payload at T + 80 seconds at an altitude of 84.5 kilometers. At T + 90 seconds, the Target Boost Assist Module (TBAM) and target separated from the PMB at an altitude of 104.2 kilometers. The target/TBAM then used a cold gas GN_2 axial booster to thrust itself away from the PMB. The PMB commanded the EIU to power up the kill vehicle at T + 439.7 seconds.

After power up and completion of a built in test, the PMB performed a maneuver so that the kill vehicle could perform its non-uniformity compensation without the target or celestial objects within its field of view. Calibration was completed at T + 457. After reorienting toward the PMB, the target Viper motor was ignited at T + 464 seconds and burned for 6.36 seconds. A serial message containing the PMB body rates was transmitted to the kill vehicle and received at T + 468 seconds. The Helium pyro isolation squib was initiated at T + 470 seconds allowing pressurization of the propulsion system. The kill vehicle thermal battery was squibbed at T + 470.4 seconds.

As the target closed toward the PMB with a velocity of approximately 773 meters/second, the kill vehicle acquired and tracked the target. Target range at acquisition was approximately 16.5 kilometers. As previously discussed, the target range and velocity information was not transmitted to the kill vehicle. In a backup mode, the kill vehicle used a predetermined set of target range and velocity values to initialize guidance. However, the actual closing velocity was significantly lower than predicted. At T + 474.7 seconds, the kill vehicle was ejected from the canister. The kill vehicle used its lateral divert thrusters and attitude control system to maintain track on the target while diverting for more than 16 seconds toward the target. This test fully demonstrated kill vehicle performance although an intercept was not possible.

System Performance Overview

The Army LEAP projectile performance was thoroughly demonstrated during the LEAP 2 space test. The kill vehicle flew for more than 16 seconds toward the target successfully acquiring, ejecting, tracking, guiding and maintaining attitude throughout the divert. A summary of the LEAP 2 objectives and indications of successful operation of both hardware and software is given below.

Guidance performance: The kill vehicle successfully performed closed loop guidance, sensing and steering out target lateral position and velocity.

Attitude control: The kill vehicle maintained the target within 1.5 milliradian (< 3 milliradian required) of boresight.

Acquisition and track: The kill vehicle correctly identified the target after 3 frames. The target motion requirement and acquisition occurred after 7 frames (< 60 frames required). Target track was maintained during 100% of the frames (> 95% required).

Propulsion: The kill vehicle propulsion subsystem worked flawlessly. Thrust levels were just as predicted and all pressures were maintained with sufficient margin.

Center of gravity control: The center of mass was maintained well within the requirement.

Guidance unit: The seeker successfully performed a non-uniformity compensation of the focal plane array against a space background and imaged the target for acquisition and track. The Electronics Unit performed perfectly throughout the mission.

Inertial sensors, battery, and telemetry: Performance of all units met or exceeded expectations throughout the mission.

Canister: The canister opened properly, all lines were severed, and all squib events occurred as expected.

Cryogenic gas supply: The focal plane array was maintained at a constant temperature well within requirements. Cryo gas pressure was maintained with sufficient margin.

Electrical interface unit: The EIU properly conditioned all power and commands to the kill vehicle.

IV. Kill Vehicle Performance Validation

Validation of the LEAP 2 kill vehicle performance is done through analysis of the kill vehicle telemetry. The telemetry system transmitted data to the PMB which relayed the composite data stream to ground receiving stations at several different sites at White Sands. The 11 MBPS telemetry stream contained 128 X 128 pixels of infrared video imagery. Each video pixel was encoded in an 8-bit word. Also included are 512 16-bit words of digital performance and housekeeping data. Both the video data and the digital performance data are generated at a 60 Hz frame rate.

LEAP 2 Kill Vehicle Performance Summary

The LEAP 2 space flight kill vehicle performed exactly as predicted. All performance parameters were within the specifications required for mission success. Table 1 provides an assessment of the overall kill vehicle performance and compares required or predicted values to actual measured space test values. Figures 3 through 11 are a selection of plots of the actual flight data used to verify specific performance parameters.

Table 1. Key Performance Parameters

MEASURED PARAMETER	REQUIRED	MEASURED	FIGURE
Gyro Noise: 1-sigma single-sided PSD	≤6.77E-8 $(rad/s)^2/Hz$	1.5E-8 pitch 1.5E-8 yaw 2.5E-8 roll $(rad/s)^2/Hz$	N/A
Accelerometer Noise: 1-sigma single-sided PSD	≤ 0.027 $(m/s^2)^2/Hz$	0.00135 $(m/s^2)^2/Hz$	N/A
FPA Temperature	89 - 105 K	95 K	N/A
Propellant Pressure	1300±65 PSI	1305±27 PSI	3
Solo Divert Thrust	163.8 ± 25 N	165 N	4
CG Offset Axial CG Offset Radial	≤ ± 2.0 mm ≤ ± 1.0 mm	- 0.7 mm +0.3 mm	5 6
Acquisition Frames	≤ 60 frames	7 frames	N/A
Valid Aimpoints	≥ 95 %	100%	N/A
Pointing Error After Ejection Transient	≤±3mrad pitch ≤±3mrad yaw	1.5 mrad max 0.9 mrad max	7 7
Angular Body Rate After Ejection Transient	≤±150mrad/s p ≤±150mrad/s y ≤±250mrad/s r	90mrad/s 90 mrad/s 235 mrad/s	8 9 10

Propellant pressure: The propellant tank pressure is required to be maintained at 1300 ± 65 psi for the duration of the mission. The divert and ACS repeatability are directly proportional to the propellant tank pressure. Figure 3 shows that the propellant tank pressure from initial pressurization to loss of track was maintained at 1305 ± 27 psi, a factor of two tighter than was required. Initial pressurization to 1300 psi took only 2.2 seconds (< 3 seconds required).

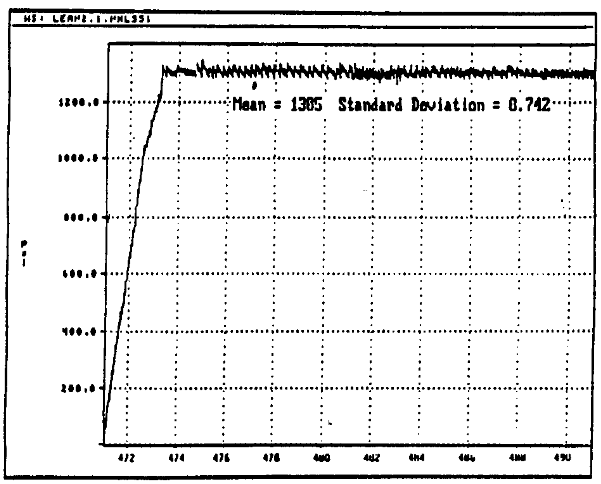

Figure 3. Propellant Tank Pressure

Thrust levels: The thrust levels produced by the LEAP divert engines were as predicted. The predicted solo and dual divert thrusts are 163.8 N and 143.3 N, respectively. The divert force is computed from the product of the vehicle estimated mass and sensed acceleration. The kill vehicle estimates mass by using measured initial mass and adjusting for propellant usage during each thruster firing. Figure 4 shows a plot of the azimuth and elevation divert forces.

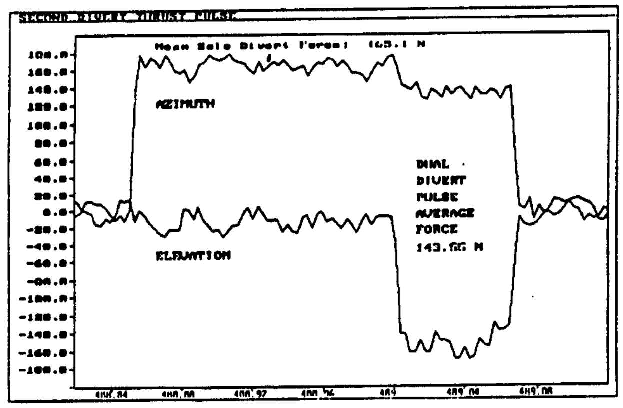

Figure 4. Measured Divert Thrust Force

Center of Gravity control: Center of gravity (CG) migration is a key issue in control of the kill vehicle. The propulsion system is designed to prevent drift of the kill vehicle center of mass during the mission. Helium pressure is used to move pistons, expelling propellant from the two fuel and two oxidizer tanks. The tanks are symmetrically located about the kill vehicle longitudinal axis. The pistons in the two sets of tanks are positioned at opposite ends of the tanks and move towards each other as propellant is used. Figures 5 and 6 show the axial and radial CG offset during the LEAP 2 mission. Both axial and radial CG were maintained within the required offset. The mean axial CG was held to - 0.7 millimeters and the mean radial CG to + 0.3 millimeters.

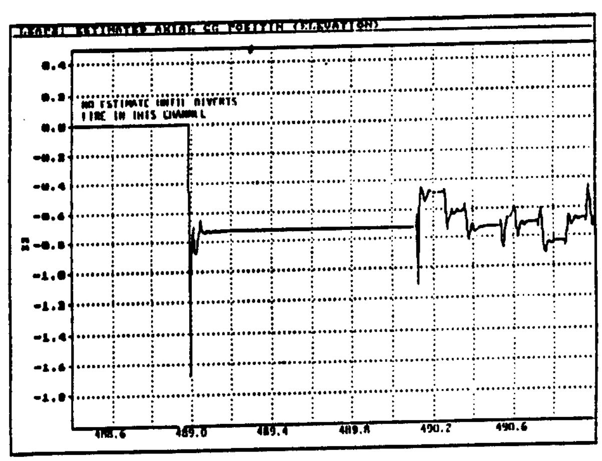

Figure 5. Axial CG Offset

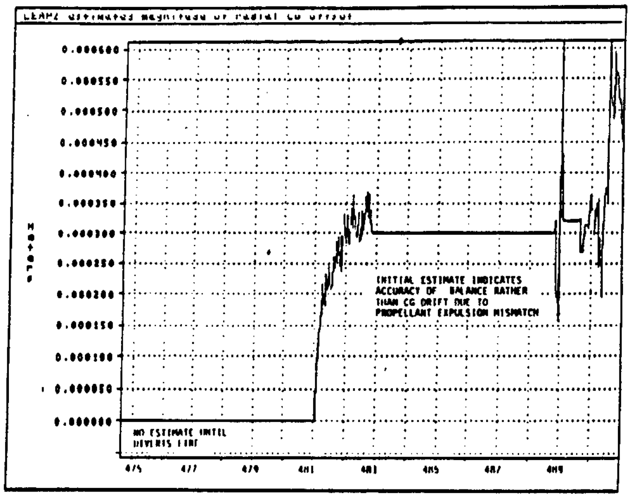

Figure 6. Radial CG Offset

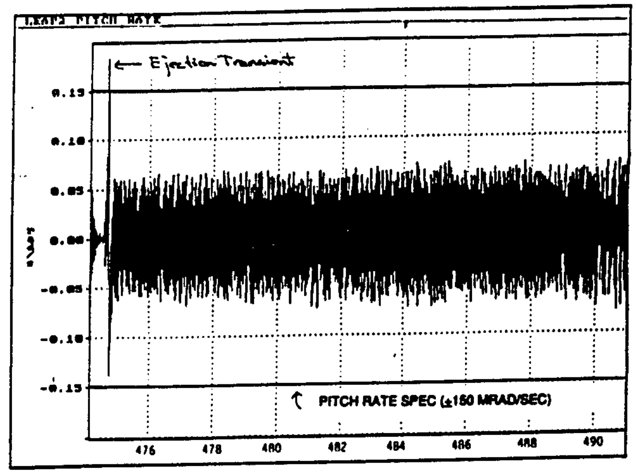

Figure 8. Pitch Body Rate After Ejection Transient

Attitude control system: Figure 7 shows the attitude control system performance during the flight. It shows the position of the target in the kill vehicle's field of view. The attitude control system is required to maintain the target within 3 milliradian of boresight after the ejection transient. The target was maintained well within 1.5 milliradian of boresight for as long as the target was tracked.

Pitch and yaw body rates are required to be maintained within 150 milliradian/second and roll within 250 milliradian/second. Pitch and yaw body rates were held to less than 90 milliradian/second while the roll rate was less than 235 milliradian/second Figures 8, 9, and 10 show plots of the pitch, yaw and roll rates after the ejection transient.

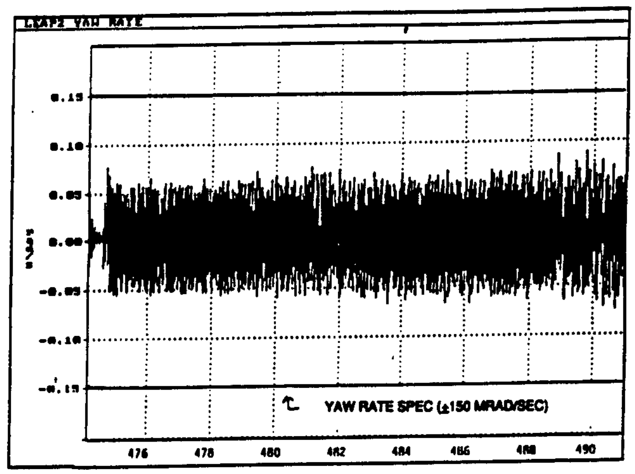

Figure 9. Yaw Body Rate After Ejection Transient

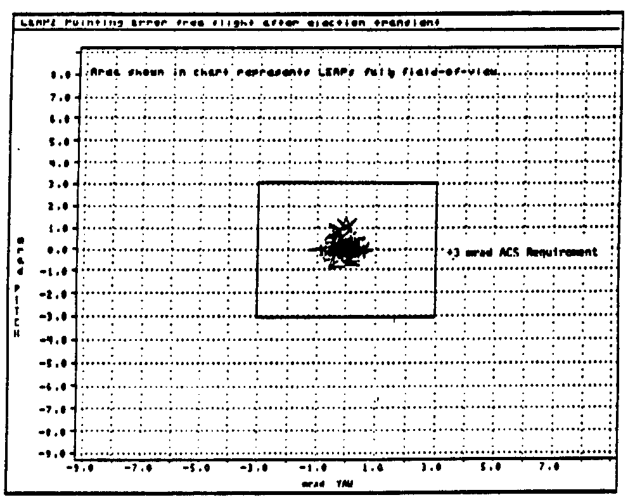

Figure 7. Pointing Error After Ejection Transient

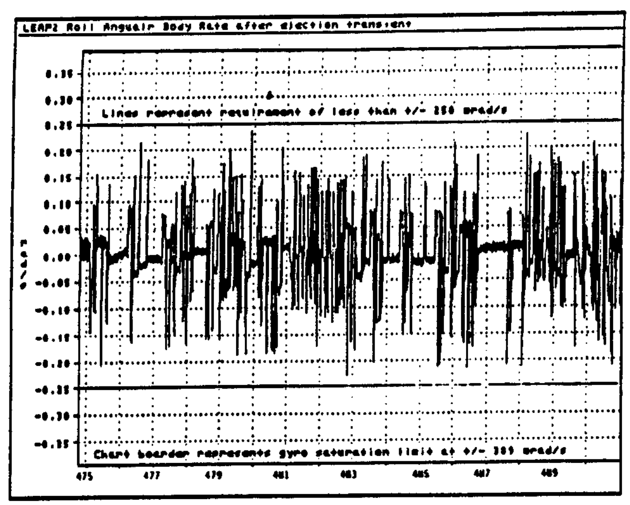

Figure 10. Roll Body Rate After Ejection Transient

Simulation Matching/Validation

Data from the LEAP 2 mission successfully validates the Hughes LEAP 6 Degree of Freedom (DOF) and End-to-End Simulations. The End-to-End simulation is a complete kinetic kill vehicle simulation, consisting of extended target models, IR sensor model, detailed tracker and guidance algorithms, structural dynamics, rigid body dynamics, attitude control system (ACS), and engagement geometry.

In the End-to-End simulation the sensor focal plane array is superimposed on the object grid and, pixel by pixel, incident energy is computed and convolved with the diffracted optics pattern (point spread function). The resultant target 8-bit video image is input to the tracker to define an aimpoint. A proportional navigation guidance law is used to develop lateral acceleration commands. The resulting divert thrust will produce disturbance torques due to center of gravity offsets. The ACS then steers out the disturbance with the attitude control thrusters. The lateral and ACS thrust forces excite structural dynamic vibrations and drive the 6-DOF rigid body dynamics and geometry computations. Trajectory information is generated from the geometry and the guidance loop is closed through the target model. Structural vibrations create deflections at the inertial measurement unit (IMU) and seeker locations. These are superimposed in the rigid body parameters.

The 6-DOF portion of the simulation is a complete three dimensional missile dynamics and guidance simulation. Six degrees of freedom of the kill vehicle motion (3 translation, 3 rotation) are modeled as well as translational motion of the target. Any engagement scenario can be specified, allowing the user to select the kill vehicle and target position, velocity, and acceleration vectors. The target state is specified by initial position, initial velocity and a time history of acceleration. Gyro misalignments, drift errors and noise are also modeled in the simulation.

Deterministic IMU characteristics, measured CG offsets, measured thrust levels and initial angular body rates and pointing at the time of LEAP ACS enable were loaded into the 6-DOF and End-to-End simulations. The simulations generated plots of key performance parameters. When compared to plots of measured parameters from the space flight, the simulations are validated as accurate predictors of kill vehicle performance. The simulations predicted the same ACS duty cycles and amplitudes, ejection transients, divert pulses and Kalman filter virtual miss estimation. It is important to note that flight test data represents one sample while simulation data is an average of multiple random samples. Flight test results do not match simulation results exactly, but the differences are statistically insignificant. Figures 11 through 17 show comparisons of flight test data with simulation results for a selection of key parameters.

Pitch body rate: Figure 11 shows the measured pitch body rate including gyro characteristics and the ejection transient. The simulation accurately models the initial pitch ejection transient of 0.184 rad/s. After the ejection transient, the simulation models the amplitude within 10% and matches the frequency of the pitch rate exactly.

	FLIGHT TEST DATA	SIMULATION
AMPLITUDE	60 mrad/s	55 mrad/s
FREQUENCY	30 Hz	30 Hz

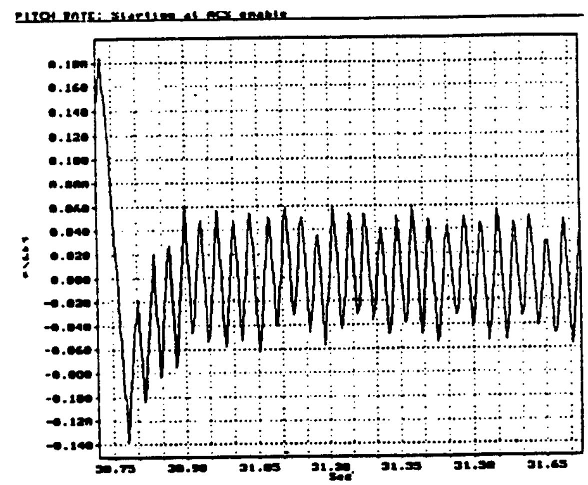

Figure 11A. Pitch Rate - Flight Test

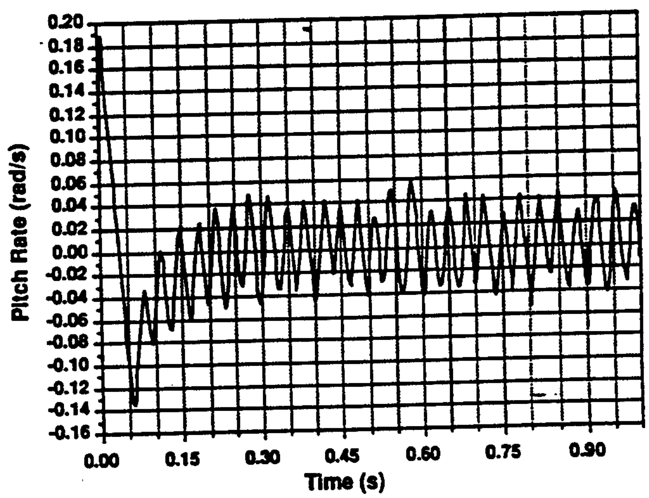

Figure 11B. Pitch Rate - Simulation

Yaw body rate: Figure 12 shows the measured yaw body rate including gyro characteristics and the ejection transient. After the ejection transient, the simulation models the amplitude within 10% and matches the frequency of the yaw rate exactly.

	FLIGHT TEST DATA	SIMULATION
AMPLITUDE	55 mrad/s	50 mrad/s
FREQUENCY	30 Hz	30 Hz

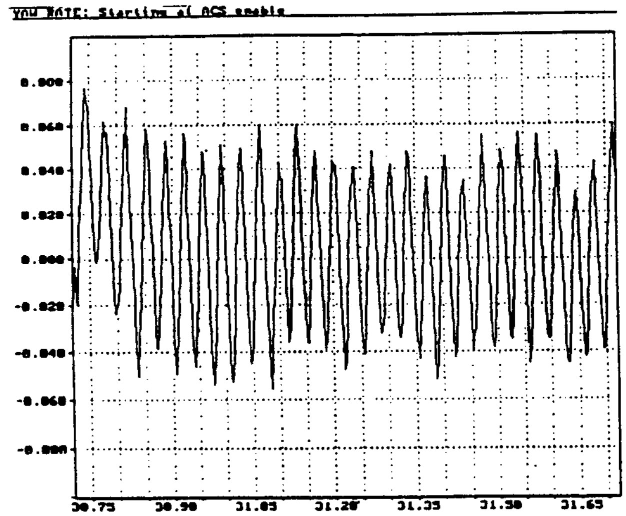

Figure 12A. Yaw Rate - Flight Test

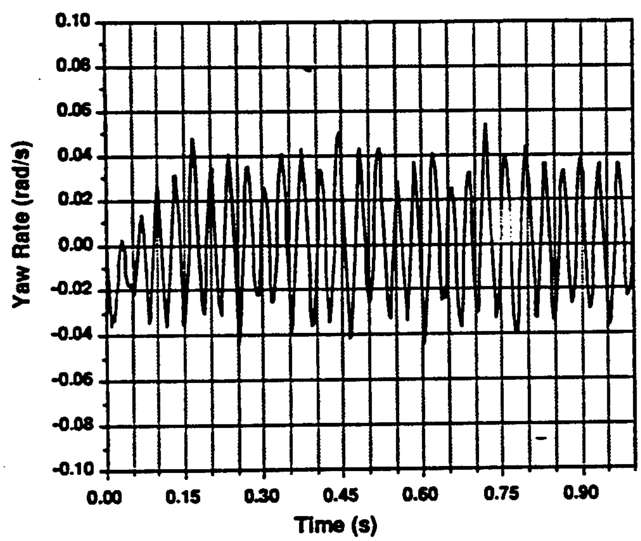

Figure 12B. Yaw Rate - Simulation

Pitch pointing error: Figure 13 gives the pitch pointing errors including the ejection transient. The simulation accurately models the initial pitch ejection transient of 3.0 milliradian. After the ejection transient, the simulation closely models the amplitude of the pitch pointing error. A maximum amplitude of 5.25 mrad was seen in the flight test while the simulation had a maximum amplitude 6.25 mrad.

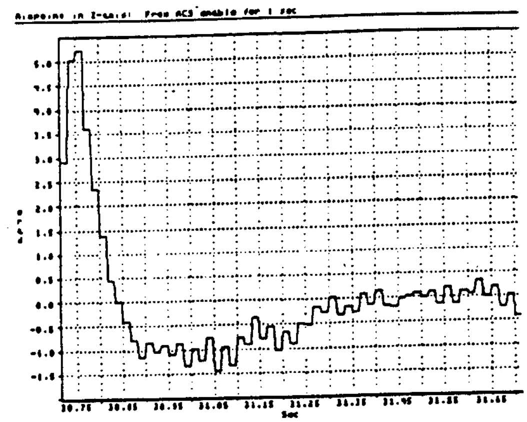

Figure 13A. Pitch Pointing Error - Flight Test

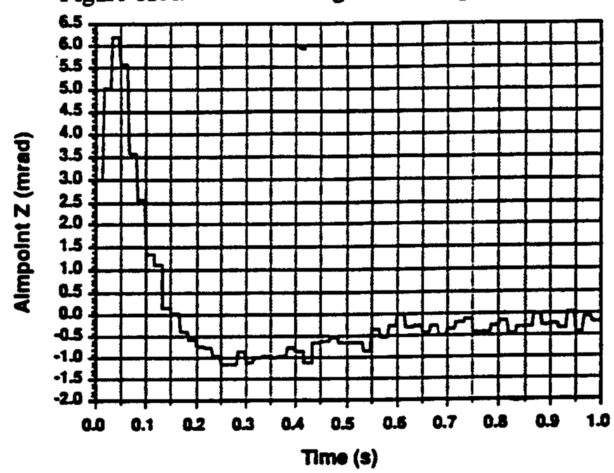

Figure 13B. Pitch Pointing Error - Simulation

Yaw pointing error: Figure 14 gives the yaw pointing errors including the ejection transient. The simulation accurately models the initial yaw ejection transient of 2.3 milliradian. After the ejection transient, the simulation closely models the amplitude of the yaw pointing error. A maximum amplitude of 2.3 mrad was seen in both the flight test and simulation results.

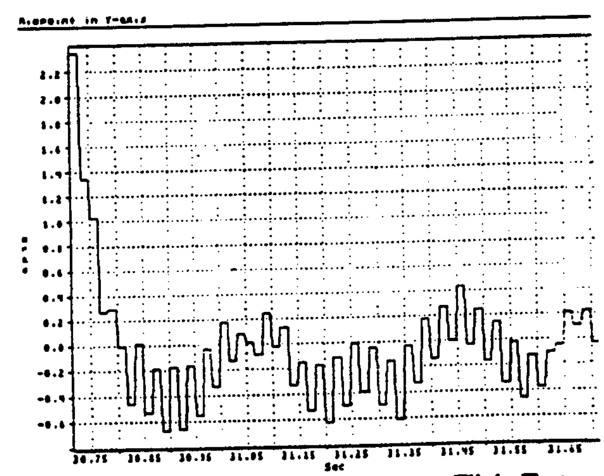

Figure 14A. Yaw Pointing Error - Flight Test

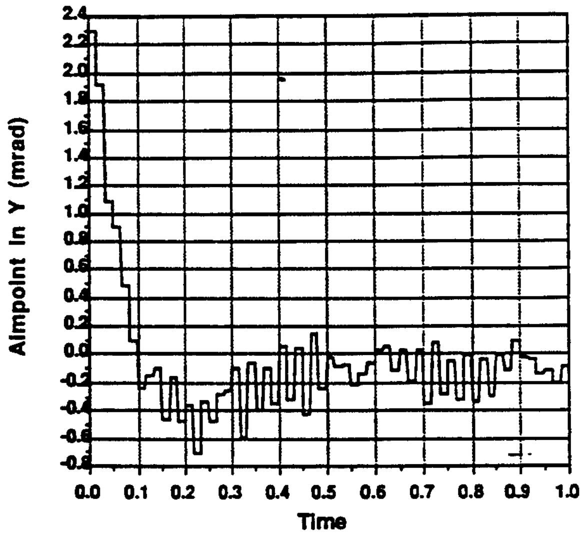

Figure 14B. Yaw Pointing Error - Simulation

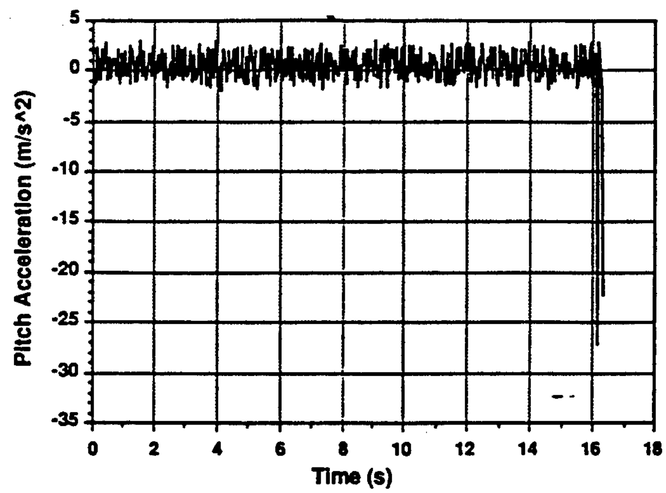

Figure 15B. Pitch Acceleration - Simulation

Divert initialization and duration: Figure 15 illustrates the pitch acceleration profile. In both flight test and simulation plots, the first pulses occur during 60 Hz Adaptive Pulse Width Modulation. In the flight test data, the first pulse occurs at 14.25 seconds. In the simulation, the first pulse occurs at 16.2 seconds. In the flight test data, the shift in the pitch acceleration occurs during a divert pulse in the yaw channel. Part of the yaw divert pulse is seen in the pitch acceleration due to a known misalignment between the accelerometers and the divert thrusters. This misalignment will be included in future simulation upgrades.

Figure 16 illustrates the yaw acceleration profile. In the flight test data, the first pulse occurs at 6.28 seconds for a duration of 1.8 seconds. The simulation data closely matches as shown . The first pulse occurs at 5.8 seconds for a duration of 1.6 seconds. The end game pulses in the simulation also closely match the actual flight test data in duration and time of occurrence.

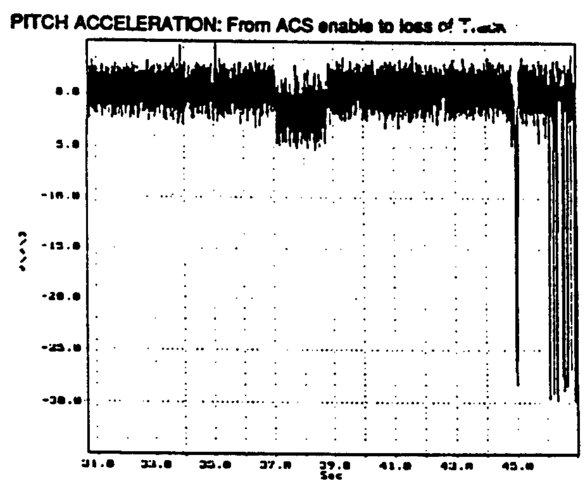

Figure 15A. Pitch Acceleration - Flight Test

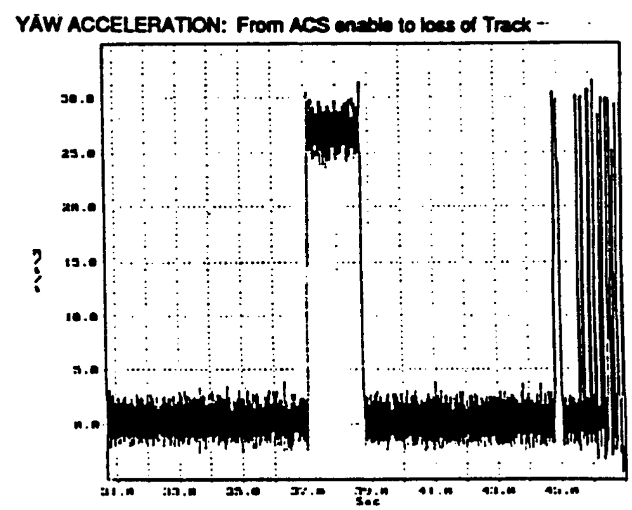

Figure 16A. Yaw Acceleration - Flight Test

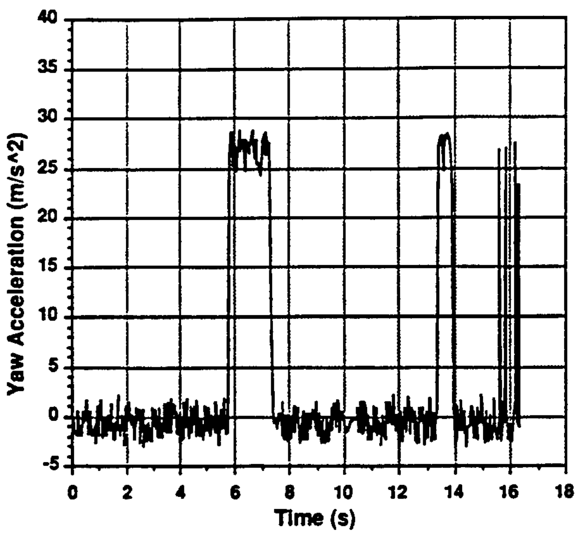

Figure 16B. Yaw Acceleration - Simulation

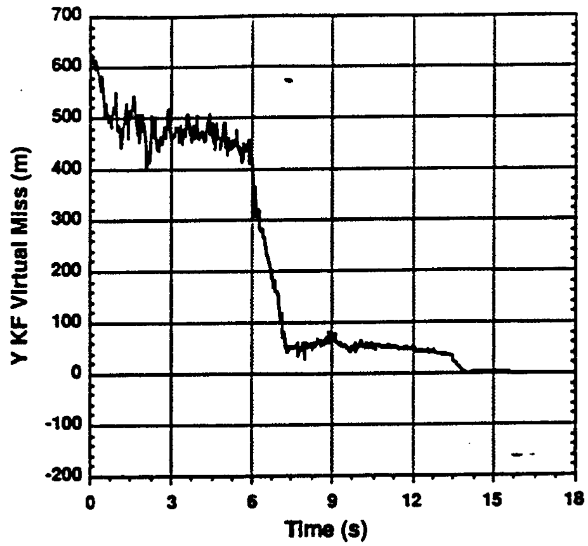

Figure 17B. Kalman Filter Virtual Miss - Simulation

Kalman filter virtual miss: Figure 17 shows the azimuth axis Kalman Filter virtual miss estimates for the flight test and simulation. The simulation closely matches the flight test data. In both plots, the first estimate of virtual miss is approximately 460 meters followed by a linear decrease to 60 meters after 7 seconds. The simulation shows a gradual decrease to 0 meters while the flight data shows the virtual miss reduced to less than 25 meters before loss of track. Similar guidance software performance is obtained for the Kalman filter virtual miss in the elevation axis.

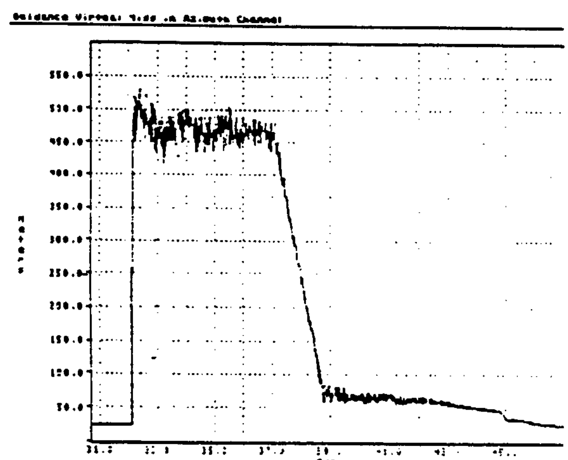

Figure 17A. Kalman Filter Virtual Miss - Flight Test

V. Summary

The Army LEAP kill vehicle design has been thoroughly demonstrated by the LEAP 2 Space Flight Test. Mission data has been used to validate kill vehicle performance simulations which will be used to reliably predict performance against targets in future hover and space flight testing. Results of the LEAP 2 flight test are important in evaluating enhancements being developed for future kill vehicles including an advanced guidance unit with a dual processor, improved IMU, and long wave infrared seeker. Current planning includes space flight testing of a long wave kill vehicle and hover testing of an advanced guidance unit with a solid propulsion system. Success of the LEAP 2 mission gives confidence that these tests will also succeed.