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To the Graduate Council:

I am submitting herewith a thesis written by Shaun C. Spang entitled "An Analysis of Target Location Error Generated by the Litening Pod as Integrated on the AV-8B Harrier II." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Ralph D. Kimberlin, Major Professor

We have read this thesis and recommend its acceptance:

Alfonso Pujol, Rodney C. Allison

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Alfonso Pujol, Jr.

Rodney C. Allison

Acceptance for the Council:

Vice Chancellor and Dean of Graduate Studies

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2005
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AN ANALYSIS OF TARGET LOCATION ERROR GENERATED BY THE LITENING POD AS INTEGRATED ON THE AV-8B HARRIER II

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Shaun C. Spang
May 2005

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ABSTRACT

The modern battlefield continues to rapidly change requiring a quick, reactive, and precise strike capability by air forces. The Litening Pod (Tpod), as integrated on the AV-8B Harrier, can now be easily used by the pilot as a target coordinate generation source for global positioning system (GPS) guided weapons. This thesis has attempted to mathematically determine the target coordinate generation accuracy of the Tpod. The total mathematical target location error (TLE) was then compared to actual flight test data.

The analytical approach to calculating the accuracy of Tpod generated target coordinates has shown to be too conservative. This is due to no consideration being given to the possibility that errors are not necessarily additive in nature but instead will most likely cancel to some extent and also that performance of the Tpod is better than specified. Because of this, the analytical approach shows the Tpod coordinate generation capability is not good enough to meet the joint direct attack munitions (JDAM) specification at reasonable standoff ranges.

Actual flight test data shows the Tpod is able to meet the specification threshold for JDAM TLE inside 6 nautical miles (nm) slant range. The number one recommendation for minimizing the TLE for Tpod generated target coordinates is to fix the aircraft software to properly set the relative bit for Tpod targeting.

PREFACE

The technical data contained in this thesis are the result of system analysis and flight evaluations of the AV-8B Harrier II aircraft integrated with the AN/AAQ-28 Litening Advanced Targeting (AT) Precision Attack Targeting System. Where required, pseudo data have been inserted to preserve the classification of "real" AV-8B and Tpod capabilities and limitations. All deficiencies identified in this thesis are the opinion of the author and may or may not represent the official position of the Naval Air Warfare Center Weapons Division, Naval Test Wing Pacific, the United States Marine Corps, or the United States Navy. The conclusions and recommendations documented by the author should not be construed as attributable to any of the aforementioned authorities or for any purpose other than fulfillment of the thesis requirement.

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GLOSSARY

ADC. Air Data Computer.

AGL. Above Ground Level.

AT. Advanced Targeting

BOC. Bomb-on-Coordinate

CCD. Charged-Coupled Device.

CEP. Circular Error Probable.

DEG. Degree.

DoD. Department of Defense.

FT. Feet.

GPS. Global Positioning System.

H2.0. Harrier 2.0 Operational Flight Program

HAE. Height Above Ellipsoid.

IMU. Inertial Measuring Unit

INS. Inertial Navigation System.

JDAM. Joint-Direct Attack Munitions.

KM. Kilometer.

KTAS. Knots, True Airspeed

LAR. Launch Acceptability Region.

LB. Pounds.

LEP. Linear Error Probable.

M. Meters.

MAGR. Miniaturized Airborne GPS Receiver.

MIL-STD. Military Standard.

MPCD. Multi-Purpose Color Display.

MRAD. Milliradian

MSC. Mission Systems Computer.

MSL. Mean Sea Level.

NAWCWD. Naval Air Warfare Center, Weapons Division.

NM. Nautical Miles.

OFP. Operational Flight Program.

PER. Performance Error Rate.

PPS. Precise Positioning Service.

ROE. Rules of Engagement.

RMS. Root Mean Square.

RSS. Root Sum Square.

SEP. Spherical Error Probable

SPS. Standard Positioning Service.

STDDEV. Standard Deviation.

TDC. Target Designator Control.

TLE. Target Location Error.

TPOD. Litening POD / Litening Precision Attack Targeting System.

WGS-84. World Geodetic System 84 Datum.

1. INTRODUCTION

1.1 BACKGROUND.

JDAM are bomb-on-coordinate (BOC) weapons, which require the input of accurate target coordinates. Target coordinates can be transferred to JDAM through mission planning data transfer devices (pre-planned missions), through on-aircraft targeting systems (self-targeting), via in-flight data transfer devices, or manually through cockpit data entry devices.

The AV-8B can transfer target coordinates using all methods. When using the preplanned data transfer method, in-flight data transfer method, or entering coordinates through cockpit data entry devices, JDAM will be released using the target coordinates in an earth-based reference frame (absolute mode). If an onboard-integrated aircraft sensor is used as a source for the coordinates, the JDAM will be released using the coordinates in an aircraft-based reference frame (relative mode).

Most sensors on-board the AV-8B can only produce accurate enough coordinates to meet the JDAM specification for TLE well inside reasonable standoff ranges. With the introduction of the Omnibus Harrier 2.0 (H2.0) operational flight program (OFP) to the AV-8B, the Tpod is now fully integrated as a remote terminal on the aircraft military-standard (Mil-Std) 1553 Multiplex Databus Interface and treated as an integrated aircraft sensor. This integration allows the pilot and aircraft to seamlessly use Tpod generated coordinates as a targeting source for JDAM giving the AV-8B a potential self-targeting capability. Unfortunately when the Tpod was integrated, the relative targeting mode was not programmed correctly and therefore the aircraft cannot take advantage of relative

JDAM targeting when using the Tpod as the target coordinate source [1]. Because of this programming error, Tpod generated target coordinates will be used by JDAM as earth based (absolute) coordinates assuming the JDAM navigation source is the GPS. Because there is no relative JDAM mode using the Tpod as a sensor, all aircraft generated errors (position, heading, and bearing error) must be included in the TLE calculations for Tpod generated target coordinates. This makes the JDAM TLE specification requirements much more difficult to meet.

1.2 PURPOSE.

JDAM targeting specifies no greater than 13 meters (m) horizontal error expressed in circular error probable (CEP) and 15 m vertical error expressed in terms of linear error probable (LEP). Contained within the 13 m total horizontal error is an allowance of 7.2 m for TLE. Preplanned mensurated coordinates are normally the best source for a minimum TLE. Unfortunately, the process for producing mensurated coordinates is typically not quick enough to allow for timely prosecution of targets by tactical airborne platforms. On modern battlefields a timely reactive capability is a must due to the battlefield situation changing rapidly.

Therefore, the purpose of this thesis is to determine if the Tpod can be used as a source for generating precise enough target coordinates for delivery of JDAM reactively by an AV-8B even with the software error. An analysis of the total TLE generated by the use of the Tpod as integrated on the AV-8B with the H2.0 OFP will be performed for the absolute and relative modes of JDAM targeting.

1.3 DESCRIPTION OF THE WEAPON SYSTEM.

1.3.1 AV-8B Harrier II.

The AV-8B Harrier II is a transonic, single cockpit, single engine, jet propelled day or night tactical fighter built by Boeing (formerly McDonnell Aircraft). The aircraft is powered by a Rolls Royce axial flow, twin spool turbo fan engine. Four exhaust nozzles can be positioned and controlled for vertical/short takeoff and landing operations. The aircraft features shoulder mounted swept back wings with trailing edge flaps and ailerons. The flight controls are hydraulically powered to provide the desired control effectiveness throughout the speed range. The cockpit is pressurized and enclosed by a sliding canopy. It is capable of performing its mission at night by utilizing low-light attack capabilities. The aircraft is 47.75 feet long with a wingspan of 30.33 feet (FT). Its maximum gross weight is 32,000 pounds (lb) [3].

The AV-8B aircraft is designed for offensive air support and air defense missions. It is equipped to carry and deliver an assortment of conventional stores, laser munitions, air-to-air weapons, and JDAM from six wing stations and a centerline station. A 25mm gun system may be attached to the lower fuselage. The aircraft has night vision goggle compatible controls and displays. The AV-8B weapons system is managed in a single seat cockpit where the pilot controls aircraft flight, navigation, and attack systems.

The Omnibus H2.0 OFP was developed and installed in the AV-8B mission systems computer (MSC) in August 2003. Developmental testing was completed in October 2004 by the AV-8B Joint Systems Support Activity. The H2.0 OFP will undergo an Operational Test Evaluation by Air Test and Evaluation Squadron 9 prior to being installed in fleet AV-8Bs. The H2.0 OFP was the first OFP to incorporate the Tpod

as a remote terminal on the aircraft MIL-STD 1553 Multiplex Databus thus allowing for direct communication between the Tpod and the MSC [1]. This integration allows for a better aircraft to Tpod inertial navigation system (INS) alignment and direct communication of data such as target coordinates. A Tpod "designation" can now be used directly by the pilot with a simple press of the target designator control (TDC) switch located on the throttle. The coordinates and elevation will then be transferred directly to the JDAM at weapon release.

1.3.2 AN/AAQ-28 Litening AT Precision Attack Targeting System.

The AN/AAQ-28 Litening AT Precision Attack Targeting System is a multi-purpose targeting and navigation system developed to provide modern tactical aircraft with a day and night precision strike capability against land and sea based targets. This targeting system is a collaborative effort between Northrop-Grumman Electronic Sensors and Systems Division and Rafael of Israel. The Tpod is designed to enhance the operational capability of the AV-8B by providing multiple-sensors (Forward Looking Infrared, Charged Couple Device (CCD) – Television, Laser marker, Laser Spot Tracker, Laser Designator/Rangefinder and a multi-functional tracker) for improved performance in various environmental conditions [4].

The Tpod is a self-contained sensor and laser designator system for target detection, recognition, weapon delivery, and support (Figure 1-1). It is 87 inches long and 16 inches in diameter. The Tpod contains: 512 x 512 pixel infra-red camera for low light level operations, CCD camera for daylight and low thermal contrast conditions, 1.06 micron laser for the delivery of laser guided weapons, and a night vision goggle compatible laser marker for interoperability with ground forces [4].

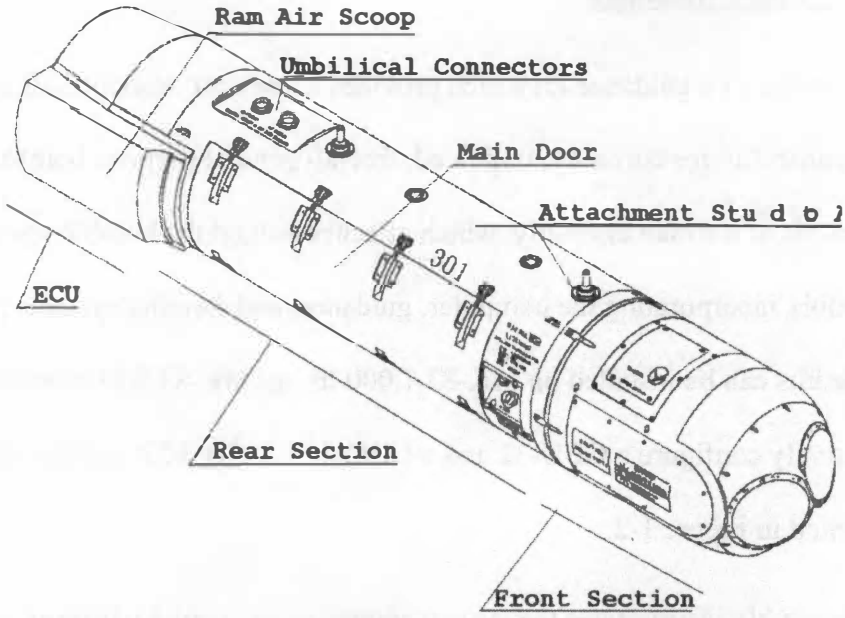


Figure 1-1 AN/AAQ-28 Litening AT Precision Attack Targeting System [4]

The Tpod currently mounts on and interfaces with the AV-8B on weapons station 5. The main purpose of the system is to assist the pilot in acquiring, recognizing, and designating ground targets in order to attack them by means of laser guided bombs (LGBs), general-purpose bombs, or cluster bombs. A secondary purpose has now become target coordinate generation for JDAM targeting.

The Tpod employs a 37 state Kalman filter to compute target coordinates and incorporates additional sensor data from the Tpod inertial measuring unit (IMU). The primary benefit is an improvement in the quality of data used to generate target coordinates in absolute reference to World Geodetic System 84 (WGS-84) [4].

1.3.3 Joint Direct Attack Munitions.

JDAM consists of a guidance kit which provides a low cost, standoff, all weather, precision strike capability for currently, unguided, freefall general purpose bombs. The guidance kit consists of a strake assembly, which attaches around the bomb body and a conical fin assembly incorporating the computer, guidance, and steering systems [2].

Guidance kits can be installed on MK-83 1,000 lb and MK-82 500 lb bomb bodies to respectively configure a GBU-32 and a GBU-38. A GBU-32 configured weapon is presented in Figure 1-2.

The fin assembly incorporates the system computer, an inertial platform, a 12 channel GPS receiver, power supply, and actuator assembly that send steering commands to the three moveable (of four) fins [2]. Target data may be programmed into the weapon

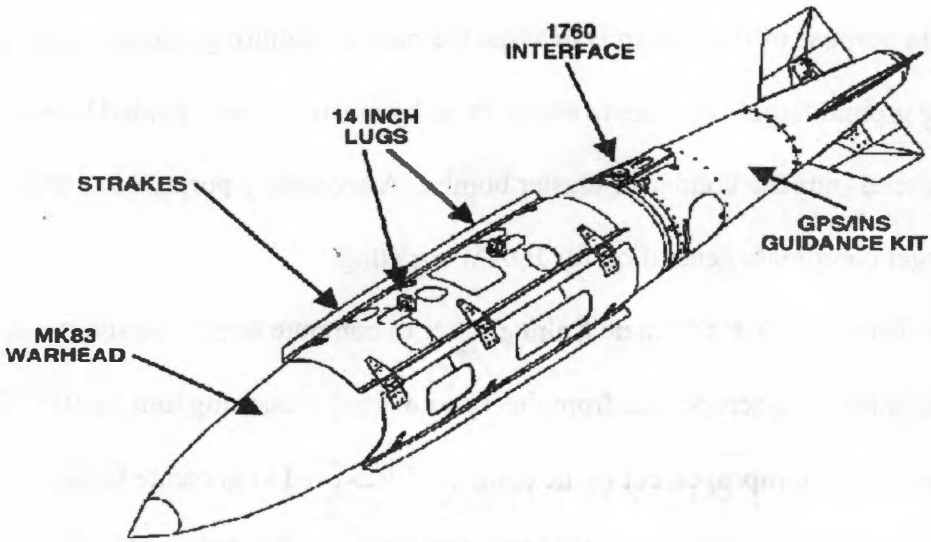


Figure 1-2 GBU-32 JDAM [4]

for preplanned missions or in a reactive role for targets of opportunity using on-board sensors. Target coordinates are passed to the weapon through the Mil-Std-1760 Multiplex Databus interface from the delivery aircraft. The aircraft also provides accurate position/velocity state vectors, GPS time, almanac and ephemeris data during weapon initialization. The weapon may be released in a tightly coupled mode with the weapon INS and GPS providing coupled steering or in an INS-only mode for degraded GPS operating environments.

JDAM requires target coordinates in latitude, longitude, and altitude (mean sea level (MSL) or height above ellipsoid (HAE)) referenced to a WGS-84 coordinate frame. JDAM accuracy is primarily a function of five key components: aircraft handoff error, weapon navigation error, weapon guidance error, TLE, and weapon impact angle [2].

Aircraft handoff error is driven by the accuracy of the aircraft navigation system. Minimizing aircraft handoff error is especially important when JDAM is released to guide to earth-based (absolute) coordinates using JDAM INS-only navigation such as in a GPS denied environment. The relative mode of the weapon is used when onboard the aircraft sensors are used to generate the target coordinates. In the relative mode, once the JDAM acquires a GPS signal after release from the aircraft, the weapon compares its GPS position to the JDAM INS position (previously aligned to the aircraft). Any difference is assumed to be an aircraft induced position error. The error is then applied as a correction factor (bias) to the coordinates (Figure 1-3). This bias is nearly zero when the weapon is aligned to a tightly coupled aircraft because both weapon and aircraft are using the same navigation source (GPS). However, if the sources are different (loosely-coupled aircraft and tightly-coupled weapon) the bias allows the aircraft to designate a

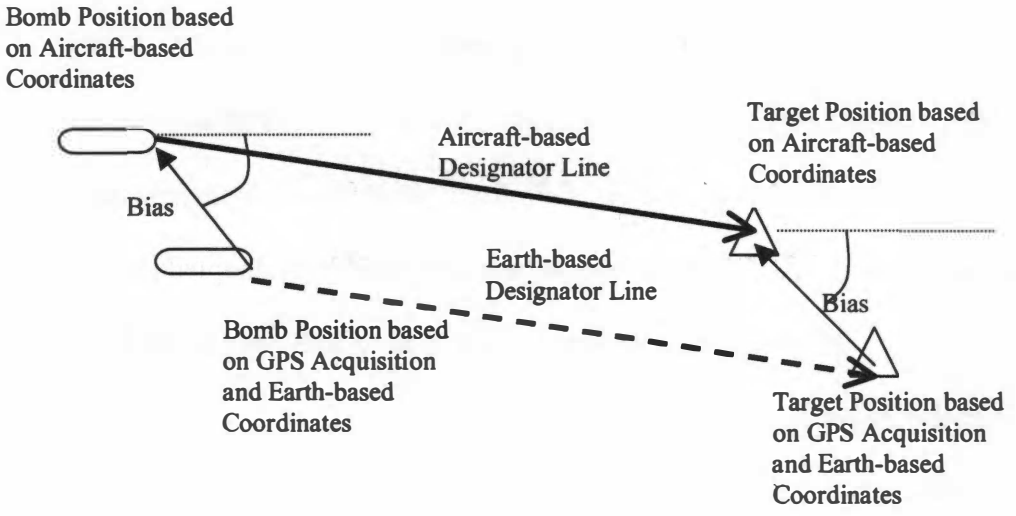


Figure 1-3 JDAM Relative Targeting Bias

position relative to its own location without concern for aircraft INS induced errors [5]. This bias to the target coordinates will be in the same direction and magnitude as the aircraft handoff error. The application of a bias to the weapon did not change the position of the target but instead changed the reference frame to the aircraft-based (relative) reference frame from the earth-based (absolute) reference frame.

JDAM navigation error is specified for two navigation modes; the primary navigation mode, GPS-aided, and the back up navigation mode, INS-only. GPS-aided means JDAM navigation uses position, velocity and time data provided by the GPS to update the position and velocity measurements provided by the JDAM INS. INS-only means GPS aiding data is not available and the JDAM INS is the only source of navigation inputs. JDAM navigation error is initially a function of aircraft handoff error and JDAM INS drift up to the point that JDAM acquires and tracks GPS satellites. When

GPS aiding is denied (or turned off), JDAM navigation (INS-only) error is a function of aircraft handoff error and JDAM INS drift for the entire flight of the weapon.

Weapon guidance error is a function of how well the JDAM responds to guidance commands and flies along the commanded flight path. Weapon guidance accuracy will not be addressed by this thesis, as the errors exist for all platforms and sensors regardless of aircraft handoff error or TLE.

TLE is a function of the accuracy of the targeting system. The horizontal TLE allotment is currently specified at 7.2 m CEP (for a 60 degree (deg) or greater weapon impact angle). The vertical TLE allotment is contained within the total of 15 m LEP.

Figure 1-4 is a graphical summation of JDAM GPS aided horizontal accuracy. Figure 1-5 shows how the horizontal errors will build over time due to INS degradation during INS-only navigation.

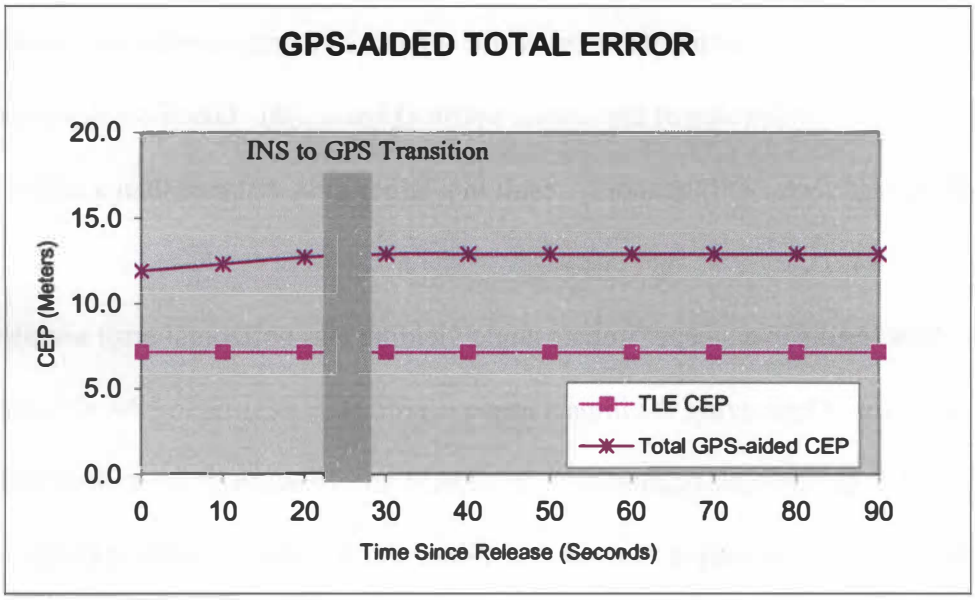


Figure 1-4 JDAM GPS – Aided Accuracy [2]

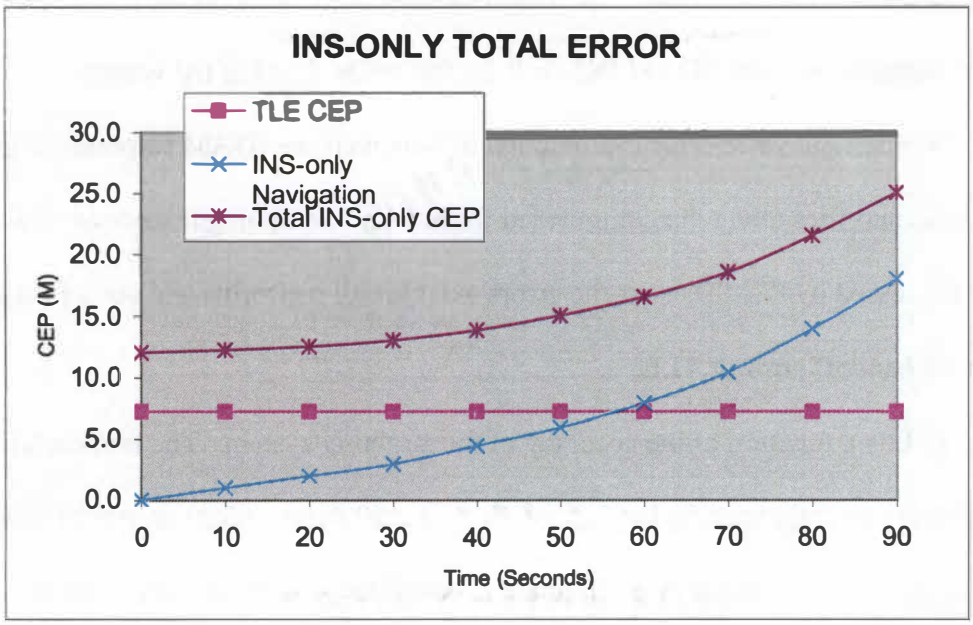


Figure 1-5 JDAM INS-Only Accuracy [2]

Weapon system accuracy is also a function of impact angle, due to elevation errors in aircraft handoff, weapon navigation, and TLE. Elevation errors will cause the JDAM to guide to a point above or below the target. The impact error associated with the elevation error is a function of the impact vector (Figure 1-6). Given an elevation error, a shallow impact vector will generally result in a larger miss distance than a steep impact angle (Figure 1-7).

This results in a steeper impact angle yielding less horizontal error sensitivity to elevation error. Optimizing the impact angle is crucial in minimizing the elevation error. The impact angle error associated with the JDAM specification being used in this thesis is for an impact angle steeper than 60 deg. Since the AV-8B is restricted at the current time for a weapon impact angle of 65 deg [1], this error will not be addressed in this analysis.

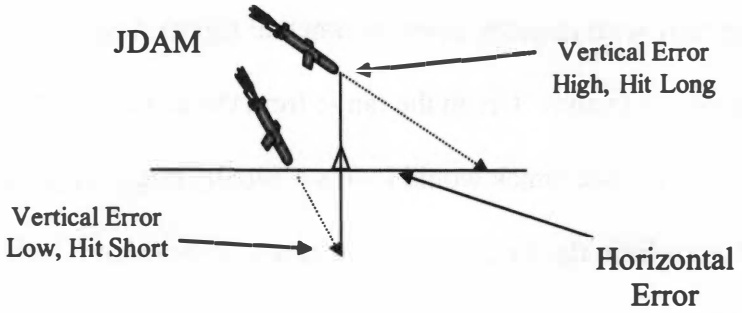


Figure 1-6 Horizontal Error Sensitivity to Vertical Error [6]

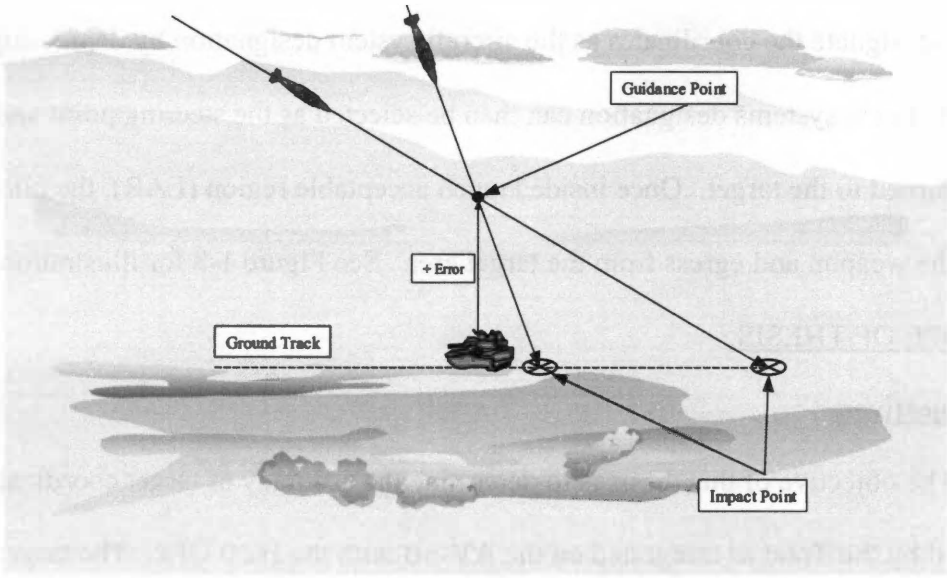


Figure 1-7 Impact Angle Effect on Miss Distance [2]

1.3.4 Attack Profile.

JDAM can be released throughout most of the AV-8B flight envelope. The attack timing will vary greatly with target size, environmental significance, aircrew proficiency, weather, and many more factors. Given the range from the target and the time to do so, the best-case medium altitude attack would involve initially targeting somewhere between 20 and 10 nm from the target. Once a target is obtained and locked, the laser designator should be turned on and some sensor line of sight rate developed to allow the Tpod to converge on a target position solution as the coordinates are developed through the Tpod Kalman filter. This can be affected by arcing around the target until the confidence level on the Tpod is labeled as "HI". A "HI" confidence level is determined by the Tpod software and is generally assigned only if using laser ranging as the source signifying hi confidence level of the generated coordinates [4]. Once this is complete, the pilot can designate the coordinates as the aircraft system designation by depressing the TDC. This new systems designation can then be selected as the steering point and the aircraft turned to the target. Once inside launch acceptable region (LAR), the pilot can release the weapon and egress from the target area. See Figure 1-8 for illustration.

1.4 SCOPE OF THESIS.

1.4.1 Objectives.

The objective of this thesis is to determine the accuracy of target coordinates generated by the Tpod as integrated on the AV-8B with the H2.0 OFP. The target coordinate accuracy will be compared to the JDAM TLE specification for a horizontally and flight test data will be discussed as well as recommendations as to how to minimize the errors for each of the components. Alternative procedures will be presented and

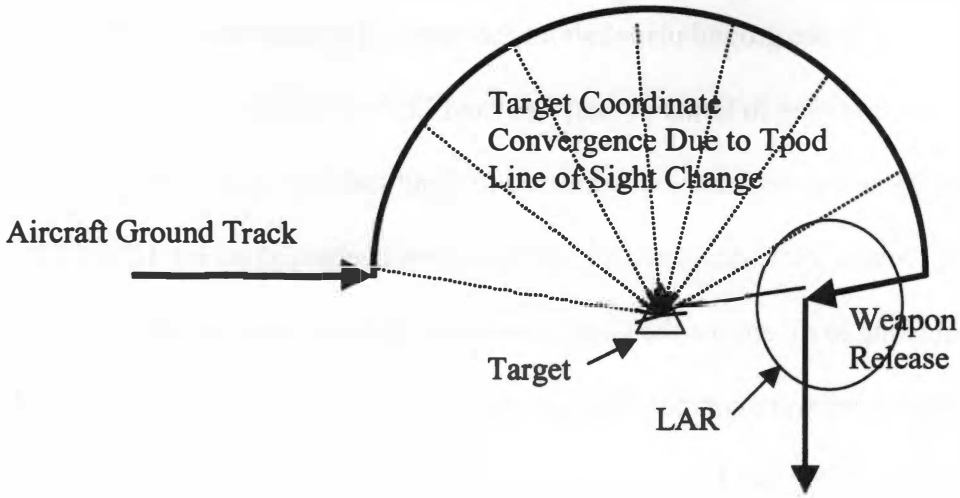


Figure 1-8 JDAM Reactive Attack

discussed for use of Tpod generated target coordinates.

1.4.2 Statistical Analysis.

This thesis assumes a tactical size horizontal target with minimal height is being targeted. Therefore, the horizontal error will be characterized in terms of circular error probable. CEP is an error where 50% of the weapons will impact within a circle a given radius about the target [2]. Vertical error will be quantified in terms of LEP. LEP is the value in a single dimension, centered at the position that contains 50% of the vertical position estimates [2]. For a horizontal target, any error in the vertical will resolve to an error in range, depending on the sensitivity of the horizontal CEP to that error.

To conduct an adequate characterization of the Tpod's ability to generate target coordinates in an earth-based and aircraft-based reference frame, an understanding of each individual error contributor is needed. An analytical approach for each error contributor will be undertaken using previous flight test data and manufacturer specifications. Each of these errors will be transformed into a CEP (in the ground plane)

and LEP (orthogonal to the ground plane) about the target. The individual CEPs and LEPs will then be combined in terms of total CEP and LEP to obtain total TLE.

The analytical data will then be compared to flight test data in an effort to validate the analytical approach. Nine dedicated TLE flights were conducted during H2.0 OFP developmental testing to determine the target coordinate generation capability of the Tpod. Tpod coordinates were compared to the target's surveyed location to derive total Tpod TLE in terms of CEP and LEP.

1.4.3 Assumptions.

During the course of this thesis, general and specific assumptions are made. The following are the general assumptions for this thesis. Specific assumptions are noted during the analysis of each error source.

1. Flight test aircraft equipment and sensors are operationally representative.
2. The pilots who conducted the flight test were trained in the use of the Tpod.
3. All errors represent one-sigma values.
4. Small angle approximations are made with respect to milliradians. A milliradian is an angular measurement equal to 1/1000 of a radian. It equals 1 meter at 1000 meters of range.
5. All JDAM are released with greater than 30 seconds time of fall ensuring adequate time for GPS acquisition, unless otherwise noted.
6. The aircraft and weapon are not operating in a GPS denied or spoofed environment.

7. No dive deliveries or loft maneuvers are performed during weapon delivery. The targeting process and release of the weapon are conducted at a constant altitude.
8. A transfer alignment is properly performed for the weapon and Tpod prior to the targeting process. A transfer alignment is a maneuver where the attached systems (Tpod and JDAM for this thesis) INSs align to the aircraft INS. Typically this is accomplished by performing a turn of some sort either on the ground or once airborne. This maneuver is performed prior to beginning the targeting process.

2. AIRCRAFT POSITION ERROR

2.1 GPS-INS INTEGRATION.

AV-8B current aircraft position is determined using an INS tightly coupled with a GPS. The aircraft INS is a self-contained, fully automatic dead reckoning navigation system. The INS detects aircraft motion and provides acceleration, velocity, present position, pitch, roll, and true heading to related systems [4]. The AV-8B currently has a Litton AN/ASN-139 Cains II Ring Laser Gyro INS installed. The ASN-139 is specified to a position accuracy of 1 nm/hour CEP although significantly better accuracies have been obtained regularly during flight.

Testing of the Miniaturized Airborne GPS Receiver (MAGR) in the AV-8B occurred in 1993. The MAGR continuously provides corrections to the INS for precise position keeping, ensuring a "tight" INS to continue the mission even if the GPS signal is lost.

The GPS is a space-based radio positioning system, which provides suitably equipped users with highly accurate position, velocity, and time data. This service is provided globally, continuously, and under all weather condition to users at or near the surface of the earth. GPS receivers operate passively, thus allowing an unlimited number of simultaneous users. The GPS has features that can deny accurate service to unauthorized users, prevent spoofing, and reduce receiver susceptibility to jamming [4].

Two levels of navigation are provided by the GPS, the precise positioning service (PPS) and the standard positioning service (SPS). The PPS is a highly accurate positioning, velocity, and timing service that is made available only to authorized users

(i.e. Department of Defense (DoD) users with the correct crypto loaded). The SPS is less accurate positioning and timing service, which is available to all GPS users.

In order for a user to receive PPS capability it must be able to synchronize with the precise-code (P-code). The P-code is a 267 daylong code sequence; with each of the GPS satellites assigned a unique one-week segment of this code. The P-code is protected against spoofing by encryption called the Y-code. The P(Y)-code can only be accessed by authorized users. This thesis assumes the AV-8B MAGR is utilizing PPS with P(Y)-code.

The MAGR receives ranging codes and a navigation data messages from NAVSTAR satellites through the GPS antenna. The ranging codes broadcast by the satellites enable the MAGR to measure the transit time of the signals and determine the range between the satellite and the aircraft. The navigation data messages enable the MAGR to calculate the position of each satellite at the time of transmission. The MAGR can track five GPS satellites and calculate the aircraft exact position from the four best satellites being tracked. The MAGR provides time, aircraft position, ground track, ground speed and altitude data to the MSC. Position and velocity calculations are based on WGS-84 geodetic datum [4].

There are three position-keeping sources in the AV-8B: INS, GPS, and Air Data Computer (ADC) in order of priority. The MSC will automatically upgrade to the best available position-keeping mode when the better mode becomes available. The MSC also downgrades to the next best available position-keeping source in the event the current source is deemed erroneous or unavailable. The navigation system coupling mode, which controls the interface between the GPS and the INS, is pilot selectable using

the INS mode select switch. The two coupling modes, tightly coupled and loosely coupled, are independent of the position-keeping mode.

Tightly coupled refers to a navigation system in which the GPS is aided by ADC and INS data and continually returns corrections to the INS platform. The aiding data permits the GPS to keep satellite lock and to stabilize the internal Kalman filter. The platform correction data provides the INS with data it can use to better estimate its internal platform errors. For this thesis, the AV-8B is assumed to be operating in the tightly coupled mode unless otherwise noted.

2.2 ERROR ANALYSIS.

2.2.1 Derivation.

This section discusses aircraft handoff position error in terms of horizontal and vertical error. Because the target coordinates generated by the Tpod are in direct relation to what the aircraft thinks is its present position, any error in present aircraft position translates directly to error in target location. Therefore any target that depends on the horizontal position of the aircraft will also have a horizontal uncertainty about the target's position in direct proportion. See Figure 2-1 for an illustration.

Any vertical error in aircraft position will also result in a vertical error about the target of the same magnitude. See Figure 2-2 for an illustration.

So the aircraft horizontal position error ($CEP_{A/C}$) equals target horizontal error position (CEP_{TGT}). Aircraft vertical position error ($LEP_{A/C}$) equals target vertical position error (LEP_{TGT}). This error is handed to the JDAM at release of the weapon but will be negated if the JDAM acquires GPS satellites (assuming the weapon is released in the earth-based coordinate mode.) If aircraft-based coordinates are being used (relative

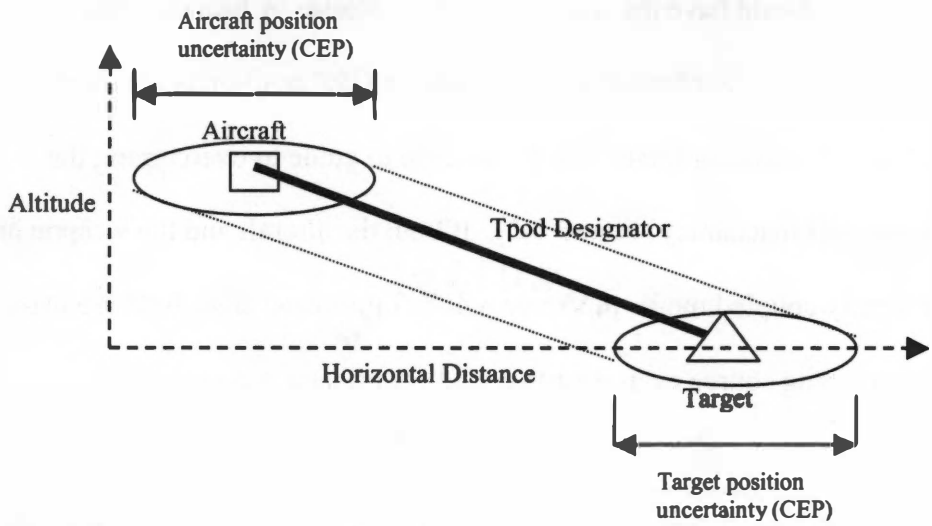


Figure 2-1 Horizontal TLE Due to Aircraft Position Error

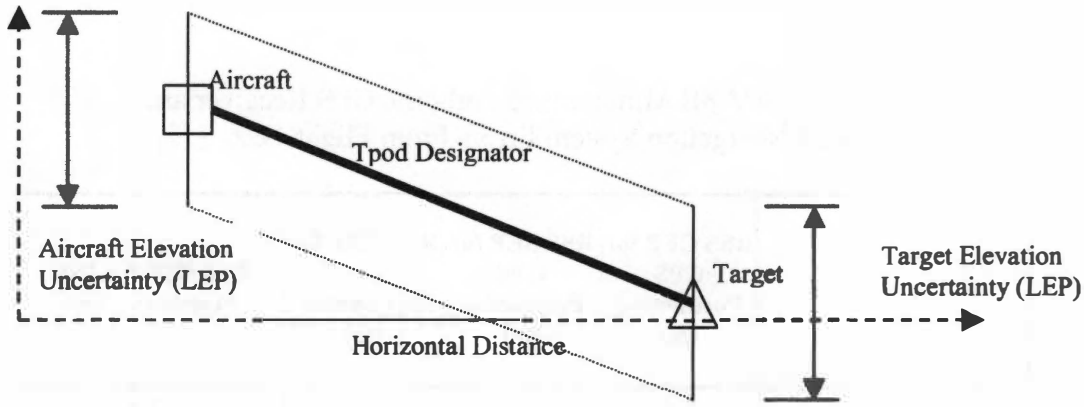


Figure 2-2 Vertical TLE Due to Aircraft Position Error

mode) then the JDAM should have the relative bit set at release. A bias can then be applied to the aircraft-based coordinates once the weapon GPS position is obtained resulting in new earth-based coordinates for the weapon to guide to overcoming the aircraft position handoff inaccuracy (Figure 1-3). If both the aircraft and the weapon are operating in the tightly coupled mode, this error will be minimized since both are using the same position-keeping source even if earth-based coordinates are used.

2.2.2 Test Results.

GPS and INS position keeping capability was tested on the AV-8B in June 1993. A differential GPS was used as a truth source to characterize the position keeping capability of the ASN-139 and the MAGR separately as installed on the AV-8B [7]. Table 2-1 shows the results of the seven flights.

Table 2-1 AV-8B Miniaturized Airborne GPS Receiver and Inertial Navigation System Errors From Flight Test[1, 2] [7]

Flight Number	RSS CEP for GPS Positioning (m)	RSS SEP for GPS Positioning (m)	RSS CEP for INS Positioning (m)	RSS SEP for INS Positioning (m)
N855	9.3	17.1	10.5	17.8
N878	5.6	9.9	8.3	61.8
N879	7.1	7.7	8.0	55.6
N880	6.6	11.2	7.3	96.8
N881	5.9	8.4	7.3	142.0
N863	6.1	10.3	5.7	13.0
N864	5.6	12.4	7.1	13.8
STD DEV	1.3	3.1	1.5	48.6
RMS	6.7	11.4	7.9	72.8

1. AV-8B GPS Integration Test Results, 06/01/93.
2. Differential GPS Truth Source

Flight test results indicate the GPS is a more accurate aircraft position-keeping source than the INS. This is in keeping with the GPS-INS software integration completed for the aircraft, which uses the GPS to update the INS position continuously when operating in a tightly coupled mode.

2.2.3 Aircraft Position Error Analysis.

The equation for spherical error probable (SEP) is [8]:

$$SEP_{A/C} = 0.87\ CEP_{A/C} + 0.76\ LEP_{A/C}$$

Using the flight test results from the previous section, SEP and CEP and known. LEP can then be calculated using the equation above. Results are contained in Table 2-2. The horizontal CEP of the aircraft position error using the GPS MAGR as a position-keeping source is 6.7 meters and the vertical LEP is 7.6 meters. Adding one standard

Table 2-2 AV-8B Miniaturized Airborne GPS Receiver and Inertial Navigation System Errors From Flight Test Including LEP[1, 2]

Flight Number	RSS CEP for GPS Positioning (m)	RSS SEP for GPS Positioning (m)	RSS LEP for GPS Positioning (m)	RSS CEP for INS Positioning (m)	RSS SEP for INS Positioning (m)	RSS LEP for INS Positioning (m)
N855	9.3	17.1	11.9	10.5	17.8	11.4
N878	5.6	9.9	6.6	8.3	61.8	71.8
N879	7.1	7.7	2.0	8.0	55.6	64.0
N880	6.6	11.2	7.2	7.3	96.8	119.0
N881	5.9	8.4	4.3	7.3	142.0	178.5
N863	6.1	10.3	6.6	5.7	13.0	10.6
N864	5.6	12.4	9.9	7.1	13.8	10.0
STD DEV	1.3	3.1	3.3	1.5	48.6	64.1
RMS	6.7	11.4	7.6	7.9	72.8	89.1

1. AV-8B GPS Integration Test Results, 06/01/93.
2. Differential GPS Truth Source

deviation to these values results in 8.0 m CEP and 10.9 m LEP respectively. These results will be used throughout the remainder of this thesis for aircraft position error.

3. OPERATOR ERROR

3.1 INTEGRATION.

3.1.1 Multipurpose Color Display.

There are two multipurpose color displays (MPCD) located on either side of the main instrument panel. Both are a 5-inch by 5-inch displays surrounded by 20 multi-function pushbutton switches. Each MPCD mode selection is accomplished either automatically, as determined by the MSC, or manually. The display computer converts information received from the MSC to symbology for display on one of the MPCDs. Each MPCD has the capability to display color moving map information, Tpod information, and other tactical data and display pages [4].

3.1.2 Tpod Image Presentation.

The pilot chooses which MPCD to display the Tpod image. The Tpod image is a 512 x 512 pixel presentation. The smallest increment available to the pilot for resolution of the target is 1 pixel. In the narrow field of view mode, the Tpod image is 1 deg by 1 deg [4]. This transforms to 0.034 milliradian (mrad) by 0.034 mrad for each pixel using the below equation:

$$17.45 \text{ (mrad / deg)} \times 1 \text{ deg} / 512 \text{ pixels} = 0.034 \text{ mrad/pixel}$$

As the pilot zooms the display, the Tpod employs a digital zoom so the actual number of pixels never changes. However, the Tpod employs a variety of functions to help improve the quality of the digital zoom picture and help avoid pixilation such as image derotation and image enhancement. Image derotation is an electronic derotation of the image vice mechanical. This allows the Tpod the ability to recover high spatial

frequency information. The increase in the high spatial frequency retained in the derotation yields an effective improvement in the quality of the image at a particular zoom level. Image enhancement is a technique by which the image is convoluted by sharpening and enhancing the image on a pixel-by-pixel basis. In addition, multiple video frames are integrated to increase the signal to noise ratio by the square root of the frames integrated. Typically, only four frames are integrated due to time requirements. This reduces noise by a factor of two, improving the clarity of the original scene in display images [4].

3.1.3 Operator Pointing Error.

In the narrow field of view, at zoom level of 6, the image presented is a 1/3-deg by 1/3-deg field of view (171 by 171 pixels available for image presentation due to digital zoom.) This is the most used level for final picture clarity as it offers the most zoom with the least degradation in picture quality in the opinion of the author. At this level of zoom, most tactical targets will be clear enough to select the proper targeting point at tactical slant ranges. This thesis assumes no error by the operator in selecting the exact target point. It also assumes no pixel resolution correction to the error because no data exists to reduce the error values. Therefore, any additional operator-pointing error beyond pixel resolution considerations will not be addressed in this analysis.

3.2 ERROR ANALYSIS.

3.2.1 Derivation.

This section describes the effects of the error generated by the ability to resolve a pixel to 0.034 mrad. Using 0.034 mrad as the error magnitude, CEP_{MAX} and LEP_{MAX} can

be calculated. See appendix A for derivation of CEP_{MAX} and LEP_{MAX} for Tpod pointing errors.

3.2.2 Results.

Table 3-1 shows the effects and resolution in CEP for horizontal error and LEP for vertical error.

As can be seen in Table 3-1, the errors are minimal especially inside 9 nm of slant range from the target (2.0 m or less in CEP and LEP). To minimize this error the Tpod pixel resolution ability must be increased. This could be accomplished by incorporating better image resolution techniques when they become available.

Table 3-1 TLE Due to Pixel Size of Tpod Image[1]

Slant Range (NM)	Horizontal Range (NM)	CEP Max Due to Operator Error (m)	LEP Max Due to Operator Error (m)	Slant Range (NM)	Horizontal Range (NM)	CEP Max Due to Operator Error (m)	LEP Max Due to Operator Error (m)
15.0	14.7	5.1	2.8	9.0	8.6	1.8	1.8
14.5	14.2	4.7	2.7	8.5	8.0	1.6	1.7
14.0	13.7	4.4	2.6	8.0	7.5	1.4	1.6
13.5	13.2	4.1	2.6	7.5	7.0	1.3	1.5
13.0	12.7	3.8	2.5	7.0	6.4	1.1	1.4
12.5	12.2	3.5	2.4	6.5	5.9	1.0	1.3
12.0	11.7	3.2	2.3	6.0	5.3	0.8	1.3
11.5	11.2	3.0	2.2	5.5	4.7	0.7	1.2
11.0	10.6	2.7	2.1	5.0	4.1	0.6	1.1
10.5	10.1	2.5	2.0	4.5	3.5	0.5	1.1
10.0	9.6	2.3	1.9	4.0	2.9	0.4	1.0
9.5	9.1	2.0	1.8	3.5	2.1	0.3	1.1

1. Constant 17,000 ft AGL

4. LITENING POD ERROR

4.1 TPOD GENERATED ERROR SOURCES.

4.1.1 Sensor Integration.

The Tpod, as discussed in chapter 1, is a multi-purpose targeting and navigation system developed to provide modern tactical aircraft with a day and night precision strike capability against land and sea based targets. The main purpose of the system is to assist the pilot in acquiring, recognizing, and designating ground targets in order to attack them by means of LGBs, general-purpose bombs, or cluster bombs. A secondary purpose has now become target coordinate generation for JDAM deliveries.

4.2 ERROR ANALYSIS.

There are eight sources of error that result in TLE for Tpod generated target coordinates. The first two, aircraft position error and operator error, were discussed in chapters 2 and 3 respectively. Two additional errors are due to the inaccuracies of the aircraft INS but directly affect the performance of the Tpod in generating target coordinates and therefore will be discussed in this chapter. These two errors are aircraft heading error and aircraft bearing error. The fifth error source is generated when the Tpod IMU aligns itself with the aircraft INS via the transfer alignment process. This alignment results in a slight error between the two units. The sixth possible error source is pointing error in the Tpod. The seventh error is range uncertainty (ΔR) or the difference in actual distance between the Tpod and the target and what the Tpod thinks is the distance. The final error occurs when the Tpod target coordinates are sent to the weapon. The Tpod sends the elevation in MSL and the weapon has to convert it to HAE.

4.2.1 Heading Error.

Heading error is error resulting from the aircraft INS's ability to resolve actual heading from indicated heading. Even though the actual aircraft INS drift is corrected by the GPS with a tightly coupled system, at any instant in time the INS has a certain amount of drift inherent. This drift results in heading error. This heading error transfers directly to the Tpod and degrades its ability to resolve actual heading of the sensor line of sight.

4.2.1.1 Derivation.

The aircraft INS has a specification of less then 1.0 nm per hour drift rate. Actual flights have shown the INS to be more accurate than 1.0 nm per hour drift rate. Table 4-1 shows actual INS performance error rates (PER) over the last nine months of China Lake based aircraft with ASN-139 INSs installed. (See appendix A for definition and equation for root mean square (RMS) and Standard Deviation.) This data was obtained by flying the aircraft in the loosely-coupled mode. When these flights were complete a GPS

Table 4-1 ASN-139 Performance Error Rate From Flight Data

Aircraft Side Number	Date	Performance Error Rate (nm per hour)
83	15 Sep 04	0.2
83	29 Oct 04	0.3
83	23 Dec 04	0.0
84	29 Jun 04	0.4
84	27 Jul 04	0.2
84	06 Oct 04	0.3
84	21 Oct 04	0.2
84	13 Dec 04	0.4
RMS of all Flights		0.28
Standard Deviation of all Flights		0.13

position update was manually performed and a PER obtained for INS performance analysis.

Since actual flight data exists, this thesis will use the actual flight data of the ASN-139 performance error rate vice the specification limit of 1.0 nm per hour. The PER RMS value of 0.28 nm per hour plus one standard deviation of 0.13 nm per hour for a total of 0.41 nm per hour error rate from Table 4-1 will be used for this analysis and considered fleet representative.

4.2.1.2 Results.

This thesis assumes that the entire performance error rate is experienced in a direction orthogonal to the aircraft vector. This assumption results in the maximum effect of this error on target coordinate generation (Figure 4-1).

The maximum heading error that the aircraft could experience is found by the following equation:

$$TAN(\alpha) = PER / True\ Airspeed.$$

Table 4-2 is a summary of the heading error (α) as a function of airspeed using the previous equation.

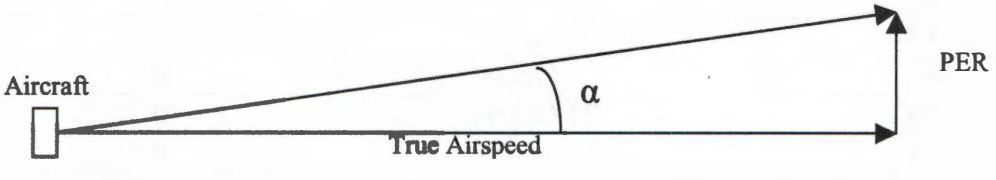


Figure 4-1 Aircraft Heading Error Due to INS Drift

Table 4-2 Heading Error as a Function of PER and Airspeed

True Airspeed (nm/hour)	α (mrad) (Using a PER of 0.41 nm per Hour)
550	0.75
500	0.82
450	0.91
400	1.02
350	1.17
300	1.37

The error of the INS with respect to heading is dependent on airspeed as shown in Table 4-2. For purposes of this thesis 400 knots true airspeed (KTAS) will be used throughout the remainder of error calculations. This airspeed is a reasonable compromise of time available for targeting and maneuverability at medium altitudes for the AV-8B in the opinion of the author. Faster airspeeds will reduce the magnitude of the errors. Slower airspeeds will result in longer exposure to the threats. Using 400 KTAS, the result of the calculation is a one-sigma error of 1.02 mrad.

Assuming a heading error transforms directly to the Tpod's ability to generate coordinates, the resulting CEP with respect to range can be seen in Table 4-3 using the CEP_{MAX} derivation in appendix A. Heading error will not translate into the vertical plane since the heading is by definition in the horizontal plane. Therefore LEP will not exist for this error.

Improving this error can be realized by developing newer technologies in compass hardware and the air data computer. The current technologies were sufficient in the past but now need to be addressed for newer sensors and targeting. The proper performance tracking and repair of a poorly performing INS will also help minimize this

Table 4-3 TLE Due to Heading Error as a Function of Range[1]

Slant Range (nm)	Horizontal Range (nm)	CEP (m)	Slant Range (nm)	Horizontal Range (nm)	CEP (m)
15.0	14.7	152.9	9.0	8.6	54.9
14.5	14.2	142.8	8.5	8.0	49.0
14.0	13.7	133.1	8.0	7.5	43.4
13.5	13.2	123.8	7.5	7.0	38.1
13.0	12.7	114.7	7.0	6.4	33.2
12.5	12.2	106.1	6.5	5.9	28.6
12.0	11.7	97.7	6.0	5.3	24.4
11.5	11.2	89.7	5.5	4.7	20.5
11.0	10.6	82.1	5.0	4.1	16.9
10.5	10.1	74.8	4.5	3.5	13.7
10.0	9.6	67.8	4.0	2.9	10.8
9.5	9.1	61.2	3.5	2.1	8.3

1. Constant 17,000 ft AGL and 400KTAS

error. In addition, increasing the airspeed during the targeting process can minimize the error but this has to be weighed against having less time available for the pilot to accomplish cockpit tasking.

4.2.2 Bearing Error.

Bearing error is the difference between the actual ground track and what the aircraft INS thinks is the aircraft ground track. This error can be of the same magnitude and direction as the heading error resulting in the worst case of doubling the heading error. Therefore it will be treated separate and additive. This error will not be realized in the vertical plane for the same reasons as stated in the heading error section. The same values for errors, as presented in Table 4-2, will be used again for this error. The same procedures for minimizing this error as stated in the heading error section are applicable as well.

4.2.3 Alignment Error.

Alignment error is the error generated by the inability of the Tpod IMU to absolutely align itself with the aircraft INS. The Tpod IMU is designed to align itself to the aircraft INS during the transfer alignment process once an acceptable aircraft INS alignment quality is obtained. Any difference between the two after the alignment process is the alignment error.

4.2.3.1 Derivation.

Alignment error is currently specified by the manufacturer to be no more than 0.35 mrad (one sigma deviation) [9] of error between the Tpod IMU and the aircraft INS. The derivation of CEP_{MAX} and LEP_{MAX} from appendix A, once again, will be used to calculate TLE for this particular error.

4.2.3.2 Results.

Table 4-4 is a summation of the alignment error CEP_{MAX} and LEP_{MAX} as a function of slant range. No flight test or analytical data exists to justify using any less error for this calculation. The manufacturer tightening the tolerance for the specification can decrease this error.

4.2.4 Pointing Error.

Pointing error is the error generated when the Tpod is pointed at the target. It is due to the slight misalignment of the laser and the sensor bore sight. The pilot may think the Tpod is exactly on the spot for which the weapon is to impact but it may actually be somewhere about the spot in a given radius (Figure 4-2).

Table 4-4 Tpod Alignment Error as a Function of Range[1]

Slant Range (nm)	Horizontal Range (nm)	CEP (m)	LEP (m)	Slant Range (nm)	Horizontal Range (nm)	CEP (m)	LEP (m)
15.0	14.7	52.3	29.1	9.0	8.6	18.8	18.0
14.5	14.2	48.8	28.1	8.5	8.0	16.8	17.1
14.0	13.7	45.5	27.2	8.0	7.5	14.9	16.3
13.5	13.2	42.3	26.3	7.5	7.0	13.1	15.4
13.0	12.7	39.3	25.3	7.0	6.4	11.4	14.6
12.5	12.2	36.3	24.4	6.5	5.9	9.8	13.7
12.0	11.7	33.4	23.5	6.0	5.3	8.4	12.9
11.5	11.2	30.7	22.6	5.5	4.7	7.0	12.2
11.0	10.6	28.1	21.7	5.0	4.1	5.8	11.5
10.5	10.1	25.6	20.7	4.5	3.5	4.7	10.9
10.0	9.6	23.2	19.8	4.0	2.9	3.7	10.7
9.5	9.1	21.0	18.9	3.5	2.1	2.8	11.1

1. Constant 17,000 ft AGL

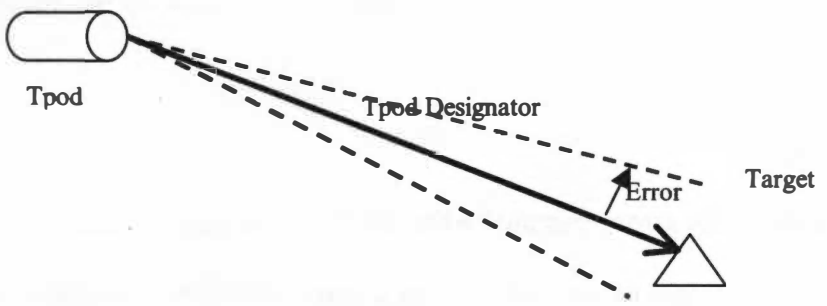


Figure 4 -2 Tpod Pointing Error

4.2.4.1 Derivation.

The manufacturer defines the pointing error associated with the Tpod as 0.1 mrad (one sigma deviation) [9]. The derivation of CEP_{MAX} and LEP_{MAX} from appendix A are used once again to calculate CEP and LEP.

4.2.4.2 Results.

Table 4-5 is a summation of the alignment error as a function of slant range. Tpod pointing error has been speculated to be better than the manufacturer's specification during actual flight test but no data exists analytically or through flight test to justify adjusting the error for this analysis. The manufacturer tightening the tolerance of the specification can decrease pointing error.

Table 4-5 Tpod Pointing Error as a Function of Range[1]

Slant Range (nm)	Horizontal Range (nm)	CEP (m)	LEP (m)	Slant Range (nm)	Horizontal Range (nm)	CEP (m)	LEP (m)
15.0	14.7	14.9	8.3	9.0	8.6	5.4	5.2
14.5	14.2	13.9	8.0	8.5	8.0	4.8	4.9
14.0	13.7	13.0	7.8	8.0	7.5	4.2	4.7
13.5	13.2	12.1	7.5	7.5	7.0	3.7	4.4
13.0	12.7	11.2	7.3	7.0	6.4	3.2	4.2
12.5	12.2	10.4	7.0	6.5	5.9	2.8	3.9
12.0	11.7	9.5	6.7	6.0	5.3	2.4	3.7
11.5	11.2	8.8	6.5	5.5	4.7	2.0	3.5
11.0	10.6	8.0	6.2	5.0	4.1	1.7	3.3
10.5	10.1	7.3	5.9	4.5	3.5	1.3	3.1
10.0	9.6	6.6	5.7	4.0	2.9	1.1	3.0
9.5	9.1	6.0	5.4	3.5	2.1	0.8	3.2

1. Constant 17,000 ft AGL

4.2.5 Range Error.

Range error (ΔR) is the ability of the Tpod to resolve exact range as shown in Figure 4 -3.

4.2.5.1 Derivation.

The manufacturer specifies the ability of the Tpod to resolve exact range using the laser designator as ± 5 m up to 10 kilometer (km) (one sigma deviation) [9]. Beyond 10 km the error is specified as ± 0.05% of the range. The derivations of CEP_{MAX} and LEP_{MAX} for this error are shown in appendix A and are used to calculate CEP and LEP.

4.2.5.2 Results.

Table 4-6 summarizes the range error as a function of range. This error has been speculated to be significantly less than the manufacturers' specification but no quantifiable flight test data exists to justify using less than the amounts specified by the

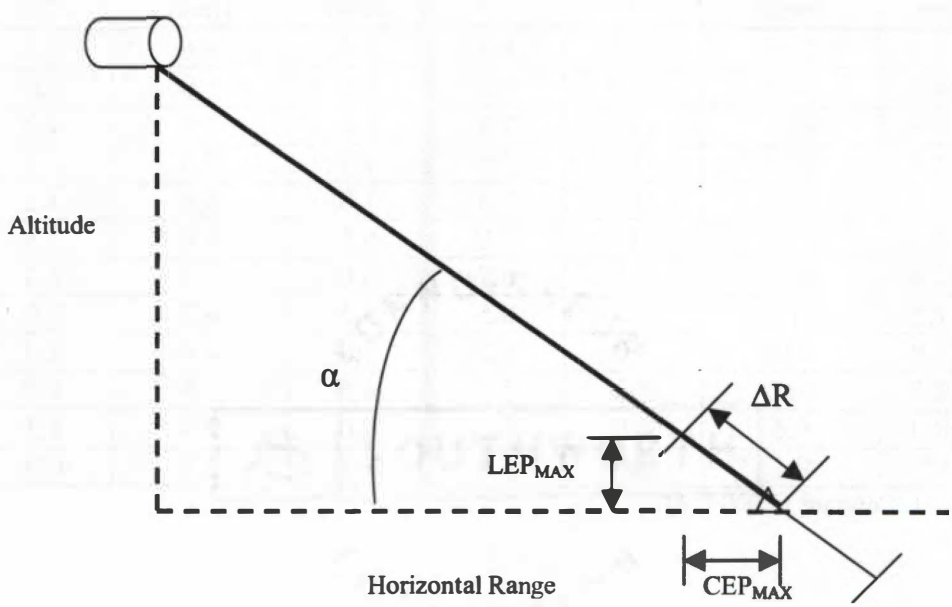


Figure 4 -3 Tpod Ranging Error

Table 4-6 Tpod Ranging Error as a Function of Range[1]

Slant Range (nm)	Horizontal Range (nm)	CEP (m)	LEP (m)	Slant Range (nm)	Horizontal Range (nm)	CEP (m)	LEP (m)
15.0	14.7	13.7	2.6	9.0	8.6	7.9	2.6
14.5	14.2	13.2	2.6	8.5	8.0	7.4	2.6
14.0	13.7	12.7	2.6	8.0	7.5	6.9	2.6
13.5	13.2	12.2	2.6	7.5	7.0	6.4	2.6
13.0	12.7	11.8	2.6	7.0	6.4	5.9	2.6
12.5	12.2	11.3	2.6	6.5	5.9	5.4	2.6
12.0	11.7	10.8	2.6	6.0	5.3	4.9	2.6
11.5	11.2	10.3	2.6	5.5	4.7	4.4	2.6
11.0	10.6	9.9	2.6	5.0	4.1	4.1	2.8
10.5	10.1	9.4	2.6	4.5	3.5	3.9	3.1
10.0	9.6	8.9	2.6	4.0	2.9	3.6	3.5
9.5	9.1	8.4	2.6	3.5	2.1	3.0	4.0

1. Constant 17,000 ft AGL

manufacturer. To minimize the effects of range error the manufacturer will need to tighten the tolerance of the range receivers to remove component errors.

4.2.6 MSL Altitude to HAE.

JDAM requires target coordinates in latitude, longitude, and altitude (MSL or HAE) referenced to a WGS-84 coordinate frame which the AV-8B provides. JDAM navigation and guidance algorithms use HAE, however. Because the AV-8B can only provide target altitude to the weapon as MSL, JDAM will convert the MSL altitude to HAE using a table with EGM 84 conversion values every 10 deg in latitude and longitude. Values in between the table values are linearly interpolated. Average conversion error is 2 to 6 m [2]. For the purposes of Tpod TLE calculations the maximum of 6 m error will be used in all LEP calculations (unless otherwise noted) for this thesis since coordinate generation is not always directly on the 10 deg EGM-84 lines.

5. ANALYTICAL TARGET LOCATION ERROR ANALYSIS

5.1 TOTAL ERROR FROM ALL SOURCES.

5.1.1 Derivation.

There are eight sources of error for Tpod generated coordinates. The first two, aircraft position error and operator error, were discussed in chapters 2 and 3 respectively. Tpod specific errors are aircraft heading and bearing errors, Tpod IMU alignment error, pointing error, and ranging error. An additional error in the coordinate handoff is the conversion of elevation from MSL to HAE in the weapon itself since it is given elevation of the target in terms of MSL. These last six errors were all discussed in chapter 4.

All eight sources for error can be combined using the root-sum-square (RSS) method to determine the total target location error in terms of CEP and LEP by the following equations:

$$TLE_{CEP} = [(CEP_{pos})^2 + (CEP_{op})^2 + (CEP_{hdg})^2 + (CEP_{brg})^2 + (CEP_{imu})^2 + (CEP_{point})^2 + (CEP_{\Delta R})^2]^{1/2}$$

$$TLE_{LEP} = [(LEP_{pos})^2 + (LEP_{op})^2 + (LEP_{imu})^2 + (LEP_{point})^2 + (LEP_{\Delta R})^2 + (LEP_{HAE})^2]^{1/2}$$

CEP due to the MSL to HAE conversion is not included in the calculation of total TLE_{CEP} since its effects are apparent in the vertical plane only. CEP due to bearing and heading error are not included in the calculation of total TLE_{LEP} since the effects of these two errors are in the horizontal plane only.

5.1.2 Results.

Data for total CEP and LEP are listed in Table 5-1 as a function of slant range. The TLE_{CEP} and TLE_{LEP} are plotted as a function of slant range in Figure 5-1.

Table 5-1 Total Tpod Analytical TLE as a Function of Range[1]

Slant Range (nm)	Horizontal Range (nm)	TLE_{CEP} (m)	TLE_{LEP} (m)	Slant Range (nm)	Horizontal Range (nm)	TLE_{CEP} (m)	TLE_{LEP} (m)
15.0	14.7	223.6	32.9	9.0	8.6	80.9	22.7
14.5	14.2	208.9	32.0	8.5	8.0	72.3	22.0
14.0	13.7	194.8	31.1	8.0	7.5	64.1	21.2
13.5	13.2	181.1	30.2	7.5	7.0	56.5	20.5
13.0	12.7	168.0	29.4	7.0	6.4	49.4	19.8
12.5	12.2	155.3	28.5	6.5	5.9	42.8	19.2
12.0	11.7	143.2	27.6	6.0	5.3	36.8	18.5
11.5	11.2	131.6	26.8	5.5	4.7	31.2	18.0
11.0	10.6	120.4	26.0	5.0	4.1	26.3	17.5
10.5	10.1	109.8	25.1	4.5	3.5	21.9	17.2
10.0	9.6	99.7	24.3	4.0	2.9	18.1	17.1
9.5	9.1	90.0	23.5	3.5	2.1	14.8	17.5

1. Constant 17,000 ft AGL and 400 KTAS

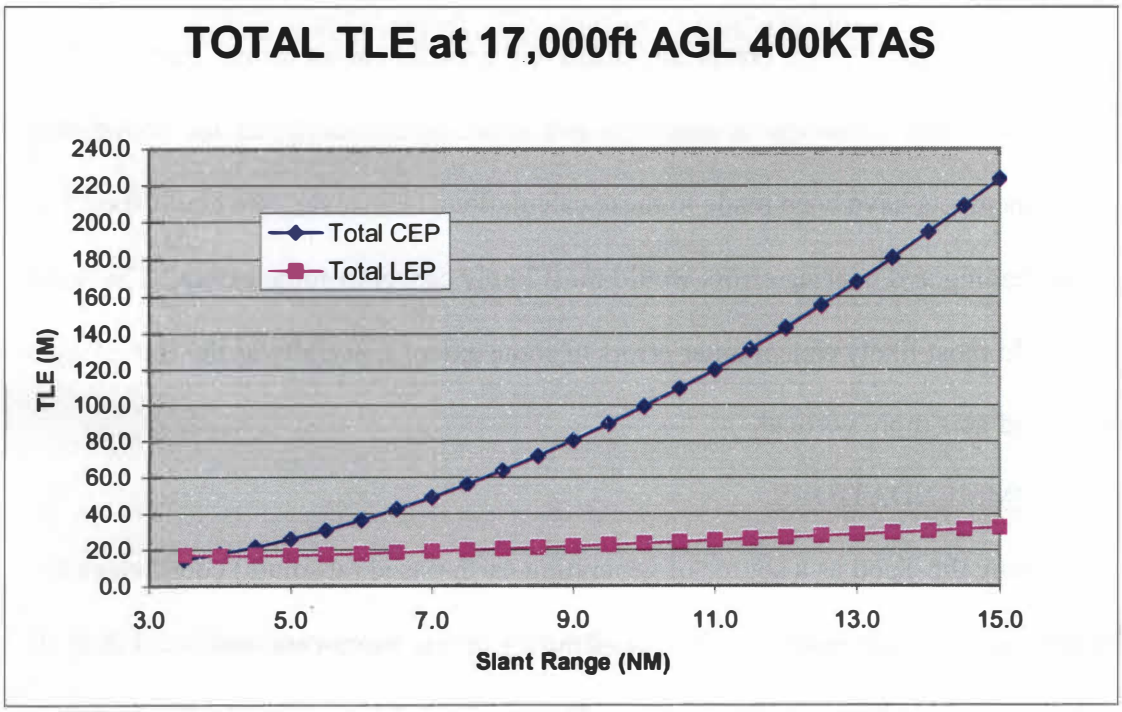


Figure 5-1 Total Tpod Analytical TLE

5.2 ANALYSIS.

Developing a line of sight rate for Tpod coordinate generation will help the Tpod converge on target coordinates faster. An arcing maneuver as shown in Figure 1-9 can be used to help develop the line of sight rate. However based on Figure 5-1, the coordinate generation capability of the Tpod shows this maneuver could be performed as close to the target as possible and still not achieve the JDAM TLE specification. Therefore by taking only analytical data of total TLE into consideration, the Tpod is not able to develop adequate accuracy of target coordinate generation to satisfy the JDAM TLE specification for CEP and LEP.

Since the Tpod cannot set the relative targeting bit properly, all error sources must be considered. This thesis has assumed all errors are additive and each component of error performs as bad as the Tpod manufacturer's specification. Instead, it is more realistic to think some of the errors calculated will actually cancel (either partially or completely.) There is no way to analyze which errors will cancel given the known data so no adjustments have been made to these calculations. However, one could speculate that the heading and bearing errors would most likely cancel to some extent. The range error would most likely cancel other errors to some extent especially as the line of sight of the Tpod gets more vertical.

5.3 RECOMMENDATIONS.

Using the Tpod as a source of generating earth-based (absolute) coordinates for JDAM targeting is not recommended based purely on the worst-case analytical data. If analytical data is to be used then it will need to be adjusted to account for some of the

error mitigation in the calculation. This error adjustment is beyond this thesis and would require flight test to quantify.

5.4 ALTERNATIVES.

An alternative to using the total error analytical approach is to adjust TLE for the relative targeting mode. Using a relative mode some of the error can be eliminated. There are two methods of targeting JDAM in a relative mode. The first is to set the relative mode of the JDAM via aircraft software. This is accomplished by the aircraft setting the correct bit at release of the weapon. The AV-8B is capable of setting this bit using all other on-board sensors except the Tpod due to a software error as discussed previously. The second method of targeting in the relative mode is to turn the GPS tracking capability of the JDAM "off" prior to release by performing the "GPS halt" procedures. This is not a straightforward procedure but can be performed in the cockpit during flight by the pilot with training. The same results will be achieved if the GPS signal is not obtained during the flight of the weapon for any reason such as when operating in a GPS denied environment or when the time of fall is shorter than the GPS acquisition time. By not using GPS guidance during weapon flight, an additional error must be added to the TLE. This additional error occurs during the course of flight of the weapon due to the drift rate of the JDAM INS operating without GPS corrections (see Figure 1-6).

If either of these relative modes is used, the aircraft position error, heading error, and bearing error can be removed from the analysis. This is because the solution for the coordinates is relative to the aircraft and will guide to those relative coordinates vice earth-based coordinates. By deleting these errors from the total TLE, the relative mode

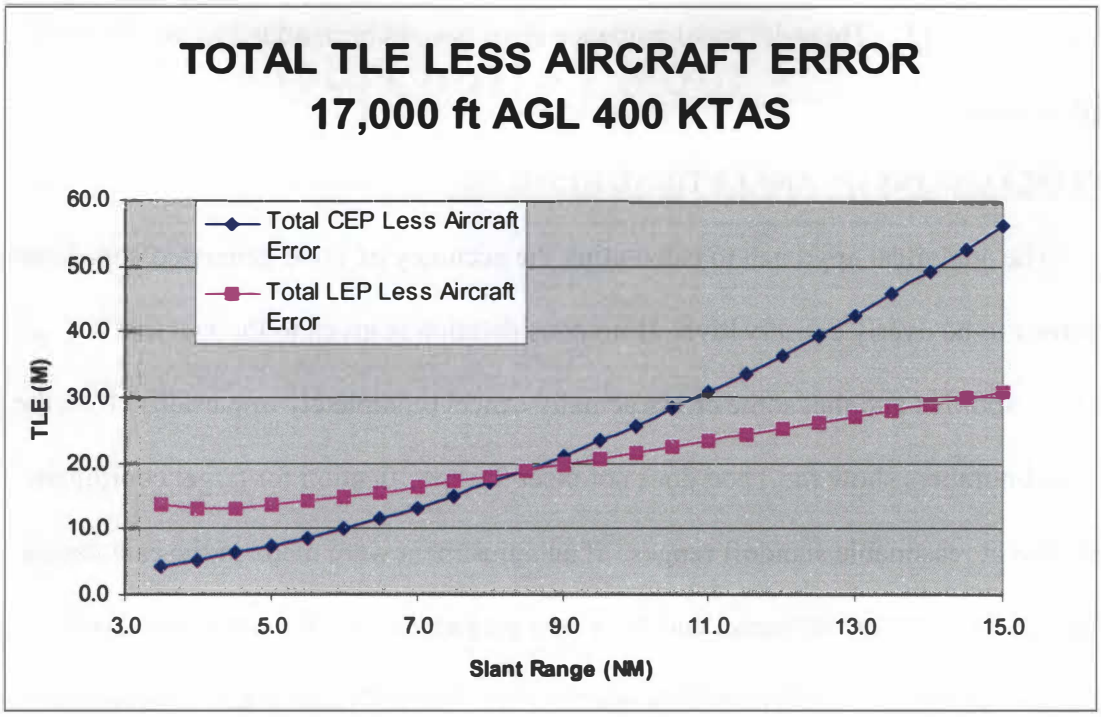
TLE_{CEP} and TLE_{LEP} are significantly decreased as shown in Table 5-2. Figure 5-2 is a graphical presentation of the data in Table 5-2.

An arcing maneuver as shown in Figure 1-9, once again, will help develop the needed line of sight rate for quick Tpod coordinate generation. However, the coordinate generation capability of the Tpod in the relative mode using analytical data still shows this maneuver should be performed well within 5 nm of the target. This is closer than desired to the target allowing for very little standoff capability. Keep in mind, the errors determined analytically even from the relative targeting mode are still the worst-case possible for each of the errors being used in the calculation. The magnitude of the difference in total analytical TLE and relative mode analytical TLE is what is important.

Table 5-2 Total Tpod Analytical TLE Less Aircraft Error as a Function of Range[1]

Slant Range (nm)	Horizontal Range (nm)	TLE_{CEP} Less A/C Error (m)	TLE_{LEP} Less A/C Error (m)	Slant Range (nm)	Horizontal Range (nm)	TLE_{CEP} Less A/C Error (m)	TLE_{LEP} Less A/C Error (m)
15.0	14.7	56.3	31.1	9.0	8.6	21.2	19.9
14.5	14.2	52.7	30.1	8.5	8.0	19.0	19.1
14.0	13.7	49.2	29.2	8.0	7.5	17.0	18.2
13.5	13.2	45.9	28.2	7.5	7.0	15.1	17.4
13.0	12.7	42.7	27.3	7.0	6.4	13.3	16.5
12.5	12.2	39.5	26.3	6.5	5.9	11.6	15.8
12.0	11.7	36.6	25.4	6.0	5.3	10.0	15.0
11.5	11.2	33.7	24.5	5.5	4.7	8.5	14.3
11.0	10.6	31.0	23.6	5.0	4.1	7.3	13.7
10.5	10.1	28.3	22.6	4.5	3.5	6.3	13.3
10.0	9.6	25.8	21.7	4.0	2.9	5.3	13.1
9.5	9.1	23.4	20.8	3.5	2.1	4.2	13.6

1. Constant 17,000 ft AGL



*Does not include JDAM INS-only navigation error in any data

Figure 5-2 Total Tpod Analytical TLE Less Aircraft Error

Analytically, the error decreases by a magnitude of 2 to 3 when aircraft position error, heading error, and bearing error are factored out. The relative targeting mode shows promise if one considers some of the errors will cancel and the individual performance of each component is typically better then the specification for the Tpod.

If the JDAM is launched in an INS-only mode either due to not acquiring the GPS satellites or because the pilot performed GPS halt procedures then the errors will be slightly worse then shown in Figure 5-2. This is because the weapon has to rely only on its internal INS for navigation. This induces an additional error, which is added to the TLE in Figure 5-2 based on the amount of time the weapon is in flight. After 30 seconds an additional error of 3 m should be added. After 60 seconds an additional error of 8 m

should be added [2]. This additional guidance error has not been added to any tables or figures presented.

5.5 CONCLUSIONS OF ANALYTICAL RESULTS.

The analytical approach to calculating the accuracy of Tpod generated coordinates has shown to be overly conservative. If no consideration is given to the fact that not all errors are additive and that some errors actually cancel (completely or partially) then the analytical numbers show the Tpod does not meet the specification for target coordinate generation at reasonable standoff ranges. If an adjustment were made to the calculation because some of the errors cancel and the actual performance of the individual Tpod errors is better than the manufacturer's specification, the analytical approach shows there is promise to using the Tpod for target coordinate generation.

The analytical approach has also shown that if the source of the coordinates is an aircraft sensor, the best method of releasing the weapon is in the relative mode. Unfortunately, due to a software coding error, the AV-8B is not capable of setting the relative bit properly to achieve the relative targeting mode using the Tpod as the target coordinate source. Because of this, the weapon will guide to earth-based coordinates unless the GPS navigation mode of the weapon is interrupted somehow such as by performing GPS halt procedures. Unfortunately, this also induces additional error due to degradation of the JDAM INS error over time.

6. FLIGHT TEST RESULTS

6.1 DESCRIPTION OF FLIGHT TEST.

Over the course of the developmental flight-testing of the H2.0 OFP from the summer of 2003 to the summer of 2004, nine test sorties were dedicated to collecting actual Tpod generated TLE data. The target was a surveyed point via classified sources. All nine test flights were conducted on a dedicated telemetry capable range. All flight profiles were performed at approximately 17,000 ft above ground level (AGL) from 20 to 3 nm in slant range. Airspeeds varied, but were generally conducted at maximum endurance. These flights were dedicated to capturing the total TLE capability of the Tpod. No attempt was made to determine aircraft position errors during this testing since the relative targeting bit could not be set.

The pilot set the center of the Tpod on the surveyed spot of the target. Once the Tpod was centered, the laser designator was turned on and the pilot flew directly toward the target. An arcing maneuver to produce sensor line of sight rate was not performed as discussed in previous chapters because quick coordinate convergence was not considered at the time. The only line of sight rate achieved was due to target over flight. Once the target was over flown, the pilot secured the laser and the pass was complete.

The latitude, longitude, and elevation in MSL, collected through on board the aircraft and telemetry sources, was sent to the Precision Targeting Branch at Naval Air Warfare Center, Weapons Division (NAWCWD), China Lake, California for analysis.

6.2 RESULTS OF FLIGHT TEST.

The Precision Targeting Branch compared the coordinates generated by the Tpod to the classified surveyed coordinates of the target. The data was plotted as total TLE verses slant range. The data includes all possible errors, the same discussed throughout this thesis with the exception of the MSL to HAE conversion, in earth-based (absolute) coordinates. The MSL to HAE conversion was not part of the TLE collection effort because this conversion takes place in the weapon itself. There were no weapons on board the aircraft for these flights. The TLE of the actual Tpod generated coordinates using the laser designator is plotted in Figure 6-1. Using the 50% confidence error data provided by the Targeting Branch results in the horizontal CEP and vertical LEP shown.

Actual flight test generated Tpod target coordinates met the JDAM specification for horizontal CEP at less then 6.0 nm slant range. The vertical TLE met the specification throughout the range presented.

Based on the analytical data in chapter 5, a speculation can be made of what would happen if aircraft errors (position, bearing, and heading) were factored out of the flight test data to show a relative mode capability. Figures 5-1 and 5-2 show the magnitude of difference in total error analytical data and relative error analytical data. If this same magnitude of error is factored out of the flight test data then the data shown in Figure 6-1 should have no problem meeting the TLE requirements throughout the range of the graph. This would significantly increase the stand off range at which target coordinates could be generated.

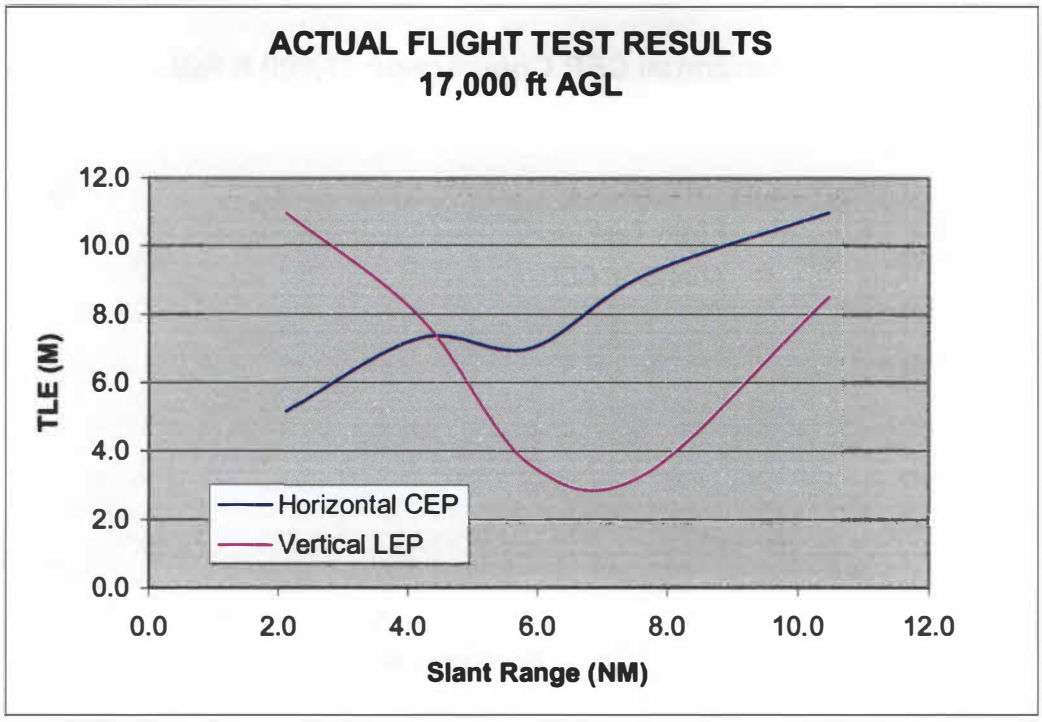


Figure 6-1 Flight Test Tpod TLE [10]

6.3 COMPARISION TO ANALYTICAL DATA.

Flight test data was then plotted against analytical data for comparison as shown in Figure 6-2 (horizontal CEP) and Figure 6-3 (vertical LEP). As can be seen from these two figures there is a significant difference in analytical data and flight test data. This difference shows that most likely some error cancellation occurred and better than advertised Tpod component performance is apparent in the actual flight-test data.

Since the actual flight test data contains all error sources with the exception of the MSL to HAE conversion, the analytical data has been adjusted for all error sources without the HAE conversion error included.

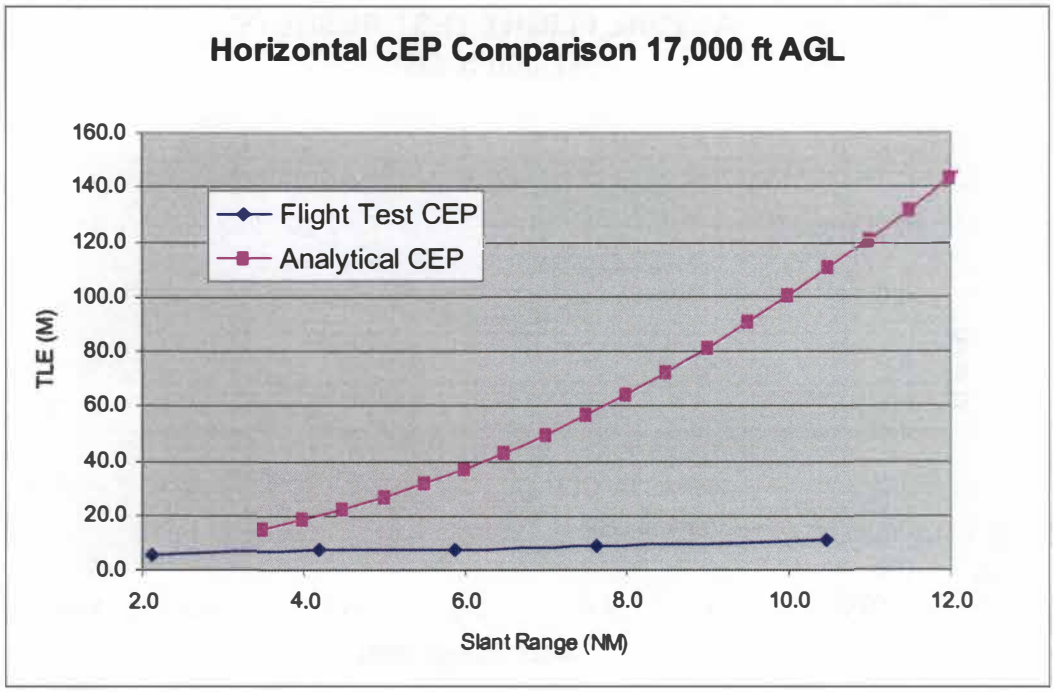


Figure 6-2 Horizontal TLE Comparison

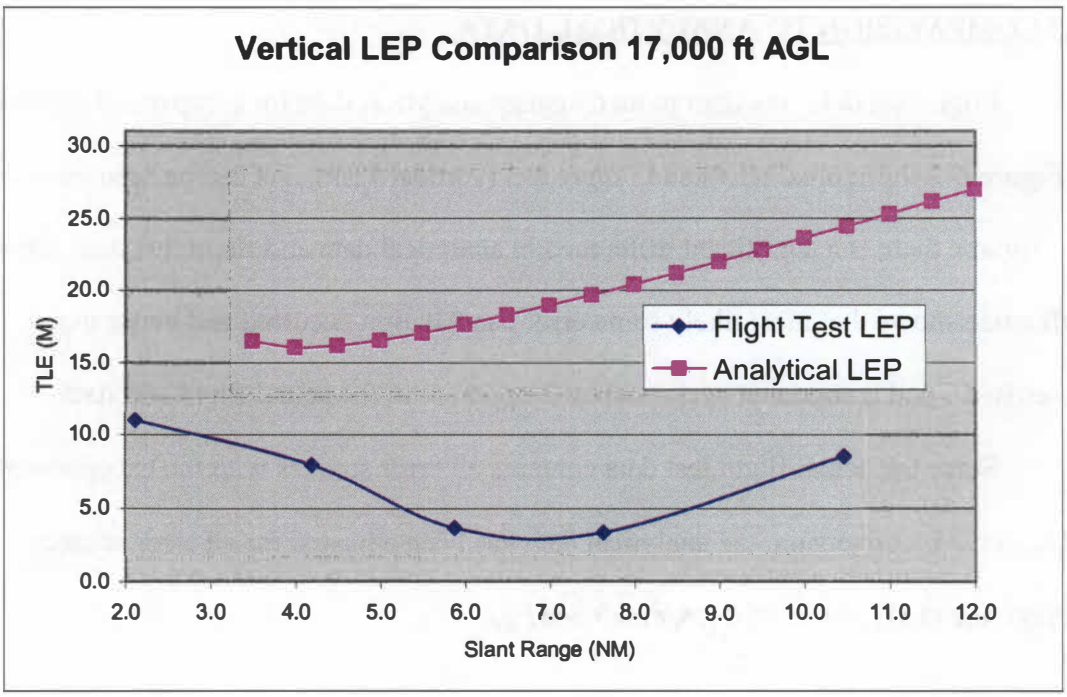


Figure 6-3 Vertical TLE Comparison

6.4 CONCLUSIONS OF FLIGHT TEST RESULTS.

Based upon the results of flight test data, the arcing portion of the profile should be conducted inside 6 nm if possible. This will help ensure JDAM TLE requirements are met for JDAM specification compliance. If and when the aircraft, using the Tpod as a source for target coordinates, can set the relative targeting bit properly, then the arcing maneuver can be performed at significantly greater ranges as speculated in section 6.2.

7. CONCLUSION

7.1 DECISION TREE.

A JDAM targeting decision diagram is shown in Figure 7-1. This decision tree is a summary of which coordinate type will be used based on the source of the coordinates and what capabilities the source brings for targeting JDAM. The important point to remember is any mensurated coordinates (minimum TLE) used for targeting should not be over-written and should be released in the earth-based reference frame. If the source of the coordinates is an "on aircraft" sensor then the relative bit should be set if possible and the weapon released in a relative targeting mode.

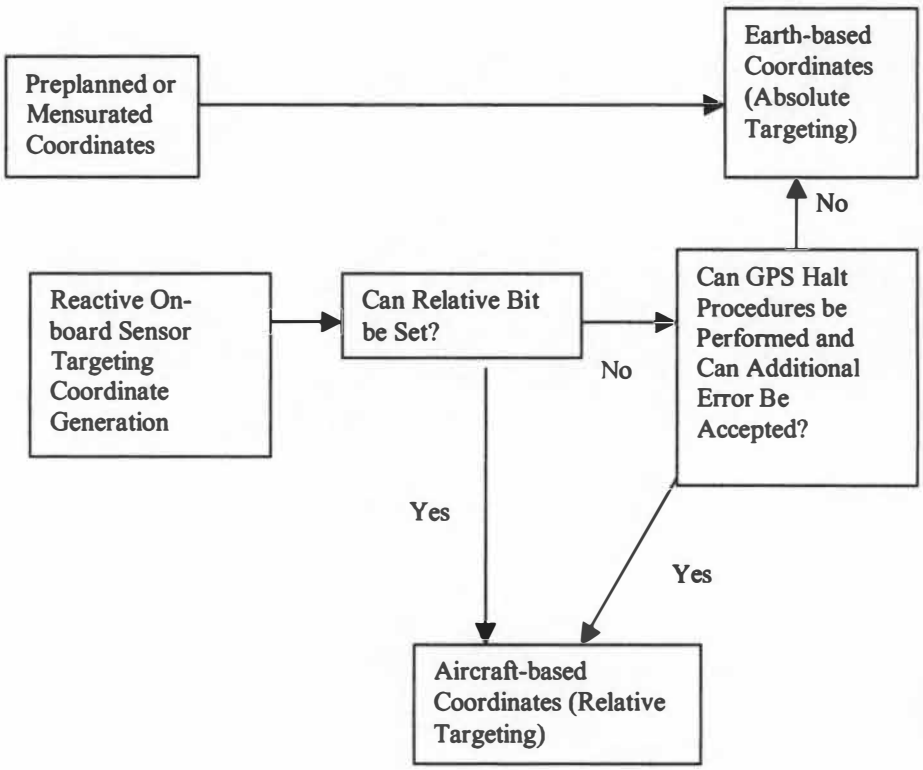


Figure 7-1 JDAM Targeting Decision Diagram

If the relative bit can not be set for a sensor such as the Tpod then an analysis of the total error will have to be made such that if TLE is acceptable then perform the JDAM GPS halt procedures and release the weapon in the aircraft-based reference frame (relative mode). If those errors are unacceptable then release the weapon in the earth-based coordinate reference frame depending on rules of engagement (ROE). The battlefield commander determines the level of accuracy desired for GPS guided weapons based upon the battlefield situation by setting the ROE. If at any time the TLE is greater then the ROE then the weapon should not be released.

7.2 OVERALL CONCLUSIONS.

The analytical approach to calculating the accuracy of Tpod generated coordinates by this thesis has shown to be too conservative. This is due to giving no consideration to the possibility that the errors are not all additive in nature but instead partially or totally cancel in some cases. In addition, the individual Tpod error components cannot be adjusted to more accurate values because no data exists to justify the correction. Because no consideration is given to the possible cancellation of errors or actual performance of Tpod components, the analytical numbers show the Tpod coordinate generation capability does not meet the JDAM specification for TLE at reasonable standoff ranges. There is no way to know which errors will cancel and to what magnitude without conducting further testing. There is also no way to predict actual performance without further testing. Even if further testing is conducted, the actual error cancellations may not be consistent. However, the analytical approach to calculating errors has shown the magnitude of difference between relative targeting and earth-based targeting and gives insight into what would happen with flight test data if adjusted for relative targeting.

Actual flight test data also shows the Tpod TLE data is only able to meet the specification threshold for JDAM TLE as currently implemented in the AV-8B at slant ranges less than 6 nm. If, however, the aircraft software is corrected and the relative targeting bit can be set, the data shows potential of easily meeting the JDAM specification threshold for TLE at ranges significantly greater then 6 nm.

Aircraft position error should be adjusted based upon known improvements in GPS accuracy that cannot be discussed in this thesis due to the source. By making this adjustment the total error of the weapon would either decrease or additional error could be allowed in different areas such as TLE to still maintain the specification of a 13 m weapon. If the TLE were increased, the Tpod (and other sensors for that matter) might be able to more easily meet the specification of target coordinate generation accuracy.

In reality, the battlefield commander will determine what level of accuracy is acceptable for a given mission by setting the ROE. A 13 m CEP specification for JDAM was great for driving design requirements, but now that the system has been designed and fielded the commander will use the weapon system as needed for a given situation. For a particular mission, the commander not need a CEP of 13 m but may be willing to accept something greater. In this case, using the Tpod as the target coordination source may be sufficient to meet the commander's ROE.

7.3 RECOMMENDATIONS.

The first recommendation is to **fix the aircraft software to set the relative bit properly for Tpod targeting**. The only potential work-around for this particular issue is to **perform JDAM GPS halt procedures and force the weapon to guide to aircraft-**

based (relative) coordinates. This unfortunately also induces JDAM INS-only drift errors making the accuracy of the weapon worse over the time of flight of the weapon.

The next recommendation is to **generate elevation in HAE vice MSL if possible.** This will reduce, by as much as 6 meters, elevation error caused when the weapon converts MSL to HAE. In addition, to reduce elevation error even further, the **pilot should be allowed to select a steeper impact angle than 65 deg.** The impact angle needs to be selectable by the pilot based on the accuracy of the sensor generating the coordinate.

The most precise position-keeping mode of the aircraft should always be used. Thought should be given to **installing a more accurate INS and air data computer in the AV-8B** when one becomes available to help minimize aircraft position handoff and heading errors. When it becomes available, **incorporate better processing of the Tpod image** to help minimize any pixel size induced errors. To help minimize heading and bearing errors during earth-based coordinate targeting, **increase the airspeed of the aircraft during the targeting process.** Continue to pressure the manufacturer to **tighten the tolerance level for the Tpod INS alignment, pointing accuracy, and ranging accuracy** to help minimize the remaining errors. **Flight test should also be performed to determine rules of thumb for target coordinate generation accuracy for use on the battlefield.**

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APPENDICES

APPENDIX A

This section describes the theory behind the statistical analysis and provides some insight into the terms and quantities used in the thesis.

STATISTICAL THEORY, FORMULA, AND DERIVTIONS.

1. All error distributions are considered to be normal (i.e. Gaussian).
2. The root mean square (RMS) and standard deviations (StdDev) for flight test data were calculated using the Microsoft Excel spreadsheet for RMS and the Excel function for StdDev.
3. Circular Error Probable and Linear Error Probable are used throughout this thesis in order to compare the results to the JDAM specification, which is calculated in those terms.
4. Circular Error Probable is defined as an indicator of the delivery accuracy of a weapon system used to determine probable damage to a target. CEP is the radius of a circle within which half of the weapons are projected to fall. For the purposes of this thesis all horizontal error terms are calculated in terms of CEP.
5. LEP is the value in a single dimension, centered at the position that contains 50% of the vertical position estimates. For a horizontal target, any error in the vertical will resolve to an error range, depending on the sensitivity of the horizontal CEP to that error. For this thesis, the conversion of vertical error to a horizontal error was not made since the AV-8B sets the weapon impact angle to 65 deg by default. This meets the JDAM specification for horizontal CEP with a weapon impact angle greater than 60 deg.

DERIVATIONS.

Chapter 1 - Introduction

None.

Chapter 2 - Aircraft Position Error

Aircraft horizontal error (CEP) and spherical error (SEP) were given as results in reference 8. Vertical error (LEP) was calculated using an equation from the test report. Given SEP and CEP from the test report, LEP can be calculated via the following equation:

$$SEP_{A/C} = 0.87\ CEP_{A/C} + 0.76\ LEP_{A/C}$$

This equation originally came from the Integrated Multi-service Test and Evaluation Master Plan for NAVSTAR GPS (reference 8).

Chapter 3 - Operator Error

Operator error is defined as only the error associated with resolution of the pixel size for the purposes of this thesis. No other errors were taken into consideration because the point to be targeted is assumed to be the point under the center of the Tpod display. If the center of the display is not on the correct spot then the operator is assumed to have adjusted the Tpod appropriately. The pixel size presented to the operator is 0.034 mrad. This is derived from the following equation:

$$17.45\ (\text{mrad / deg}) \times 1\ \text{deg} / 512\ \text{pixels} = 0.034\ \text{mrad / pixel}$$

The amount of error in meters with respect to range can be calculated in terms of CEP_{MAX} and LEP_{MAX}. CEP_{MAX} is defined as the maximum CEP in the horizontal plane projected by a one-sigma deviation from actual of a bearing, heading, INU alignment, pointing, and ranging error as shown in Figure A-1.

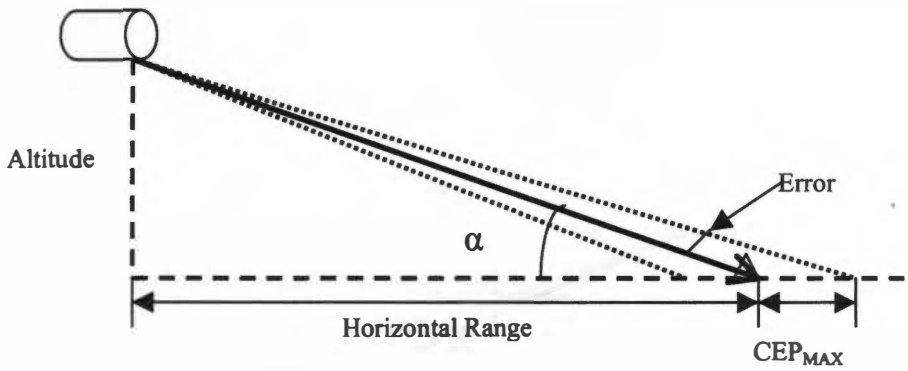

Figure A-1 CEP$_{MAX}$ Graphical Presentation

LEP$_{MAX}$ is defined as the maximum LEP in the vertical plane orthogonal to the CEP$_{MAX}$ within the footprint of the CEP, projected by a one-sigma deviation from actual of a bearing, heading, INU alignment, and pointing error as shown in Figure A-2.

Figure A-3 shows a line orthogonal to the laser vector emanating from the Tpod used in follow on calculations.

The error orthogonal to the laser vector = sin(angular error)x slant range (m). The slant range in meters = slant range (nm) x 6079 ft/nm x 0.3048 m/ft. The CEP$_{MAX}$ in now defined in the following equation:

CEP$_{MAX}$ = error orthogonal (m) / sin (α – error).

LEP$_{MAX}$ is defined through the following formulas using Figure A–3 for reference:

X = Altitude / tan (α + error)

Y = Altitude / tan (α – error)

Z = y – x = Altitude (1 / tan (α – error) – 1 / tan (α + error))

LEP$_{MAX}$ is then defined by the equation:

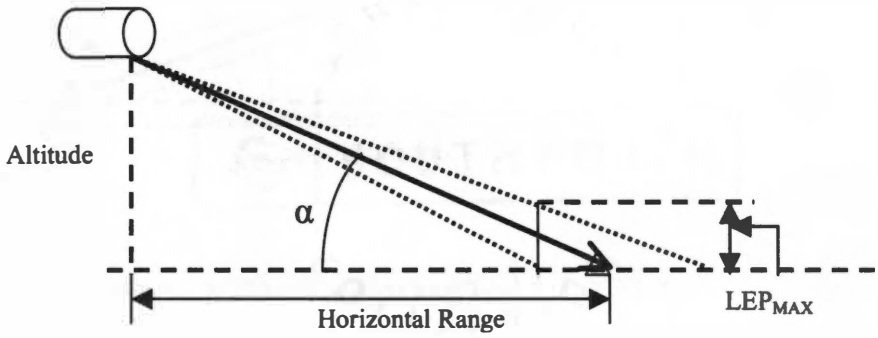

Figure A-2 LEP$_{MAX}$ Graphical Presentation

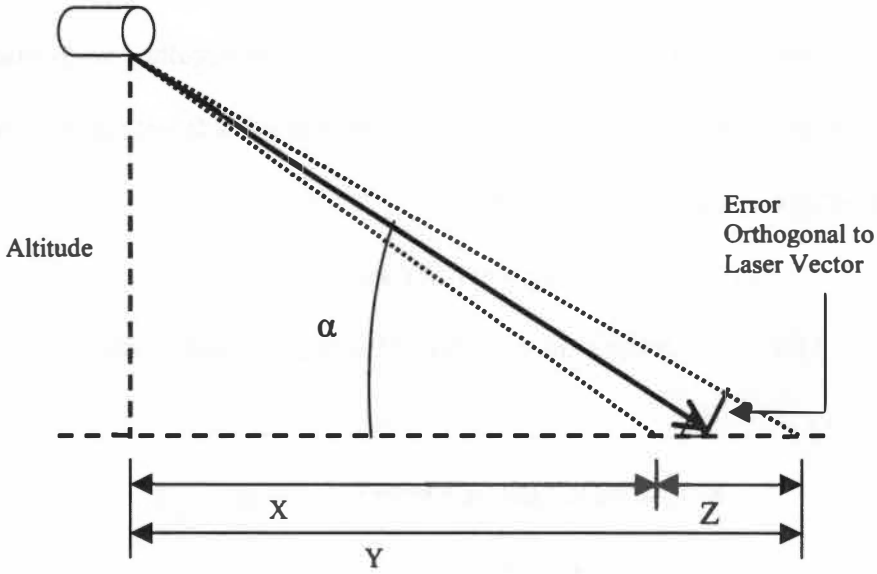

Figure A-3 Error Orthogonal to Laser Vector

LEP_{MAX} = Z (tan (α – error)) = Altitude (m) (1 - tan (α – error) / tan (α + error)) (tan(α – error))

Chapter 4 – Litening Pod Error

Heading and bearing error were calculated using an RMS value of Performance Error Rate (PER) of actual aircraft INS data. RMS was calculated using the following formula:

RMS = (((N1)^2 + (N2)^2 + (N3)^2 + …+ (Ni)^2) / i)^(1/2)

A standard deviation was then calculated using Microsoft Excel Spreadsheet StdDev equation. The two were added together to achieve a maximum PER resulting in a PER of 0.41 nm/hr. To calculate the maximum angular error using this error rate the PER is then plotted orthogonal to the aircraft vector (as in Figure 4-1) because this is where the error will cause the most deviation in heading and bearing. To obtain the angular error the equation is:

$$\tan(\alpha) = PER / KTAS \text{ or}$$

$$\alpha = \tan^{-1} (PER/KTAS).$$

This then gives an error α (mrad) to use in the calculation of CEP_{MAX} and LEP_{MAX} as defined in the chapter 3 section of this appendix.

Alignment error and pointing error were also calculated using CEP_{MAX} and LEP_{MAX} as in the previous section to this appendix.

The error due to Tpod ranging error (ΔR) is shown in Figure A-4.

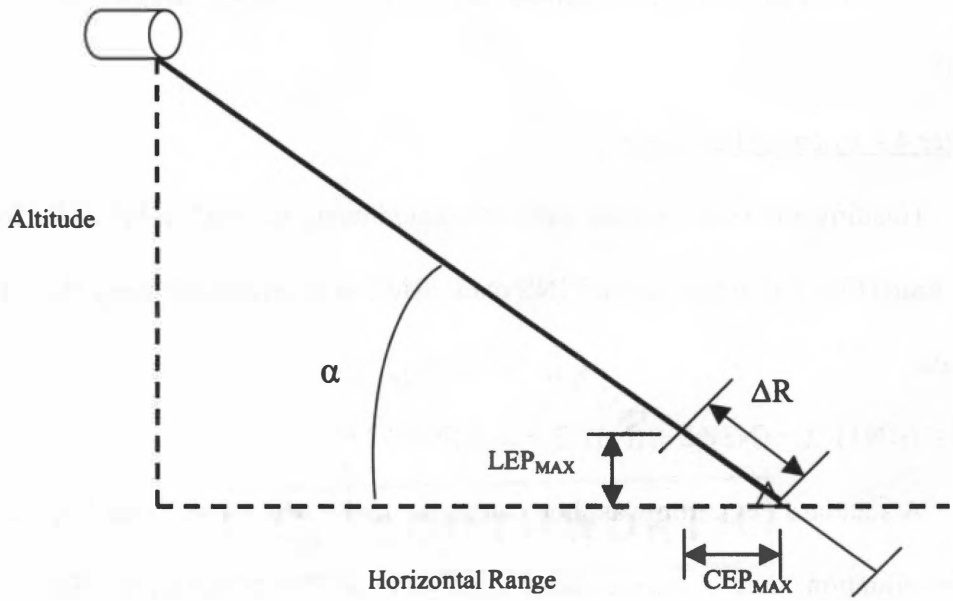

Figure A-4 Error Due to Tpod Ranging Error

The magnitude of ΔR is specified by the manufacturer and can be converted into terms for CEP_{MAX} and LEP_{MAX} through the follow equations:

$$CEP_{MAX} = (\Delta R) \cos(\alpha) \quad \text{and} \quad LEP_{MAX} = (\Delta R) \sin(\alpha).$$

<u>Chapter 5 – Total Error</u>

The following definitions apply:

CEP_{pos} is the total horizontal aircraft position error from chapter 2.

CEP_{op} is the total horizontal operator error from chapter 3.

CEP_{hdg} is the total horizontal heading error from chapter 4.

CEP_{brg} is the total horizontal bearing error from chapter 4.

CEP_{imu} is the total horizontal Tpod alignment error from chapter 4.

CEP_{point} is the total horizontal Tpod pointing error from chapter 4.

$CEP_{\Delta R}$ is the total horizontal Tpod ranging error from chapter 4.

LEP_{pos} is the total vertical aircraft position error from chapter 2.

LEP_{op} is the total vertical operator error from chapter 3.

LEP_{imu} is the total vertical Tpod IMU alignment error from chapter 4.

LEP_{point} is the total vertical Tpod pointing error from chapter 4.

$LEP_{\Delta R}$ is the total vertical Tpod ranging error from chapter 4.

LEP_{HAE} is the total vertical MSL to HAE conversion error from chapter 4.

The total TLE of Tpod generated target coordinates was defined as the RSS of all CEP error sources and the RSS of all LEP error sources:

$$TLE_{CEP} = [(CEP_{pos})^2 + (CEP_{op})^2 + (CEP_{hdg})^2 + (CEP_{brg})^2 + (CEP_{imu})^2 + (CEP_{point})^2 + (CEP_{\Delta R})^2]^{1/2}$$

$$TLE_{LEP} = [(LEP_{pos})^2 + (LEP_{op})^2 + (LEP_{imu})^2 + (LEP_{point})^2 + (LEP_{\Delta R})^2 + (LEP_{HAE})^2]^{1/2}$$

The total TLE Less aircraft error was calculated using the same formula minus the aircraft generated errors as in the following equations:

$$TLE_{CEP} = [(CEP_{op})^2 + (CEP_{imu})^2 + (CEP_{point})^2 + (CEP_{\Delta R})^2]^{1/2}$$

$$TLE_{LEP} = [(LEP_{op})^2 + (LEP_{imu})^2 + (LEP_{point})^2 + (LEP_{\Delta R})^2 + (LEP_{HAE})^2]^{1/2}$$

These resulting TLE_{CEP} and TLE_{LEP} were then plotted with respect to range.

Chapter 6 – Flight Test

None.

Chapter 7 - Conclusions

None.

APPENDIX B

Table B-1 Angle and Range at Constant 17,000 ft AGL

Angle and Range at Constant 17,000 Ft AGL					
Slant Range (NM)	Slant Range (ft)	Slant Range (M)	Horizontal Range (NM)	Angle (Rad)	Angle (Deg)
15.0	91,185.0	27,793.2	14.7	0.187531	10.7
14.5	88,145.5	26,866.7	14.2	0.194079	11.1
14.0	85,106.0	25,940.3	13.7	0.201104	11.5
13.5	82,066.5	25,013.9	13.2	0.208660	12.0
13.0	79,027.0	24,087.4	12.7	0.216811	12.4
12.5	75,987.5	23,161.0	12.2	0.225631	12.9
12.0	72,948.0	22,234.6	11.7	0.235205	13.5
11.5	69,908.5	21,308.1	11.2	0.245638	14.1
11.0	66,869.0	20,381.7	10.6	0.257050	14.7
10.5	63,829.5	19,455.2	10.1	0.269588	15.4
10.0	60,790.0	18,528.8	9.6	0.283431	16.2
9.5	57,750.5	17,602.4	9.1	0.298796	17.1
9.0	54,711.0	16,675.9	8.6	0.315954	18.1
8.5	51,671.5	15,749.5	8.0	0.335246	19.2
8.0	48,632.0	14,823.0	7.5	0.357106	20.5
7.5	45,592.5	13,896.6	7.0	0.382098	21.9
7.0	42,553.0	12,970.2	6.4	0.410973	23.5
6.5	39,513.5	12,043.7	5.9	0.444751	25.5
6.0	36,474.0	11,117.3	5.3	0.484861	27.8
5.5	33,434.5	10,190.8	4.7	0.533392	30.6
5.0	30,395.0	9,264.4	4.1	0.593544	34.0
4.5	27,355.5	8,338.0	3.5	0.670589	38.4
4.0	24,316.0	7,411.5	2.9	0.774177	44.4
3.5	21,276.5	6,485.1	2.1	0.925636	53.0

Table B-2 CEP_{MAX} and LEP_{MAX} at Constant 17,000 ft AGL Page 1

Slant Range (NM)	Horizontal Range (NM)	CEP Max Due to X rad (m)	LEP Max Due to X rad (m)	CEP Max Due to X rad (m)	LEP Max Due to X rad (m)
15.0	14.7	14.9	8.3	5.1	2.8
14.5	14.2	13.9	8.0	4.7	2.7
14.0	13.7	13.0	7.8	4.4	2.6
13.5	13.2	12.1	7.5	4.1	2.6
13.0	12.7	11.2	7.3	3.8	2.5
12.5	12.2	10.4	7.0	3.5	2.4
12.0	11.7	9.5	6.7	3.2	2.3
11.5	11.2	8.8	6.5	3.0	2.2
11.0	10.6	8.0	6.2	2.7	2.1
10.5	10.1	7.3	5.9	2.5	2.0
10.0	9.6	6.6	5.7	2.3	1.9
9.5	9.1	6.0	5.4	2.0	1.8
9.0	8.6	5.4	5.2	1.8	1.8
8.5	8.0	4.8	4.9	1.6	1.7
8.0	7.5	4.2	4.7	1.4	1.6
7.5	7.0	3.7	4.4	1.3	1.5
7.0	6.4	3.2	4.2	1.1	1.4
6.5	5.9	2.8	3.9	1.0	1.3
6.0	5.3	2.4	3.7	0.8	1.3
5.5	4.7	2.0	3.5	0.7	1.2
5.0	4.1	1.7	3.3	0.6	1.1
4.5	3.5	1.3	3.1	0.5	1.1
4.0	2.9	1.1	3.0	0.4	1.0
3.5	2.1	0.8	3.2	0.3	1.1
		Error (rad) =	0.0001	Error (rad) =	0.000034

Table B-3 CEP_{MAX} and LEP_{MAX} at Constant 17,000 ft AGL Page 2

Slant Range (NM)	Horizontal Range (NM)	CEP Max Due to X rad (m)	LEP Max Due to X rad (m)	CEP Max Due to X rad (m)	LEP Max Due to X rad (m)
15.0	14.7	152.9	84.4	52.3	29.1
14.5	14.2	142.8	81.7	48.8	28.1
14.0	13.7	133.1	79.0	45.5	27.2
13.5	13.2	123.8	76.3	42.3	26.3
13.0	12.7	114.7	73.6	39.3	25.3
12.5	12.2	106.1	71.0	36.3	24.4
12.0	11.7	97.7	68.3	33.4	23.5
11.5	11.2	89.7	65.6	30.7	22.6
11.0	10.6	82.1	63.0	28.1	21.7
10.5	10.1	74.8	60.3	25.6	20.7
10.0	9.6	67.8	57.7	23.2	19.8
9.5	9.1	61.2	55.1	21.0	18.9
9.0	8.6	54.9	52.5	18.8	18.0
8.5	8.0	49.0	49.9	16.8	17.1
8.0	7.5	43.4	47.3	14.9	16.3
7.5	7.0	38.1	44.8	13.1	15.4
7.0	6.4	33.2	42.3	11.4	14.6
6.5	5.9	28.6	39.9	9.8	13.7
6.0	5.3	24.4	37.6	8.4	12.9
5.5	4.7	20.5	35.4	7.0	12.2
5.0	4.1	16.9	33.5	5.8	11.5
4.5	3.5	13.7	31.9	4.7	10.9
4.0	2.9	10.8	31.0	3.7	10.7
3.5	2.1	8.3	32.3	2.8	11.1
		Error (rad) =	0.00102	Error (rad) =	0.00035

Table B-4 TLE_{CEP} and TLE_{LEP} at Constant 17,000 ft AGL Page 1

Slant Range (NM)	Horizontal Range (NM)	TOTAL TLE_{CEP} (M)	TOTAL TLE_{LEP} (M)	TOTAL TLE_{CEP} (M) Less Aircraft Error	TOTAL TLE_{LEP} (M) Less Aircraft Error
15.0	14.7	223.6	32.9	56.3	31.1
14.5	14.2	208.9	32.0	52.7	30.1
14.0	13.7	194.8	31.1	49.2	29.2
13.5	13.2	181.1	30.2	45.9	28.2
13.0	12.7	168.0	29.4	42.7	27.3
12.5	12.2	155.3	28.5	39.5	26.3
12.0	11.7	143.2	27.6	36.6	25.4
11.5	11.2	131.6	26.8	33.7	24.5
11.0	10.6	120.4	26.0	31.0	23.6
10.5	10.1	109.8	25.1	28.3	22.6
10.0	9.6	99.7	24.3	25.8	21.7
9.5	9.1	90.0	23.5	23.4	20.8
9.0	8.6	80.9	22.7	21.2	19.9
8.5	8.0	72.3	22.0	19.0	19.1
8.0	7.5	64.1	21.2	17.0	18.2
7.5	7.0	56.5	20.5	15.1	17.4
7.0	6.4	49.4	19.8	13.3	16.5
6.5	5.9	42.8	19.2	11.6	15.8
6.0	5.3	36.8	18.5	10.0	15.0
5.5	4.7	31.2	18.0	8.5	14.3
5.0	4.1	26.3	17.5	7.3	13.7
4.5	3.5	21.9	17.2	6.3	13.3
4.0	2.9	18.1	17.1	5.3	13.1
3.5	2.1	14.8	17.5	4.2	13.6

Table B-5 TLE_{CEP} and TLE_{LEP} at Constant 17,000 ft AGL Page 2

Slant Range (NM)	Horizontal Range (NM)	TOTAL TLE_{LEP} (M) Less HAE Error
15.0	14.7	32.4
14.5	14.2	31.5
14.0	13.7	30.5
13.5	13.2	29.6
13.0	12.7	28.8
12.5	12.2	27.9
12.0	11.7	27.0
11.5	11.2	26.1
11.0	10.6	25.3
10.5	10.1	24.4
10.0	9.6	23.6
9.5	9.1	22.7
9.0	8.6	21.9
8.5	8.0	21.1
8.0	7.5	20.4
7.5	7.0	19.6
7.0	6.4	18.9
6.5	5.9	18.2
6.0	5.3	17.5
5.5	4.7	16.9
5.0	4.1	16.5
4.5	3.5	16.1
4.0	2.9	16.0
3.5	2.1	16.4

VITA

Shaun C. Spang graduated from the United States Naval Academy in May of 1991 with a Bachelor of Science Degree in Naval Architecture and was commissioned a Second Lieutenant in the United States Marine Corps. Shaun's first assignment was to attend the Marine Corps Officer's Basic School in Quantico, Virginia studying the Marine Corps mission and infantry tactics. Following the Basic School, he was directed to flight school in Pensacola, Florida. Shaun was designated a Naval Aviator in August of 1994 and directed to VMAT-203 for AV-8B Harrier training. Since that initial Harrier training, he has served in 2 fleet AV-8B Squadrons, VMA-542 and VMA-231, and also as an instructor at the training squadron VMAT-203. All three of these squadrons are located at Marine Corps Air Station Cherry Point, North Carolina. In March of 2002 he was selected for test pilot training at the United States Navy Test Pilot School, Patuxent River, Maryland with Class 123. Shaun attended Test Pilot School from July 2002 to June 2003 where he flew many different types of aircraft from the United States and other countries. Aircraft types were as small as gliders to the U. S. Navy P-3C Orion. Following Test Pilot School, Shaun was directed to his current position at Air Test and Evaluation Squadron 31 at China Lake, California and attached to the AV-8B Joint Systems Support Activity. Shaun is married to the former Kimberly Ann King of Baltimore, Maryland.

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