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Air-Bearing Guided Intercept and Line-of-sight Experiments (AGILE)

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This paper was prepared for presentation at
the First Biennial AIAA National Forum on Weapon System Effectiveness
April 6-8, 1999
Eglin Air Force Base,
Ft. Walton Beach, Florida

April 1, 1999

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AIR-BEARING GUIDED INTERCEPT AND LINE-OF-SIGHT EXPERIMENTS (AGILE)

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Abstract

This paper describes a ground based test and evaluation approach for testing an agile, lightweight, interceptor's performance on a four/five degrees-of-freedom dynamic air bearing (DAB). The key attribute of this apparatus is that it allows for a rapid turnaround test and evaluation of a fully integrated vehicle's ability to detect, acquire, and track a closing target with real-time closed loop attitude control and divert guidance. In addition it also provides a testbed for the rapid development, evaluation, and validation of new hardware components and software functionality. Unlike other hardware-in-the-loop (HWIL) tests, the final measure of performance of a DAB experiment is a vehicle's actual miss distance - a direct measure of an interceptor's "hit" capability. By conducting multiple DAB intercept experiments, a statistical estimate of a vehicle's miss distance performance can be obtained. In addition, extension of ground test concepts to include five and six degrees-of-freedom experiments are also discussed.

Introduction

This paper describes a ground based test and evaluation concept for testing an agile, lightweight, interceptor's performance on a four/five degrees-of-freedom dynamic air bearing (DAB). The key attribute of this apparatus is that it allows for a rapid turnaround test and evaluation of a fully integrated vehicle's ability to detect, acquire, and track a closing target with real-time closed loop attitude control and divert guidance. In addition it also provides a testbed for the rapid development and evaluation of new hardware components and software functionality. DAB can be configured to support both indoor and outdoor tests. The indoor air-table implementations of the dynamic air bearing, however, limits the test vehicle's divert acceleration to less than 1g. For vehicles equipped with greater than 1g acceleration and employing hypergolic propellants, other approaches such as the out-door air-rail DAB or the captive tether flight [1] may be more applicable. Unlike other hardware-in-the-loop (HWIL) tests, the final measure of performance of a DAB experiment is a vehicle's actual miss distance - a direct measure of an interceptor's "hit" capability. By conducting multiple DAB intercept experiments, statistical estimates of a vehicle's intercept capability can be obtained. The DAB can also be used to evaluate the performance of a new class of agile micro-satellites for proximity inspection of low earth orbit space assets.

Quick reaction kinetic kill vehicles (KKVs) utilizing center-of-gravity (cg) divert engines have been under an intensive engineering development effort during the past decade. Despite more than a decade of intensive flight testing, reliable hit-to-kill (HTK) technology has not been demonstrated [2]. Therefore, we believe there is a need for a more cost-effective approach to conduct ground intercept experiments to gather critical interceptor performance parameters to supplement the actual flight test program. The DAB is an improvement to the traditional stationary air bearing used for a typical HWIL test. The key improvement area, of course, is the integration of actual vehicle divert dynamics to the traditional HWIL attitude stability and control tests.

KKV derives its lethality, in part, from the kinetic energy at impact. Since the kinetic energy increases as the square of velocity, therefore the higher the closing velocity, the higher is the lethality potential. In addition the kill radius of a KKV is small, limited primarily by the cross-sectional area of a vehicle's dimensions. Thus miss distance requirement is also correspondingly small since it must stay within the nominal kill radius. Small miss distances imply the need for high resolution , high performance sensors, and vehicle agility. Furthermore, at closing speeds of 5 kilometer per second or higher and for a given target acquisition range, effective endgame time period is short; it may last for only a few seconds. Thus depending on the handover error basket, the kill vehicle must possess sufficiently high acceleration to close the miss distance. High acceleration and agility implies the need for energetic propellants, lightweight components and stiff vehicle structures. But vehicle agility usually degrades sensitive sensor performance. In short, the design of a modern quick reaction interceptor must compromise among multitudes of conflicting engineering requirements.

In order to aid the understanding of the design trade, the dynamic coupling effect between divert and line-of-sight (LOS) estimation, and the scaling principle between an actual flight intercept and a DAB guided intercept experiment, we will provide a brief

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discussion of the underlying principle of hit-to-kill (HTK) intercept.

Hit-To-Kill Intercept Fundamentals

In principle, the intercept problem is deceptively simple. Looking from a reference frame where the interceptor is at rest (see Fig. 1), the problem is to maneuver or guide the kill vehicle (**K**) in such a manner to align the closing velocity vector (**V_R**) with the relative position vector (**R**) creating the so called head-on collision scenario. The angular deviation between the two vectors is known as the heading error. A typical guidance scheme to null the heading error is the "proportional navigation (PN)" guidance where the acceleration command is proportional to the measured LOS rate ($d\theta/dt$). Mathematically speaking, the problem is to solve a second order differential equation with time varying coefficient so that the miss distance variable (Z) goes to zero when the time-to-go (tgo) clock reads zero [3]. This implies that an interceptor must be capable of doing two things: (1) to precisely estimate the intercept point (I) at some future time, and (2) to get to that same location at precisely the same time. For a non-maneuvering target, PN guidance is sufficient where the goal is to stay on a collision course by steering the LOS rate to zero without the explicit knowledge of the actual collision time[4]. On the other hand for a maneuvering target, an Augmented PN or APN is needed to drive the zero-effort-miss distance to zero. To simplify our discussion, we will focus primarily on the non-maneuvering target case so that a passive seeker plus an inertial measurement unit (IMU) are sufficient to generate the required LOS rate measurement.

Miss Distance Estimation

In order to estimate the zero-effort-miss distance ZEM or Z for short, we must rely on the measurement of the LOS angle θ (See Fig. 1). Note that if we define the coordinate frame X-Y at time $t = 0$ (first target acquisition point) to be fixed with respect to inertial space, then the LOS angle can be obtained by summing the optical axis angle (θ_{IMU}) as measured by the IMU and the target seeker angle ($\Delta\theta$). Ideally the LOS angle will remain unchanged due to any angular motion of the interceptor because any changes in the seeker angle due to vehicle angular motion must be exactly compensated for by the IMU. It is easy to establish the relation between the LOS angle and the miss distance Z.

Let's assume that at time $t=t_1$, the target is at point G, hence the LOS angle is given by:

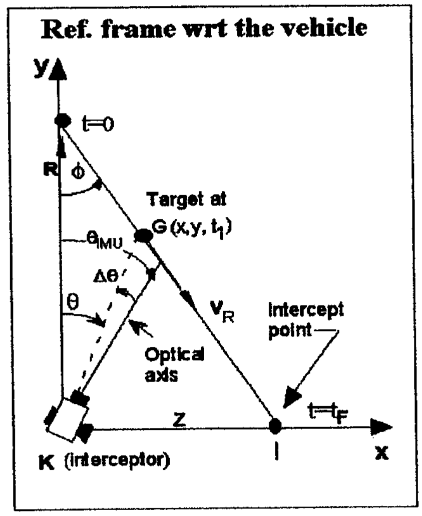

Figure 1 Intercept geometry

$$\theta=tan^{-1}\left(\frac{x(t)}{y(t)}\right)=tan^{-1}\left(\frac{v_R t\, sin\,\phi}{R-v_R t\, cos\,\phi}\right) \tag{1}$$

from which one can compute the LOS rate as:

$$\begin{aligned}\dot{\theta} &= \frac{y\dot{x}-x\dot{y}}{x^2+y^2}\\ &= \frac{Rv_R\sin\phi}{R^2+(v_R t)^2-2Rv_R t\cos\phi}\end{aligned} \tag{2}$$

We recognize that the denominator of Eq.(2) is the square of the length KG from the law of cosine. Reapplication of the law of cosine to triangle KGI yields an equivalent expression as:

$$\dot{\theta}=\frac{Z/\left(v_R t_{go}^2\right)}{\left[1+\left(\frac{Z}{v_R t_{go}}\right)^2-2\left(\frac{Z}{v_R t_{go}}\right)sin\,\phi\right]} \tag{3}$$

where $t_{go} = t_F - t$, is the time-to-go before intercept. Since in general it is true that $Z \ll v_R$ tgo, $\phi \sim 0$, and $v_R \sim v_C$, the closing velocity, Eq.(3) can also be approximated by:

$$\dot{\theta} \cong \frac{Z}{v_c t_{go}^2} \tag{4}$$

Thus knowledge of LOS rate, closing velocity, and tgo will determine the miss distance. For tgo decreasing in time, nulling the LOS rate is equivalent to nulling the zero-effort-miss distance as resulting from closed loop PN guidance actions.

Vehicle Guidance

A crucial test of an interceptor's performance is its ability to reliably predict the miss distance or equivalently the heading error or the LOS angular rate. A reliable estimate of this parameter is needed prior to any initiation of vehicle guidance maneuvers. Note that for PN guidance, the commanded acceleration is given by:

$$A_c = -N v_c \dot{\theta} \tag{5}$$

where N is the navigation constant, and Vc is the closing velocity.

Figure 2 shows the LOS rate of a 10km/s closing target for different values of ZEM. For example for a 10m ZEM and a 3σ LOS rate precision of 100 μrad/s, divert guidance can not be initiated until 3s before intercept. Note that this condition corresponds to a heading error of ~300μrad at a range of 30km. Thus LOS rate precision or stability is a limiting factor in determining an interceptor's miss distance. In practice, the miss distance is also affected by additional vehicle parameters such as mis-alignment of divert thrusters and other hardware components, center of gravity (cg) offset due to changing vehicle mass, stability of the attitude control system, vehicle acceleration (g capability), and guidance loop bandwidth, etc.

Given the performance of an IMU in terms of drift and angle random walk [5] and the seeker IFOV and frame rate, the effective LOS rate can be estimated as follows:

$$\sigma_{\hat{\dot{\theta}}_{LOS}} = \dot{\theta}_{IMU} + \sqrt{\frac{12}{N}\frac{1}{N \bullet \Delta t}} \; x \; \sqrt{\sigma^2_{ARW} \bullet \Delta t + \sigma^2_{\theta_{Seeker}}} \tag{6}$$

where $\dot{\theta}_{IMU}$ is the IMU drift bias, N is the number of samples, Δt is the sampling interval, σ_{ARW} is the IMU angle random walk, and $\sigma_{\theta_{seeker}}$ is the seeker angular uncertainty with a typical conservative value equal to 1/3 of the pixel IFOV.

Assuming a frame rate of 100 Hz, Figure 3 below shows the effective LOS rate as a function of IMU drift and seeker IFOV. For a typical drift rate of 1°/hr and seeker IFOV of 100 μrad pixel, a LOS rate of 18 μrad/s is observed. Note that at 0.1°/hr drift, LOS rate does not reduce significantly because it is dominated by the IMU and the seeker noise. The objective of a PN guidance is to reduce or steer the LOS rate to zero, the necessary condition for a successful intercept.

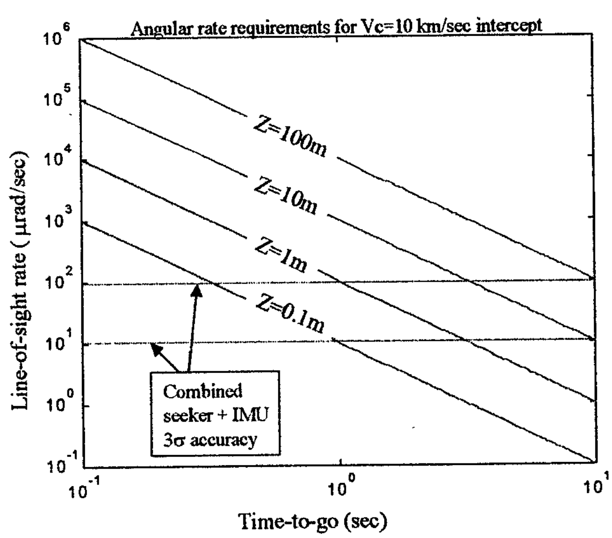

Figure 2 Line-of-sight rate for a 10 km/s closing target

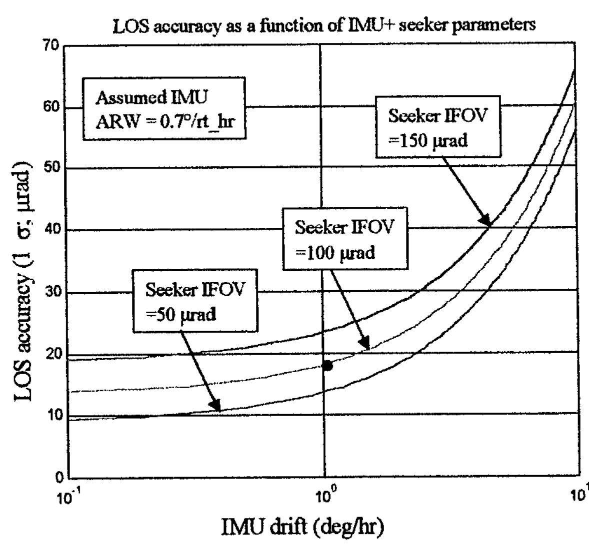

Figure 3 LOS rate accuracy as a function of IMU and seeker performance

Figure 4a shows the LOS rate time history during a closed loop PN guidance for a 6km/s closing target with an initial error basket of 200m. Note that for a 1°/hr drift IMU, the measured LOS rate becomes unreliable at 0.5s before impact. The target is still at 3km away and with a 100μrad IFOV pixel, its resolution in distance is about 0.15m. For a non zero miss distance intercept, LOS rate increases rapidly prior to impact. A KKV must, during this phase, reliably sense and keep the LOS rate at or below an acceptable level; otherwise miss distance will grow in proportion to the LOS rate error.

Figure 4b shows the corresponding requirement in position measurement if independent reconstruction of the LOS rate is desired. Note that at tgo = 1s, better than a centimeter of position resolution is required.

Figure 5a shows a simple Simulink PN block diagram to support the calculation. Figure 5b shows the similar result from a 6DOF simulation of a perfect intercept scenario using a pulse width modulation (PWM) divert guidance as is the case for a real interceptor. We note that at tgo =2s, the LOS rate drops below 100 μrad/s, however, because of the discrete guidance impulses, the LOS rate oscillates (or dithers) about zero. In order to intercept, the average LOS rate must approach zero. This is one of the mechanisms where the interceptor can measure LOS rate below the sensor threshold.

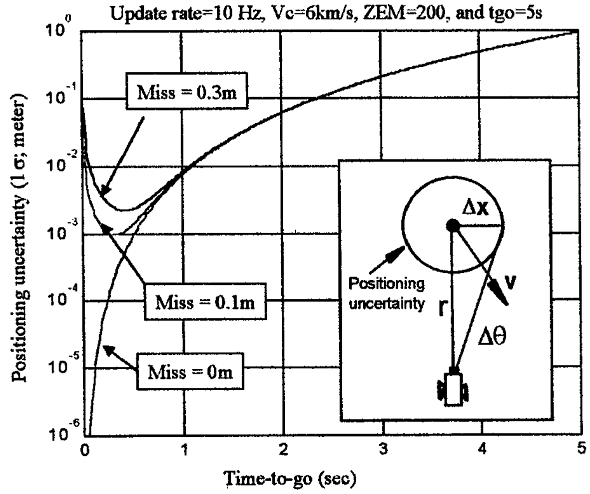

Figure 4b Required position measurement accuracy for generating independent LOS rate diagnostics

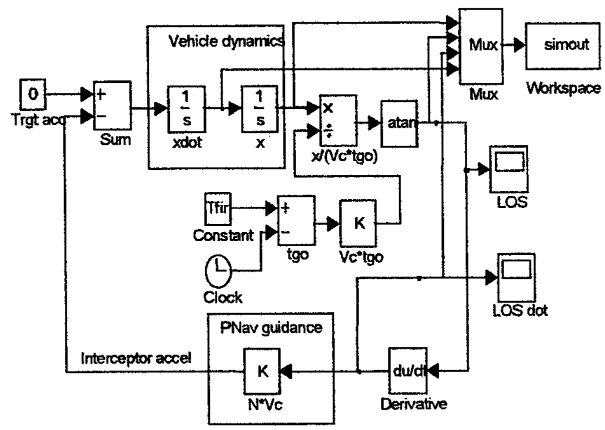

Figure 5a A simple closed loop Simulink PN guidance simulation

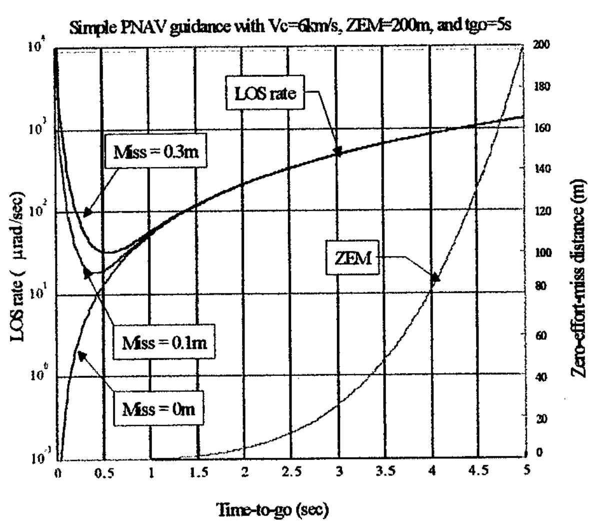

Figure 4a LOS rate time history for a closed loop PN guidance with several assumed intercept miss distances

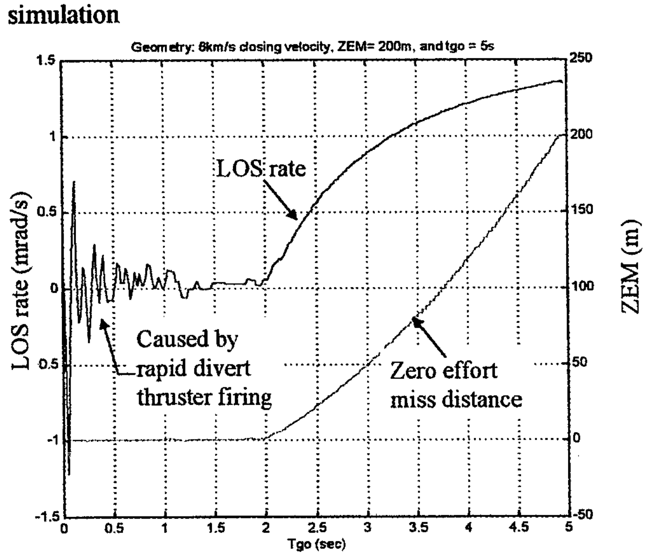

Figure 5b A 6DOF simulation showing average LOS rate approaches zero via dithering

Factors Affecting Miss Distances of a Modern Divert Interceptor

Modern interceptors employ cg thrusters with fast (~10ms) response time and agile acceleration (>3g) to drive down the miss distance. Thus the modern interceptor has a large rate of change of acceleration or gdot (jerk). A large gdot represents a forcing function with a large spectral bandwidth to excite the harmonic resonance of the vehicle structure as well as all the lightweight components. As the guidance and control bandwidth increases, more of the structural induced noise (mechanical and electrical) will be coupled into the guidance loop.

The coupling model of the gdot effect to the vehicle's "as built" structure and the actual onboard instrumentation must be determined experimentally. There exists only very limited actual intercept flight data to improve the poor correlation between models and the actual dynamically coupled response. Its consequence, however, is to degrade the LOS measurement and therefore the miss distance prediction. Thus the ability of an interceptor to maintain the LOS rate stability in the presence of vehicle divert is the key to a successful intercept.

Divert Engine Induced Dynamically Coupled Response

Let's be more specific and consider a thought experiment as follows. Figure 6 shows a sketch of the zero effort miss (ZEM) distance as a function of gdot. ZEM is defined as the predicted miss distance if the interceptor executes no more acceleration maneuvers. If X is a point on a curve, we will denote its ZEM and gdot values as ZEM(X) and gdot(X) respectively. Let's first examine the ideal response curve. ZEM does not reduce at zero gdot since the interceptor generates no lateral velocity. Miss distance then reduces gradually as gdot increases until it flattens out at a threshold value such as at points I & J. The threshold is limited by the uncertainty in miss distance prediction resulting from the LOS measurement noise.

If the miss distance requirement is r (say 1m), then the desired gdot of an interceptor must be greater than gdot(H). An interceptor with gdot less than this value must employ a kill radius enhancer. This ideal response curve is assumed by almost all of the interceptor community for their computer prediction models of interceptor performance.

Let's continue our thought experiment. Suppose an interceptor has an infinite gdot and perfect LOS rate, then the miss distance will be zero as indicated at point K. However, at infinite gdot, the interceptor will be physically split into two halves at the onset of the first divert pulse, and the result should be shown at point G. In reality, the structural yield point will have occurred at a much lower level such as at point F.

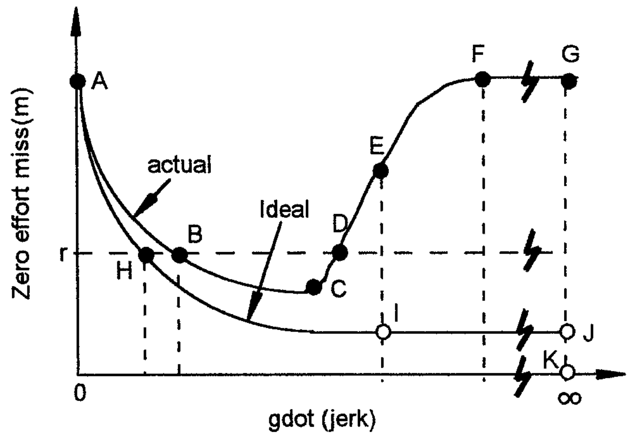

Figure 6 Miss distance response as a function of gdot

On the other hand, when we increase gdot from zero, the coupled effect will degrade the LOS precision, resulting in a larger miss distance as shown at points along A, B & C. As we continue to increase the values of gdot, corresponding values of miss distance must increase from the minimum value at C to exceeding the requirement at points D & E in order to reach point F. Knowing the actual dynamically coupled response (DCR) curve is crucial to the design of the interceptor. As shown, it specifies a much smaller design space in meeting the miss distance requirement than normally assumed. Note also that if ZEM(C) > r, the interceptor in question will fail to meet the miss distance requirement at all values of gdot. Unfortunately the DCR curve must be obtained and validated from guided intercept experiments.

Now suppose an interceptor was designed at point I using the traditional computer model of an ideal response curve, then it will fail to meet the miss distance requirement because its actual operating point is at E. One must then either redesign the vehicle structure and seeker hardware to reduce the dynamically coupled effect or reduce the gdot capability of the vehicle with a different propulsion system design or select a longer detection range (higher angular resolution) seeker. A longer t_{go} will allow more adequate time to damp out any LOS stability motions associated with the divert actions. However, since a higher resolution (smaller IFOV) seeker will be more sensitive to these motions, there is also a limit to the utility of this solution.

Intercept Experiment Scaling Laws

The purpose of scaling laws is to allow for a meaningful ground test experiment that preserves as many pertinent interceptor parameters of the actual flight experiment as possible including the use of actual interceptor flight hardware and software. The primary objective of the ground test experiment, however, is to quantify the miss distance statistics of an interceptor and identify any hardware and software deficiencies which would prevent a successful intercept. Thus, we have adopted four criteria for the scaled experiments:

(1) Preserve the LOS rates for ZEM estimation,

(2) Adjust heading error to evaluate different lateral dynamics,

(3) Maintain same engagement timeline to match mission events, and

(4) Select divert distance to effect sufficient excitation of vehicle dynamics.

Figure 7 shows that the four intercept geometry parameters are; range, ZEM, closing velocity, and heading error, only three of which are independent. These four can be scaled to satisfy the above criteria. From Eq.(4) one obtains:

$$\dot{\theta} = \frac{Z}{V_c t_{go}^2} = \frac{Z}{R t_{go}} \cong \frac{\phi}{t_{go}} = \frac{\alpha\phi}{\beta t_{go}} = \frac{\phi^*}{t^*_{go}} = \frac{Scaled\, heading\, error}{Scaled\, time-to-go} \quad (7)$$

Thus we find from Eq.(7) that LOS rate is preserved if one scales the heading error and the tgo identically. If we fix tgo and range but scale down the heading error, we are testing the interceptor's ability to stay locked on a collision course. On the other hand if we fix t_{go} but scale up the heading error (say by reducing the target range), we are testing the vehicle's dynamic transient performance to reach a collision course.

Figure 8 shows several scaled experiments. For reference, trajectory "a" is the actual trajectory. Trajectory "b" reduces the LOS rate by shortening the divert distance to test an interceptor's ability to stay on the collision course. On the other hand trajectory "c" reduces the initial range to test an interceptor's ability to reach a collision course from a higher initial LOS rate. Note the lateral intercept dynamics are preserved. In the computation of commanded acceleration, the higher LOS rate is offset exactly by a smaller closing velocity. Finally trajectory "d" preserves the initial heading error and LOS rate but scales down the closing velocity. Thus this final geometry reduces the lateral divert activity because of reduced closing velocity.

From the standpoint of testing dynamically coupled response, trajectory "c" is preferred. It requires a longer or identical divert baseline but shorter initial range since a target range of 20 to 30km may be difficult to implement. If the constraint is to reduce the divert baseline, then trajectory “d” may be a good compromise since it preserves the LOS rates.

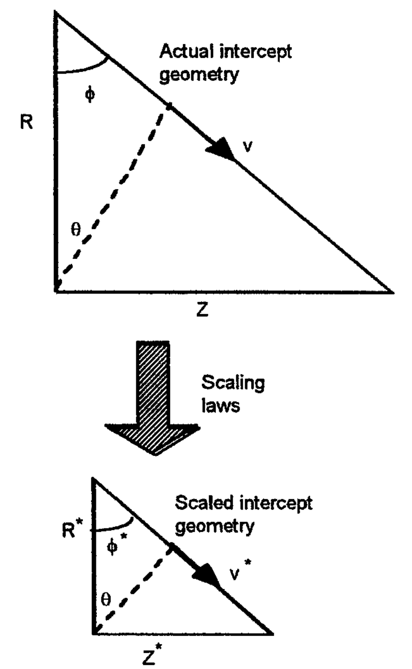

Figure 7 Scaling laws for ground experiments

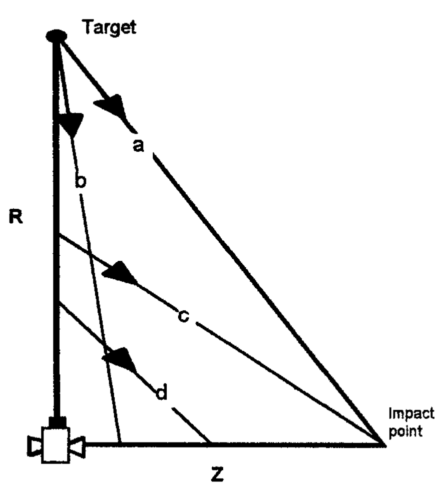

Figure 8 Effects of different scaled experiments with preserved time-to-go: (a) original trajectory, (b) goal tending, (c) transient LOS rate response, and (d) preserving LOS rate.

Air-Table Guided Intercept and LOS Experiments (AGILE)

Figure 9 depicts the basic experimental setup of AGILE. It consists of the following key components: (1) a test vehicle capable of generating five degree-of-freedom motions (three rotations and two translations), (2) a dynamic air bearing which can float the test vehicle on any low friction smooth surfaces, (3) a glass table measuring more than 3m x 10m on which guided intercept and LOS experiments can be conducted (dimension of the table can be increased to meet the specified needs), (4) a target projection laser, (5) a target projection screen, and (6) not shown in the figure is a target tracking system yielding a test vehicle's instantaneous position and attitude needed for real-time target projection.

The principle of operation of AGILE is as follows. Using the scaling laws discussed in the previous section, a closing target whose position as a function of time is defined and that its intercept point on the air-table is predetermined. At the onset of the guidance experiment the test vehicle would acquire, track, and lock onto a projected target on the screen from the target generator. The projected target is continuously calculated from the instantaneous LOS vector based on the predefined target location and the measured test vehicle position from the vehicle position tracking system. The test article onboard guidance and control software will attempt to reduce the ZEM to zero by generating appropriate divert actions. When the time-to-go clock reads zero, a miss distance is obtained from the difference between the instantaneous test vehicle's cg position and the intercept point.

Dynamic Air Bearings

The concept of a dynamic air bearing (DAB) is to integrate translation motions into a traditional three degrees-of-freedom angular motion air bearing. This enables a vehicle, sitting on the hemispherical air bearing and equipped with divert engines and attitude control jets, to achieve a five degree-of-freedom motions: three rotations and two translations. A fixture of the DAB is shown in Figure 9. The hemispherical air bearing draws air from the three high pressure tanks, which also supply air to the three air pucks. The air pucks provide a cushion of thin air between it and any smooth surfaces such as a thick glass table. The three air pucks, equally distributed on a 7.5" radius circle, can support a total weight of more than one hundred and fifty kilograms. The DAB itself weighs less than five kilograms. For a twenty-five kilogram lightweight interceptor, this represents a 20% increase in overall weight or equivalently a 20% reduction in acceleration capability[6].

Air-rail Guided Intercept and LOS Experiments

Previously we described a DAB operating indoors on a smooth glass table. While the indoor tests have many appealing qualities, it also creates additional limitations that could affect the fidelity of the test. Chief among them is the potential coupling of the vehicle motion measurement system and the projection system dynamics to the line-of-sight vector. Additionally, the relative short translational baseline (20m) most likely will be inadequate to generate sufficient lateral divert burns in both frequency and duration to mimic the actual divert burn schedule of a real flight experiment. If the dynamic structural coupling between divert and LOS stability of a high agility intercept vehicle is the key issue [1], then it is important that we use a forcing function that would excite similar structural resonance modes of the vehicle and its onboard seeker hardware as in a real flight experiment.

An outdoor DAB implementation that floats a vehicle on a smooth 40m rail is shown in Figure 10. The intent of this implementation is to eliminate some of the limitations of the indoor system and simultaneously provide a much longer divert distance. We believe that 100m to 200m diverts are technically feasible since the rail system is linearly extendable and can be built at low cost. The 4DOF DAB can be designed to capture the vehicle to the rail so that a multi-g interceptor could not "fly-away" from the apparatus as it could from (or with) a 5DOF DAB on an air table. A vehicle which does not provide access to its cg could still be flown with this system by mounting an external gimbal or air bearing assembly (several spherical pads) around the central body of a vehicle.

The outdoor rail system eliminates the requirement to project the target against a relatively close flat projection screen. Instead an actual closing target can be simulated on a target range that is several kilometers to several tens of kilometers long, eliminating the perspective problem found in the indoor system. It also removes to a large extent the vehicle divert acceleration limitation. For testing a high g vehicle on a rail, the additional mass of a DAB system is a lesser concern and because of the short test timelines and constrained geometry (4DOF) the DAB itself can be significantly light-weighted compared to a 5DOF DAB. It is estimated that a high performance 4DOF DAB could mass less than 1.5 kg, which will have even less of an impact on the acceleration of the interceptor vehicle. The greater velocities that result from these longer divert distances may however, introduce some effects from aerodynamic coupling that

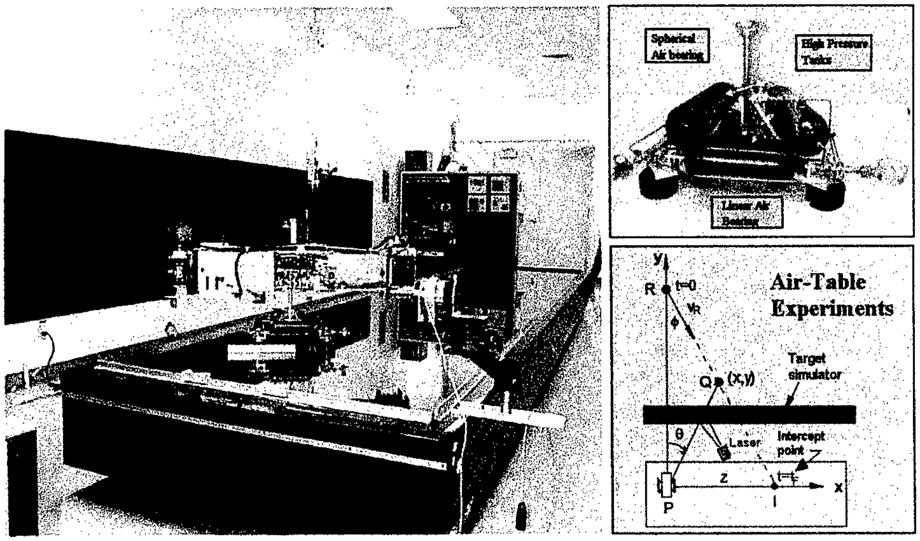

Figure 9 Key elements of an air-table guided intercept and LOS experiment

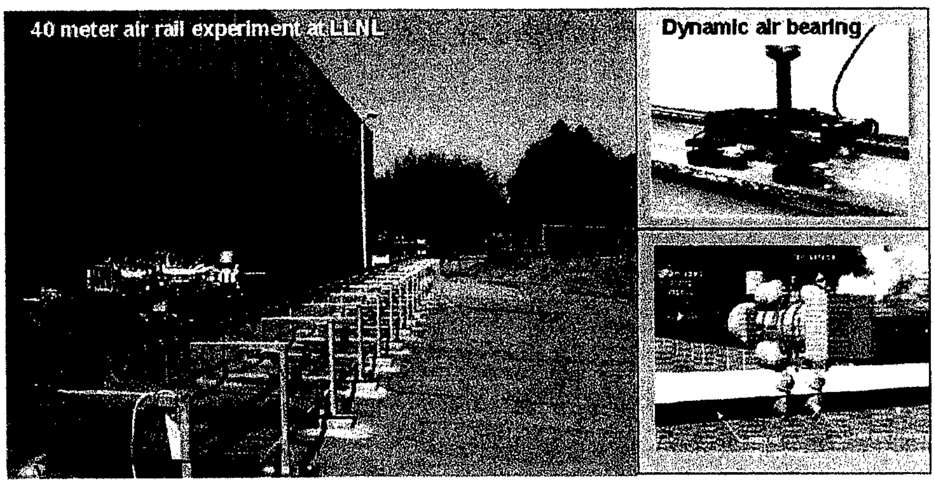

Figure 10 Key elements of a 40m outdoor air-rail guided intercept and LOS experiment

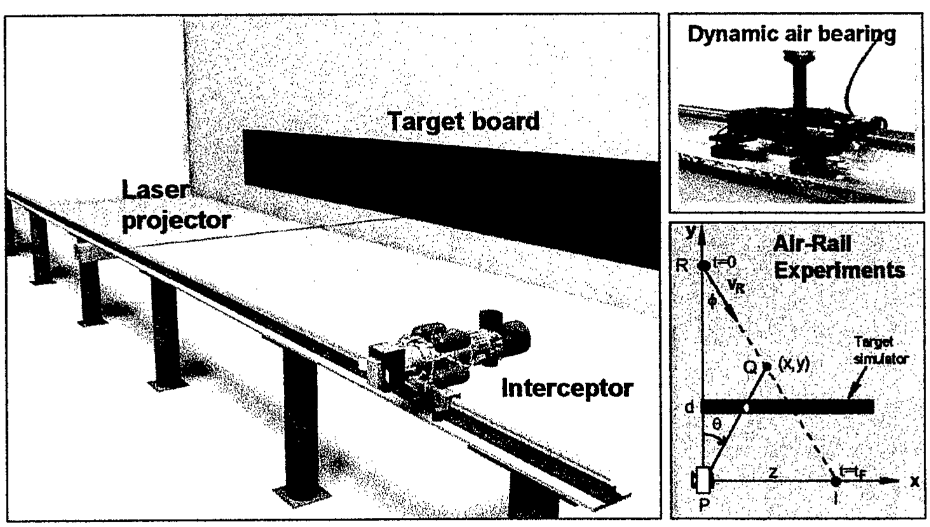

Figure 11 Key elements of a 20m indoor air-rail guided intercept and LOS experiment

could prove to be an issue and warrants further investigation. Although the rail limits the translation to one dimension, it provides a much more accurate (~mm) tracking of the vehicle position and thus allow a more precise reconstruction of the referenced LOS vector - a key attribute in debugging an interceptor's ability to predict the correct intercept point and thus affecting the miss distance performance.

The reduction from a 5DOF to a 4DOF test, appears at first glance to be a significant reduction in fidelity of the test, as compared to a 5DOF test. However, when examining the typical closing velocity scenarios for a typical intercept, one finds that any thrust components off-axis (of the rail) result in lowered on-axis components which directly are manifested in an increased miss-distance and any small accelerations (and resulting displacements) of the vehicle toward or away from the target are lost in the noise when compared to the high closing velocities of the intercept (3 to 10 km/s). In fact in cases where the interceptor divert thrusters are canted forward to compensate for aerodynamic flow field effects that rotate the divert thrust backwards, the air-rail is ideal to pin the vehicle to a lateral trajectory (at a lower divert thrust) that better simulates the intended lateral flight trajectory of the vehicle.

Previously[1] we have used a 13 km long sequence of lights, representing the path of an actual incoming target, to fly a divert experiment against using a long tether to support the vehicle. A limitation of using a fixed sequence of lights is the need to synchronize the seeker integration to the target light's on-times. However, we can overcome this problem by borrowing from the indoor DAB experiment and using a laser projection source to simulate the target. In this case we propose to project it against a long target board that is placed along a target trajectory path (just like the long row of lights) and we now illuminate this board with the laser projection source. One can consider projecting both visible and IR (SWIR-LWIR) CW laser sources and scan them along the target board generating an actual closing target source that moves along the board generating an actual closing target source that moves along the board toward the intercept point as shown in Figure 10. In addition one can consider both spatial and temporal modulations of this source to more accurately simulate a variety of targets. By using a light valve projection system, and the laser as the illumination source, one can generate actual simulated target images that will enable the interceptor to view a resolved image and to perform fine scale targeting for kill enhancement. Resolved imagery will enable the coupling of the divert experiment to seeker discrimination issues. Various backgrounds and clutter environments can be projected along with the target signatures and shapes to enable the highest fidelity end-to-end test prior to an actual flight experiment.

One additional criticism of either a air track or tethered system is the loss of the cross coupling of a vertical divert into the lateral LOS of the seeker. By constraining a vehicle to move in either a plane or line and not providing the vertical diverts that would nominally occur in an unconstrained 6DOF environment, these inputs will not be observed. However, structural cross coupling will be seen from the main lateral thrusters in an orthogonal (vertical) motion of the vehicle structure and visa versa. So even though the vehicle is vertically constrained cross coupling to vertical bending motion of the vehicle can be excited and observed. If vertical jitter is observed, than one can expect that comparable perturbations would be found in the lateral axis due to a vertical cross coupling. Rotating the vehicle 90 degrees and comparing the vehicle's performance in this orientation can also to be used to determine the structural symmetry and performance in the orthogonal axis. If we consider the basic lateral divert as a zeroth order term in a series expansion, then all first order terms can be accessed with a Dynamic Air Rail. However, some of the second order terms would not be accessible due the two translational axes being frozen out. By observing the size of the terms we can determine whether these will degrade the interceptor's performance.

The Clementine II Forerunner Test Vehicle

Using residual hardware from the successful Clementine I project, a forerunner test vehicle (see Figure 12) was designed and integrated as a software test bed. It is being used as a test article for conducting the AGILE experiments. This test vehicle weighs about 20 kg and is approximately 1.2 m in length. It is equipped with an onboard Power PC 603e processor, a Litton LN-200 IMU, a wireless ethernet link, Ni-Cad battery packs, a Star Tracker, a visible seeker, and a video camera. It is powered by high pressure cold gas capable of achieving a 0.1 m/s^2 acceleration and has a total Δv of approximately 50 m/s. The current software is capable of executing several target acquisition, tracking, pointing, divert and guidance experiments.

Interceptor Dynamically Coupled Response Experiments

As was mentioned, the coupling effect between vehicle divert and LOS jitter is a major limiting factor for a class of modern interceptors utilizing quick reaction divert engines. We have postulated that miss distance will be a function of vehicle's agility measured in terms of the gdot (or jerk) variable. Gdot can be affected by a vehicle's different g capabilities for a given reaction time or varying reaction times for a given g capability. It would be insightful to conduct such an experiment to obtain the vehicle's dynamically coupled response curve. Furthermore, for developing even more agile interceptors to go against higher closing velocity or maneuvering threats, future vehicle development may require another order of magnitude increase in g capability [7]. This will further amplify the dynamically coupling effect between agility and LOS stability.

As a first attempt to measure the DCR curve, we built a 20m indoor air-rail system as shown in Figure 11. Using a prototype micro-satellite vehicle as an initial test article, we conducted a series of guided intercept and LOS experiments at three different divert acceleration levels: 15mg, 35mg, and 75mg. The AGILE experimental results were compared to 6DoF monte-carlo simulations. Excellent results were obtained on LOS parameters and miss distances as shown in Figures 13a and 13b.

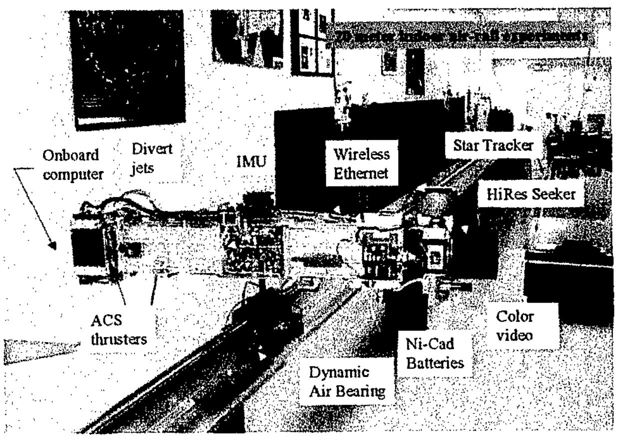

Figure 12 Prototype forerunner vehicle used for the AGILE experiments

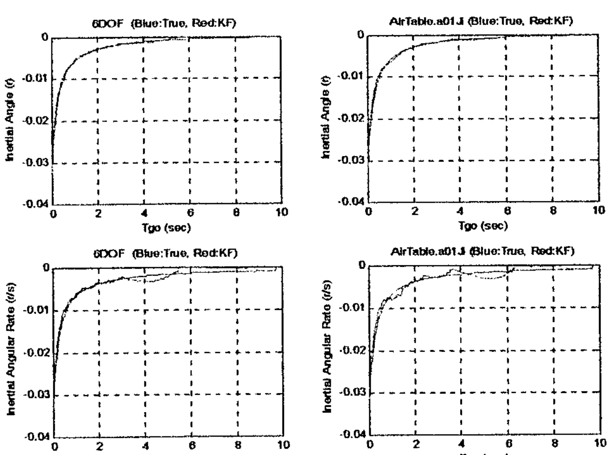

Figure 13a AGILE LOS rate prediction versus 6 DoF runs

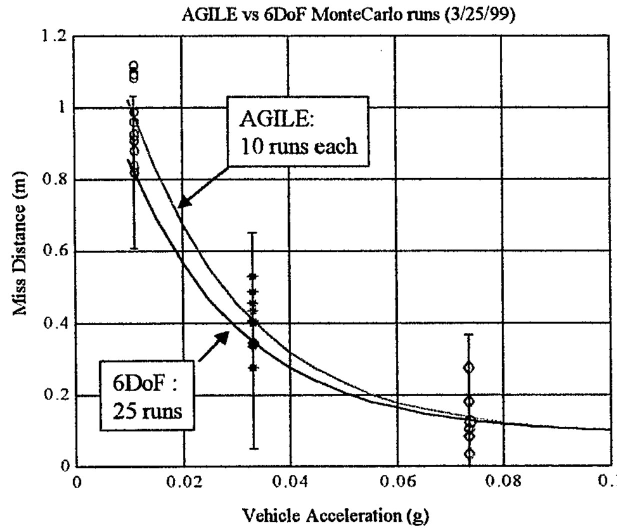

Figure 13b Dynamically coupled response curve obtained from AGILE experiments (Guidance update rate = 20 Hz)

Other Guided Intercept and LOS Experiment Approaches

One of the main technical objectives of the ground test experiment is to exercise key software and hardware functionality of a vehicle under a realistic, cost effective, test environment. For an exoatmospheric interceptor or micro-satellite functioning in near earth space, the key criteria for a realistic environment is that the vehicle must be operating in a zero g free floating space. This can be accomplished in many different ways - each with its set of advantages and disadvantages. The key therefore is to understand fully the limitations of the test environment and the correlation of ground experimental results to actual flight test objectives. As was mentioned in section III of this report, one could define a general guideline in that a good ground experiment is one that minimizes any changes in flight hardware and software configurations and provides a test scenario that can best mimic the actual flight geometry and operation.

There are three approaches to achieve a "zero g" environment on the ground: (1) Dynamic Air Bearing Test, (2) Captive Tether Flight Test , and (3) Hover Flight Test. DAB is an apparatus that achieves a zero g environment by floating the test vehicle and the DAB itself a few tens of micrometers above any smooth surfaces. Captive Tether Flight achieved the same objective by suspending the vehicle on a long tether. Hover Flight achieved the zero g environment using vehicle's own vertical divert thrusters [8]. The following paragraphs briefly comment on the technical merits of each approach.

Captive Flight Test at Nevada Test Site

In early 1993, a team of engineers and technicians from Lawrence Livermore conducted a series of guidance and control experiments with a "Brilliant Pebbles" like exo-atmospheric interceptor at the Nevada Test Site[1]. A test vehicle hung from a 500m tower with a tether through its cg, experiences an essentially zero g environment if the vehicle motion can be restricted to less than 20m. Figure 14 summarized the intercept timeline and geometry. Figure 15 shows example of tether flight results. Figure 16a shows an artist drawing of the Nevada Bren Tower Tether Facility. Figures 16b to 16d show the vehicle from various stages of the guidance and control experiment. The intercept point is 20m to the right of the vehicle determined by the exact passage of an incoming accelerating target represented by a series of lights. The lights were designed to synchronize with the frame rates of the onboard seeker. Note that the first light is at 13 km away and is simulating a head-on target. At 12s into a 30s flight, the target changes its heading to miss the interceptor at 20m away. This experiment tested the interceptor's ability to detect the changes in LOS angle and divert appropriately to the intercept point. Figure 16d shows the successive reduction in miss distances and the NTS experiments achieved a submeter intercept in ten flights.

A major problem which was discovered and which prevented a submeter intercept early on in the test sequence, was the effect of dynamic coupling between divert and LOS. These data were directly obtained from the flight telemetry data base. Development of an approach to reduce the dynamic coupling effect is what made the final submeter intercept flight realizable.

Time (sec)	Vehicle	Range
-120	• Software download	• Initial range, beacon on
-40	• Gyro/accel calibration	-
-30	• Vehicle release and stabilized	-
-20	• Vehicle searches for target	-
0.0	• Detect ignition, 9-state track	• Ignition beacon
12.5	-	• Range "actually" moves
20.0	• Lidar handover if on	• Beacon at 5 Hz
22.0	• Begin guidance	-
25.0	-	• Beacon at 10 Hz
30	• Intercept	• Photo finish

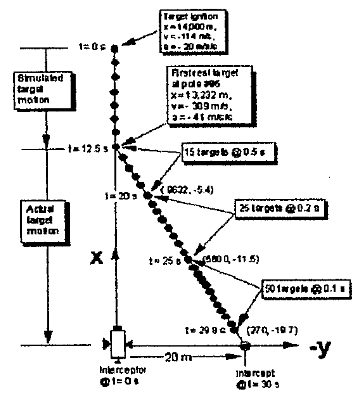

Figure 14 Tether guided intercept and LOS experiments at the Nevada Test Site

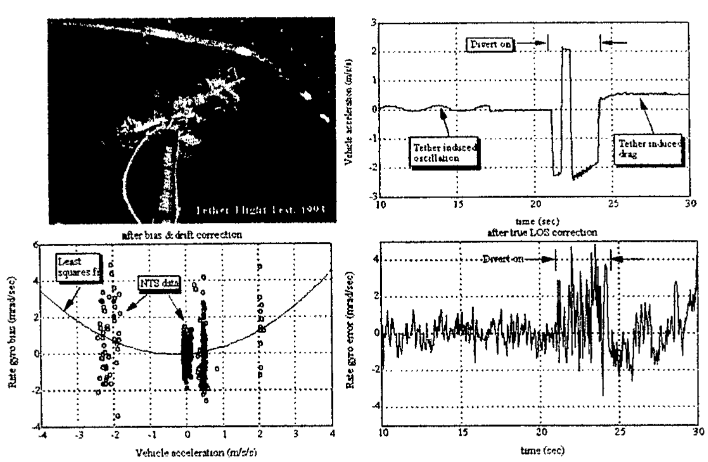

Figure 15 Examples of tether guided intercept and LOS experiment result

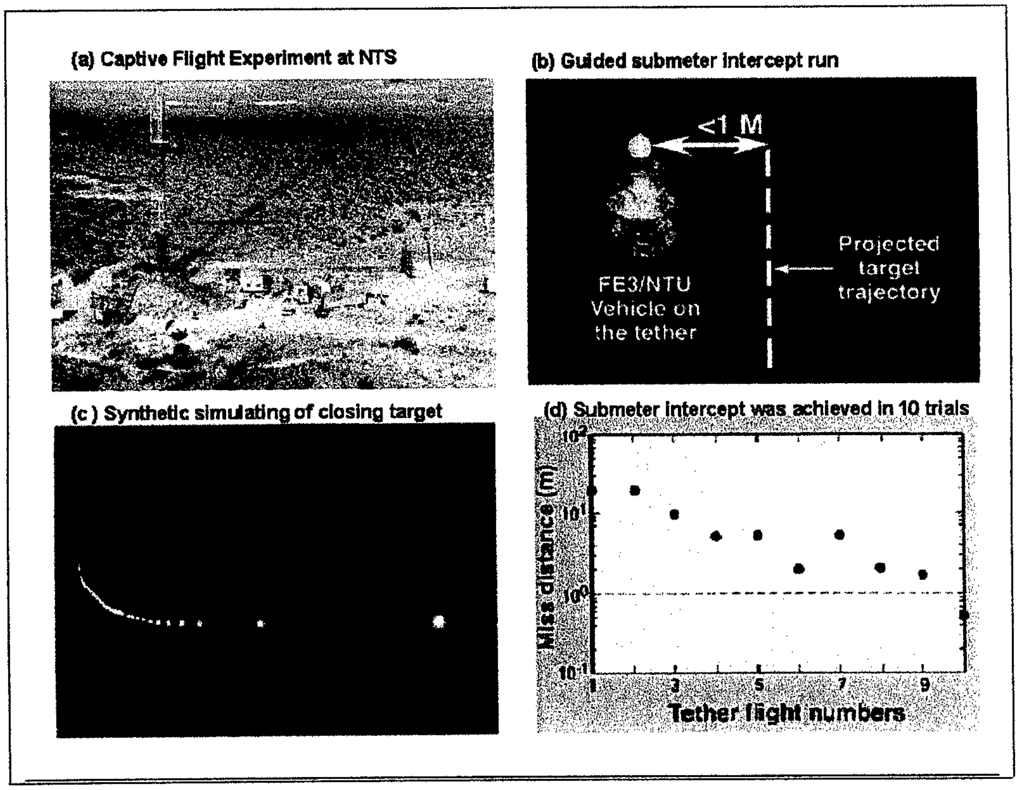

Figure 16 Tether Flight Experiments at Nevada Test Site : (a) Bren Tower Setup, (b) Guided intercept run, (c) Synthetic target, and (d) Submeter intercept experiments

Hover Test Facility

Another approach to achieve a near zero g condition is to suspend the vehicle in mid-air using the vertical divert thrusters as shown in Figures 17. This requires that the vehicle must have greater than one g divert capability. Hover Test is a good test to evaluate a vehicle's propulsion and to a lesser extent the attitude control system, it is not a closed loop guided experiment without a closing velocity target as is currently implemented at the National Hover Test Facility. Principal disadvantages of the Hover experiment are: (1) the coupling of the angular dynamics and translational dynamics by the vertical thrust control system, makes the test environment deviate significantly from actual space flight; (2) a limited (~3m) divert baseline due to various safety concerns and expenditure of Δv on g cancellation, consequently the test vehicle could not generate large divert pulses similar to a real intercept flight ; and (3) a non-closing target so software to estimate the heading error and the zero effort miss distance can not be evaluated.

As mentioned in previous paragraphs, the ideal ground test is one that mimics as closely as possible the actual exo-atmospheric flight environment. The Hover test unduly coupled the translational and rotational dynamics through the fact that when the vertical divert force is tilted with respect to the local gravity vector, the vehicle will accelerate both axially and laterally. Test vehicle acceleration can be translated to a target acceleration and coupled directly into the guidance and control loop. This coupling effect between and vehicle rotation and translation is an artifact not experienced in a free space environment.

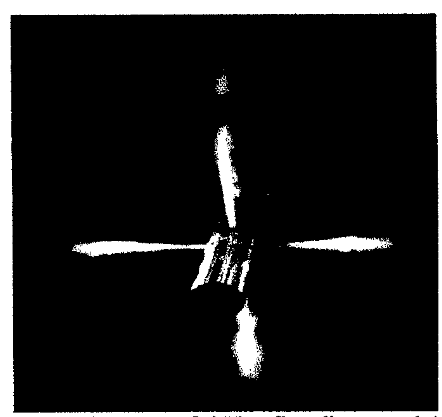

Figure 17 A successful Hot-fire divert and ACS propulsion test of a KKV at the Hover facility

Air-drop Guided Intercept and LOS Experiments

In order to gain a full 6DoF maneuvering capability for the kill vehicle, a drop test can be considered. Figure 17 shows that an interceptor-like vehicle is being dropped from a tall tower and maneuvered freely to intercept a simulated incoming target projected on a target board. The free fall essentially provided a "zero" g operational environment. The test vehicle is to be captured by an air-bag-like system so the vehicle can be reused for additional experiments. This concept is still very much in the conceptual stage. Engineering details like: means to minimize the aerodynamic effect, high g vehicle capture and recovery system, and the design of the target board etc. are still yet to be developed.

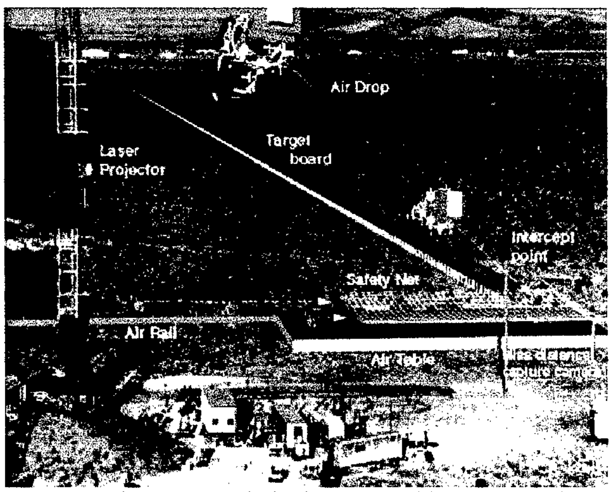

Figure 17 A conceptual air-drop guided intercept and LOS experiment setup at Nevada Test Site

Summary and Conclusions

We have examined the fundamentals of hit-to-kill intercept performance requirements and concluded that the critical factor for a modern interceptor to achieve a submeter intercept is its ability to obtain precise line-of-sight angular rate estimates in the presence of divert actions. Because of the enormous expenses in conducting an actual flight experiment, we proposed several cost effective ground test alternatives to improve the intercept assurance of an actual flight test. We have also examined the scaling laws that optimize the effectiveness of a ground test. We concluded that a longer divert baseline is most useful to provide a realistic forcing function to excite the broadband structural response of the vehicle and other onboard instruments to address the LOS rate stability problem.

We have also concluded that the best ground test environment is one that mimics, as close as possible, the free floating environment of an exo-atmospheric flight. To this end, we have designed, developed and implemented a dynamic air bearing apparatus that allows a test vehicle to float a few tens of micrometers above a smooth surface and achieves a five degree-of-freedom motion. A prototype vehicle supported by a dynamic air bearing operating on a 20m air-rail was successfully tested indoors. A series of AGILE experiments were conducted to demonstrate operability. A discussion of the various scaling options for a ground test has been presented and a comparison of several previous methods of interceptor ground testing has been made. We propose an extension of the 5DOF air-table to a much longer 4DOF air-track apparatus that provides a 100m or more divert, that operates outdoors against a synthetic moving target made up of a projected laser source illuminating a long slanted target board. This approach is proposed for testing vehicles with greater than one g propulsion capability.

Acknowledgements

We acknowledge and appreciate the support received from Joe Kordas, Jeff Robinson, Darron Nielsen, and Bill Taylor of the LLNL MicroSat team in the preparation of the AGILE experiments reported here.

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