THE EFFECT OF AIRCRAFT BIASES ON THE DELIVERY OF AN ENHANCED LASER-GUIDED WEAPON

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Abstract

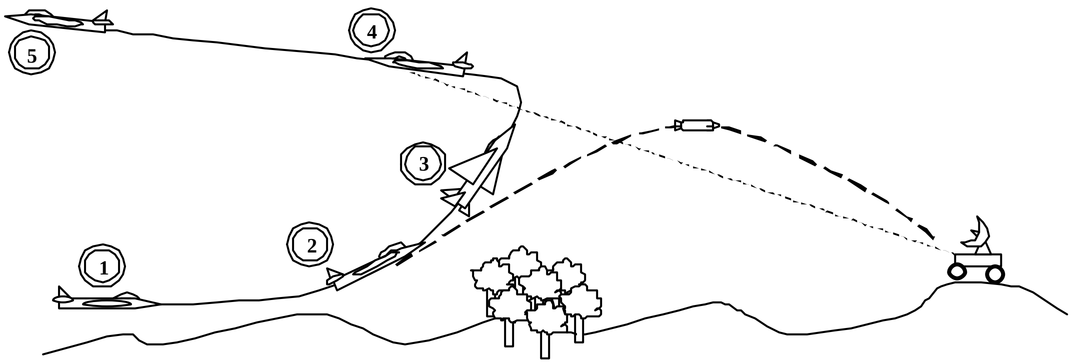
In this paper, a simulation is used to examine the sensitivity of enhanced laser-guided bombs to errors in the navigation system of the delivery aircraft. Three possible weapon configurations are considered: a laser-guided bomb with an autonomous inertial navigation system, a laser-guided bomb with a loosely-coupled inertial navigation system and global positioning system, and a standard laser-guided bomb model (which is included for comparison). The analysis considers different modes of delivery, medium-level level-flight and low-level toss deliveries, and demonstrates that the accuracy of the navigation system of the delivery aircraft plays a significant role in weapon system performance.

1 Introduction

This paper examines the limitations placed on the use of enhanced laser-guided weapons due to the presence of systematic biases in the aircraft navigation and weapon aiming/targeting systems. The paper uses a simulated model to consider a range of delivery profiles, including low-level ingress followed by a pop-up/toss manoeuvre, and discusses methods for mitigating the detrimental effects of the aircraft biases on the delivery of an enhanced laser-guided weapon.

For the purposes of this paper, the aircraft is assumed to be a fast jet with a relatively sophisticated air-to-ground capability based on a combined Forward-Looking Infrared (FLIR) pilot flying aid/navigation system and an advanced targeting system with a laser designation capability, similar to (but not the same as) the US LANTIRN system fitted to the USAF F-15E Eagle and the F-16 C/D Fighting Falcon. In addition, the aircraft is assumed to have a modern navigation system based around an integrated Inertial Navigation System (INS) and Global Positioning System (GPS).

The enhanced laser-guided weapon simulation models the behaviour of an unpowered, ballistically-delivered weapon with a laser seeker and an autonomous weapon-grade navigation system, which could either be purely inertial or an integrated INS/GPS system. It is assumed that the weapon's navigation system is aligned to the aircraft systems immediately prior to release. In doing so, the weapon navigation system inherits the systematic errors present in the aircraft navigation and targeting systems, including errors in the position of the release point, the release velocity, the aircraft attitudes and angle rates, the alignment of the targeting/laser designation systems and the estimated target location.



1. Ingress 2. Release 3. Target Acquisition 4. Target Tracking & Laser Designation 5.Egress

Figure 1 – Schematic diagram showing the five phases in the low-level delivery of an enhanced laser guided weapon.

The delivery consists of five separate tasks: ingress, release, target acquisition, target tracking and laser designation, and aircraft egress (see Figure 1). In the case of low-level ingress, the target may not be visible to the delivery aircraft at release, so the release occurs prior to target acquisition. For medium-level deliveries, target acquisition and tracking would normally occur before release, but the target track may be lost (due to errors in the tracking loop or the presence of low-level cloud cover) and require the target to be reacquired during the weapon flight. Both of these cases pose a number of problems for the weapon guidance system depending on which phase of the fly-out the weapon is in, and which of the sensors (navigation system or seeker) is taking the primary role. In this, the enhanced weapon differs from a standard laser-guided weapon, where the seeker is the primary sensor. The paper examines the conditions for optimal weapon guidance, and their dependence on the systematic aircraft errors and the effect of the different error sources on the ability of the

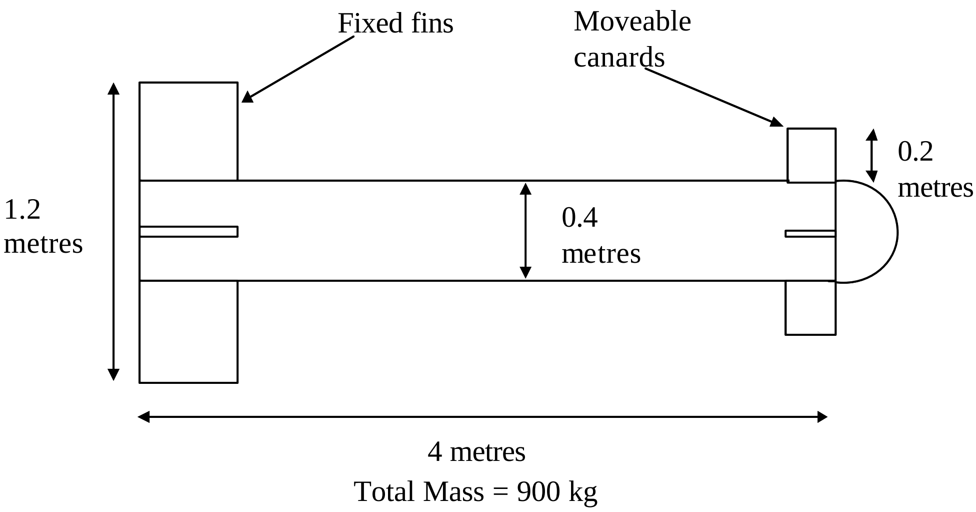


Figure 2 - Physical dimensions and general configuration of the enhanced laser-guided weapon.

weapon to derive a valid weapon guidance solution. The weapon performance is characterised in terms of the effective size of the release envelope and the fraction of releases that fall within 15m of the target (chosen to be the nominal circular error probable for this study). The majority of weapons fall within 15m of the target are considerably closer to the desired impact point than 15m, but some lose the laser spot just prior to impact which tends to reduce the accuracy of the simulation model.

2 System

The system that was studied was loosely based around the Paveway III (United States GBU-24/B [1]), which is a 2000lb Laser-Guided Weapon, and the enhanced Paveway III (United States GBU-24E/B [1]), which has an added autonomous navigation capability. However, the simulation is kept as generic as possible to reduce the introduction of system specific effects, and because the amount of technical information that has been published in the open literature about the Paveway series weapons, and the properties of laser-guided bombs in general, is comparatively small. The main difference between the model reported here and the Paveway III systems is that the guidance algorithm used in the model is a predictive proportional navigation algorithm, based on an idealised six-degree of freedom model, rather than a conventional proportional navigation algorithm. This difference means that the algorithm used in the model is more sophisticated and more computationally expensive than the one used in the operational system.

The physical configuration of the weapon under consideration is shown in Figure 2. It consists of a cylindrical weapon body, a hemispherical nose (containing a window for the seeker), four fins mounted in a X-formation at the rear, and a set of four canards mounted in an X-formation just behind the hemispherical nose, and through which the guidance controls are applied. For simplicity, the weapon is assumed to be rigid and the weapon sub-systems and payload are assumed to be distributed so that the average density of the weapon body is approximately uniform. The second assumption is used to allow the weapon centre of mass, and the moments of inertia about the centre of mass, to be calculated without specifying the precise position of each of the sub-systems.

2.1 Dynamical Model

The release of the weapon by the aircraft is characterised by an equivalent ejection velocity, as is common for the delivery of unguided air-to-ground weapons. After its release, the dynamics of the weapon are described by a conventional, six degree-of-freedom model for a rigid airframe [2]. This model includes atmospheric drag, based on typical values for the appropriate drag coefficients [3] and the NASA standard atmosphere [4]. The ballistic model includes small variations (c. 1-2%) around the standard parameter values, such as mass, drag and the centres of mass and of pressure, assumed to be due to imperfections or variations in the weapon, as well as variations around the standard atmosphere due to temperature variations and/or differences in the prevailing weather conditions.

2.2 Guidance Algorithm

The guidance algorithms are based on predictive proportional navigation algorithms described in reference 5. The algorithms navigate to an estimated target location, before attempting to lock onto the laser signal reflected from the target. Two specific algorithms are required: one for the basic laser-guided weapon without an autonomous navigation capability (but with a 3-axis gyroscope system that provides attitude information), and one for the enhanced weapon (with a simple INS or a combined INS/GPS system). In the absence of an autonomous navigation system, the weapon estimates its current position and anticipated miss-distance based on an idealised dynamical model (a simplified version of the full dynamical simulation model, not including system to system variations). When containing an autonomous navigation system, the weapon estimates its current position and anticipated miss-distance based on the position and velocity information provided by the navigation system.

The guidance algorithm is chosen to provide a near-optimal guidance solution so that the behaviour of the system will be dominated by the physical limitations of the airframe and the accuracy, or inaccuracy, of the navigation systems present in the weapon and aircraft. In this respect the weapon model used for this paper is different from the Paveway series of weapons, which are reported to employ proportional navigation guidance [1].

2.3 Navigation System Model

The basic laser-guided weapon is assumed to have a 3-axis gyroscope system to provide attitude information but no accelerometers to provide velocity and position information. The enhanced weapon has a full inertial measurement unit (IMU), and possibly a GPS receiver. The simulated INS is based on the performance figures given in reference 6. The GPS is loosely coupled, so that the GPS position updates received in flight are used to update the navigation position, limiting the drift of the INS in position, but not affecting the other navigation states. It is assumed that the weapon inertial navigation system will be initialised and aligned to the aircraft systems prior to release, and that any biases in the navigation solution of the aircraft will be added to those of the weapon navigation system. Although the alignment of weapon-grade inertial navigation systems to high grade aircraft systems is an area of current research [7], for the purposes of this paper it is assumed that the alignment process is 'single shot' (i.e. the position and attitude are downloaded at a single instance immediately prior to release, rather than as a series of measurements aimed at providing estimates of the systematic IMU biases).

Basic System Parameters	**Parameter Values (all errors 1s)**
Mass	900 kg
Length	4.0 m
Diameter	0.4 m
Fin Area	0.16 m^2
Canard Area	0.04 m^2
Maximum Fin Deflection	20 degrees
Guidance Frequency	10 Hz
Inertial Measurement Unit Errors	
Accelerometer Non-Orthogonality Errors	0.1 mrad
Accelerometer Scale Errors	0.03 %
Accelerometer Fixed Bias Errors	206 μg
Gyroscope Non-Orthogonality Errors	0.1 mrad
Gyroscope Scale Errors	0.01 %
Gyroscope Fixed Bias Errors	2 μrad
Seeker Parameters	
Waveband	Near Infrared (1.064 μm)
Field of View	30 degrees
Error in Alignment to Missile Axes	0.05 degrees
Aircraft Navigation System and Transfer Alignment Biases	
Aircraft/Alignment Position Biases	10.0 m
Aircraft/Alignment Velocity Biases	0.1 m/s
Aircraft/Alignment Angle Biases	0.2 degrees (heading) 0.1 degrees (pitch/roll)
Aircraft/Alignment Angle Rate Biases	0.01 mrad/s

Table 1 – System parameters and typical error values.

2.4 Laser Designator Model

The laser designator is based on currently available systems [8]. The laser has an operating wavelength in the near infrared waveband, at or around 1.064 microns [1], and is collimated with an angular divergence set by the optics of the designator system. It is assumed that the laser signal is encoded, but this is not modelled explicitly. The designator is assumed to be on an aircraft whose trajectory can be modelled explicitly within the simulation or fixed relative to the target. The laser energy is calculated at the target and at the laser seeker assuming that the reflection from the target surface is purely diffuse [9].

2.5 Laser Seeker Model

The laser seeker model is based on a simulated infrared imaging system [10], but in this application it simply acts as a source for measurements of the line of sight angles between the airframe body axes and the laser spot on the ground. The relevant seeker parameters are given in Table 1.

The detection process is modelled simply. A real laser designator system incorporates a Pulse Repetition Frequency (PRF) code into the laser signal to ensure that the correct laser spot is being tracked. This reduces the sensitivity of the system to countermeasures and the risk of confusion if multiple laser designation systems are being employed and are operating in the same waveband. However, for simplicity, the model used in this study assumes that if the signal power received by the laser seeker is above the required threshold then the signal is correctly detected.

2.6 Aircraft Navigation System

The aircraft navigation system is assumed to be a coupled INS/GPS system. Such a coupled system id designed to produce accurate short term and long term position and velocity information. The positional errors accumulated by the inertial navigation system are limited by the addition of GPS data (the positional errors used in this paper are based on the published specification for the Global Positioning System [11]). However, although the platform attitude is also estimated, it is more difficult to limit the attitude errors accumulated by the inertial navigation system. The drift in heading error is generally the most severe because the errors in pitch and roll couple to the gravity vector in level flight (which can be used to correct the roll and pitch drifts). The system parameter errors are given in Table 1.

3 Delivery Profiles

Two standard delivery profiles were chosen for consideration in this paper: one medium-level delivery in level flight with no explicit manoeuvre, and one consisting of low-level ingress followed by a toss delivery under 3g acceleration. These profiles are intended to represent two possible scenarios for the use of a laser-guided weapon.

The medium-level delivery is specified by:

Aircraft height at release	approx. 20-25 kft
Speed at release	450 knots.
Aircraft climb angle at release	0 degrees.
Aircraft bank angle at release	0 degrees.
Target height (above sea level)	0 m.

The low-level delivery is specified by:

Aircraft height at release	300 m = 985 ft.
Speed at release	450 knots.
Aircraft climb angle at release	30 degrees.
Aircraft bank angle at release	0 degrees.
Target height (above sea level)	0 m.

4 Results

The results of the study were generated by uniformly selecting points from a three dimensional region that contains the release envelope (assuming level flight). These points are used as initial release conditions for the simulated weapon system. To speed up the calculations, the initial points are run against a weapon simulation with no errors, and the miss distance at impact is calculated. The set of points for which the impact is within 15 metres of the target are saved in a separate file and constitute the maximum reachable set, i.e. the set of release conditions that can generate a miss distance within 15 metres under ideal ballistic conditions. This set of points is defined by the physical limitations of the system rather than the errors inherent in the guidance or navigation system. The release envelope must therefore fall within this set, and the maximum reachable set can be used to explore the sensitivity to changes in the errors. The maximum reachable set calculated for this project contained around 1000 points. This set was then used to initialise the simulation for a set of different transfer alignment errors, for the three types of weapon considered: a standard LGB, an INS-enhanced LGB and a GPS/INS-enhanced LGB. An outline view of the maximum reachable set is shown in Figure 3.

There were three different sets of transfer alignment errors used: the standard errors given in Table 1, and one where all errors were half the size of those given in Table 1, and one where the errors were twice the size of those given in Table 1. In each case, it was found that the dominant error was the heading error, but there is insufficient space available in this paper to analyse the contribution from each error independently.

The results shown in Figure 4 correspond to the standard LGB configuration. The proportion of impacts that fell within the 15 metre miss distance is shown as a function of slant range at release. The performance for the standard LGB is fairly good for the case with small transfer alignment errors, indicating that the optimum performance of the system is approximately 100-85% of weapon deliveries that fall within the 15 metre required miss distance. However, the introduction of significant alignment errors affects the performance of the system to the extent that the number of deliveries within the required miss distance is approximately 80% for large (2×)

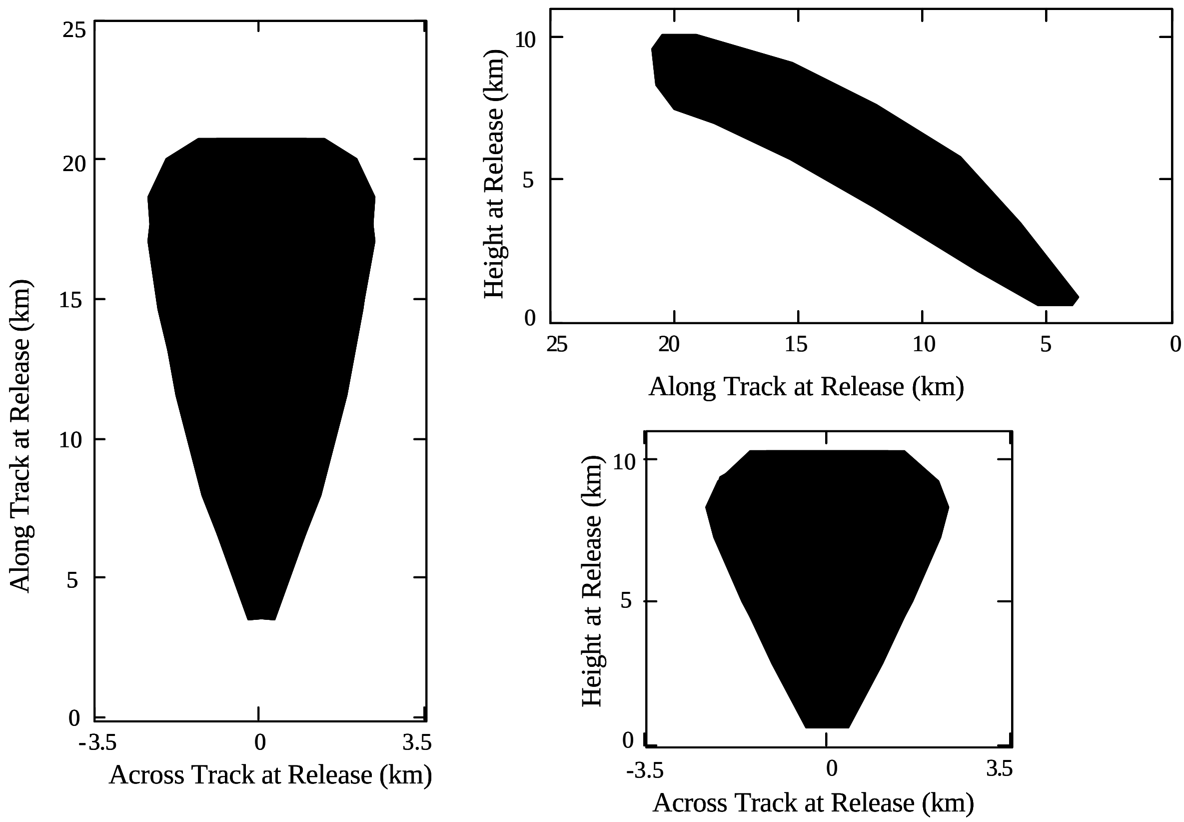


Figure 3 – Baseline release envelope/ maximum reachable set of the simulated laser-guided weapon in level flight.

alignment errors (dominated by the 0.4 degree heading error), and falls off dramatically at slant ranges beyond about 14 km.

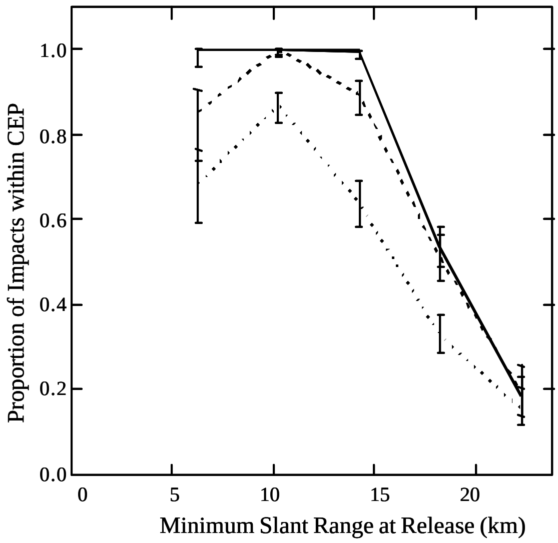


Figure 4(a) – Standard LGB release envelope as a function of slant range: 0.5 ´ errors (dashed), 1 ´ errors (solid), 2 ´ errors (dotted).

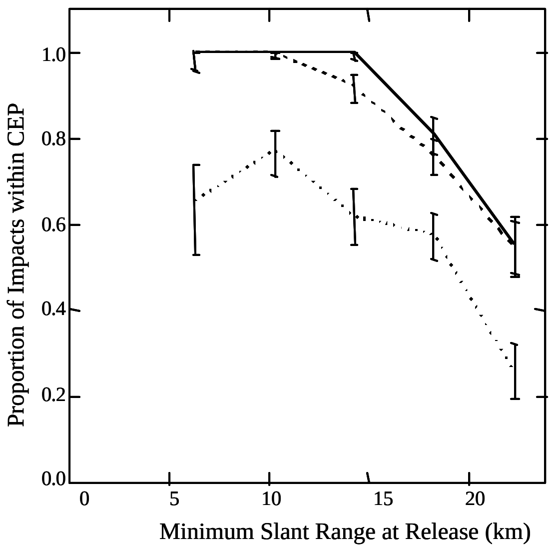


Figure 4(b) – INS-enhanced LGB release envelope as a function of slant range: 0.5 ´ errors (dashed), 1 ´ errors (solid), 2 ´ errors (dotted).

The INS-enhanced LGB shows less sensitivity to small transfer alignment errors, particularly at longer ranges. For the standard errors given in Table 1, the proportion of impact points within the required miss distance is 100-90% at ranges up to approximately 12-14 km, and even at extreme ranges (20+ km) the proportion of impacts within the required miss distance is around 60% to 50%, compared to 20% for the standard LGB. However, the figures for the INS-enhanced LGB are significantly reduced when the aircraft bias errors are increased to 2 × the standard errors (0.4 degrees heading error). The resultant performance is comparable with the standard LGB.

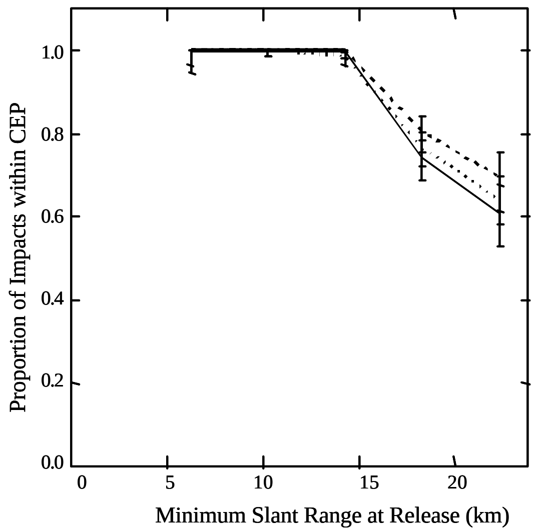


Figure 4(c) – INS/GPS-enhanced LGB release envelope as a function of slant range: 0.5 ´ errors (dashed), 1 ´ errors (solid), 2 ´ errors (dotted).

The GPS/INS-enhanced LGB results show no significant sensitivity to aircraft alignment errors. In Figure 4(c), the overall performance appears to be slightly reduced by the increased alignment errors, but the difference is within the 95% confidence intervals. As with the INS-enhanced LGB, there is a slight deterioration in performance as a function of slant range, but the releases that result in miss distances outside 15 m correspond to releases that are toward the extreme edge of the reachable set. The release points near boresight still produce impacts that meet the 15 metre requirement, even at ranges around 20 km.

The release envelope for the weapons at low-level and using a toss manoeuvre is much smaller than that for level flight at medium-level, and the maximum slant range to the target is consequently much shorter. However, the fact that the release envelope is reduced means that the time of flight of the weapon will be much less than the typical time of flight for a medium-level delivery. This means that the accumulated navigation/guidance errors will be reduced in the low-level delivery. Figure 5 shows the effect of 2 × standard errors on the release envelope for a low-level delivery for each of the three weapon types. The difference between each weapon is well within the 95% confidence intervals.

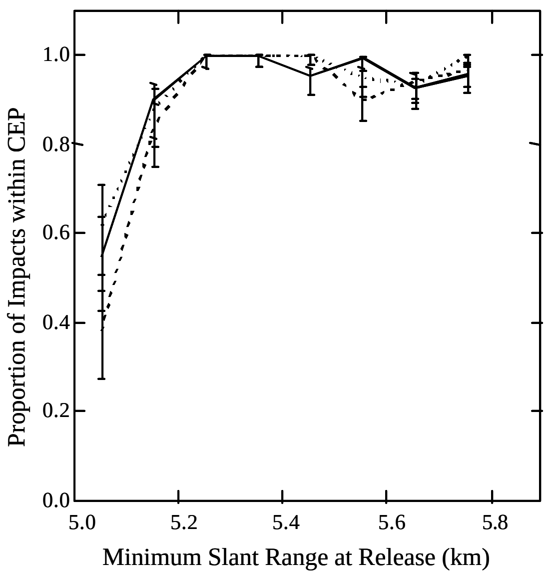


Figure 5 – Release envelope as a function of slant range for low-level toss delivery: standard LGB (dashed), INS-enhanced LGB (solid), INS/GPS-enhanced LGB (dotted) – all graphs use 2 ´ standard errors.

The enhanced weapons therefore offer better performance (in terms of their respective release envelopes) when released from medium-level. The potential advantages of an enhanced LGB in a low level delivery are not obvious from figure 5, but even where there is no significant improvement in the size of the release envelope, the enhanced laser-guided bombs offer significant advantages in terms of operational flexibility. The presence of an autonomous navigation system offers a default guidance solution without the correct laser signal being present within the field of view of the seeker, as might be the case where the laser tracking system is unable to track the target due to low lying cloud cover or obscuration of the target by ground clutter.

5 Conclusions

The study was concerned with the effect of aircraft bias errors on the performance of air-launched laser-guided weapons. The main aims were to evaluate the effect of aircraft bias errors on the performance of an enhanced laser-guided bomb, and the effect that errors are likely to have on the size of the release envelope for different types of laser-guided weapons: a standard LGB containing a three-axis gyroscope system, an enhanced LGB containing a full inertial navigation system, and an enhanced LGB containing an inertial navigation system that was augmented by a global positioning system.

The guided weapon model was loosely based around the available specification for the Paveway III and the enhanced Paveway III. Since the weapon configuration was only loosely based on the operational system, the release envelopes contained in this paper are not expected to be realistic or correspond to those of a real system. However, the general principles derived from this model, including the sensitivity of the release envelope to aircraft biases, are expected to be reflected in a real system.

As expected, the standard LGB proved to be quite sensitive to the aircraft bias errors, due to the transfer alignment of the weapon navigation system to the aircraft navigation system. The INS-enhanced LGB showed some sensitivity to transfer alignment errors, but the sensitivity was less than that found in the standard LGB. The overall performance of the INS-enhanced LGB was slightly better than that of the standard LGB (in that it has a larger release envelope), but it was still affected by transfer alignment errors and aircraft biases.

By contrast the GPS/INS-enhanced LGB showed no significant sensitivity to transfer alignment errors. None of the variations in the performance of the GPS/INS-enhanced LGB were significant at the 95% confidence level, and were typically much less than the error in the performance values. However, the baseline performance of the GPS/INS system was similar to the performance of the INS-enhanced system. The apparent insensitivity to transfer alignment errors is an advantage, but the additional complexity of a GPS/INS system is possibly only worthwhile if the heading errors are larger than about 0.2 degrees (1 standard deviation).

In all of the simulations, it was the size of the aircraft heading error that limited the ability of the laser-guided bomb to acquire and guide successfully to the target when inside the weapon's nominal (i.e. ideal) release envelope. There are several ways to limit the size of this error. One possibility would be to use GPS data combined with a dynamical model for the airframe [12], but a more conventional method would be to use information from existing aircraft sensors, such as the FLIR, to improve the accuracy of the aircraft attitude estimate by correlating the FLIR images with a database or satellite reconnaissance imagery using a scene-matching and area correlation algorithm [13]. This would have the added advantage that it also allows the accuracy of the aircraft targeting system to be improved, and allows multiple aircraft to correlate their navigation solutions to facilitate cross-platform data fusion [13,14].

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