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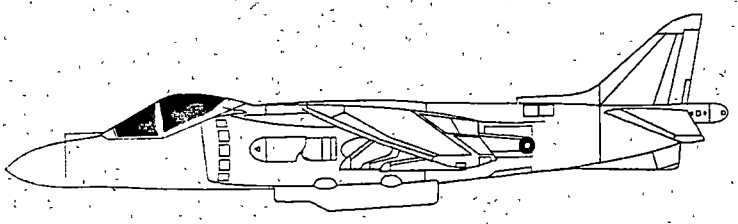
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A STATISTICAL ANALYSIS OF ERRORS ASSOCIATED WITH THE AV-8B SENSOR SUITE



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

James Frederick Kromberg
May 1999

DISCLAIMER

The technical data contained in this thesis are the result of system analysis, laboratory tests and flight evaluations of the AV-8B Harrier aircraft air-to-surface sensor suite. Where required, pseudo data have been inserted to preserve the classification of "real" AV-8B sensor capabilities and limitations. All deficiencies attributed to the aircraft and its sensor suite are the opinion of the author and may or may not represent the official position of the Naval Air Warfare Center, the Commander Operational Test Force, 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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ABSTRACT

The Marine Expeditionary Unit (MEU) battlefield continues to evolve with conflicts around the world, requiring quick, precision strike capability. In support of MEU air operations, the AV-8B Harrier needs air-to-surface munitions which, once released from the aircraft, guide autonomously to the designated target coordinates. Global Positioning System (GPS) directed bomb-on-coordinate (BOC) weapons such as the Joint Direct Attack Munition (JDAM), Joint Stand-Off Weapon (JSOW) and Joint Attack Strike Missile (JASM) fulfill this capability. In-flight targeting of BOC munitions against fixed and re-locatable targets is a derived requirement of the weapon to aircraft integration.

This paper is an analysis of the target location error (TLE) associated with target coordinates generated using the following AV-8B aircraft sensors: the AN/APG-65 radar utilizing medium resolution synthetic aperture radar (MRSAR) mapping, the Angle-Rate Bombing System (ARBS) using an electro-optical (EO)-TV designation, and the Head-Up Display (HUD) using visual Global Positioning System - Inertial Navigation System (GPS-INS) designations. The three major TLE contributors associated with each sensor designation are aircraft position error, operator error and sensor error.

This analysis validates the use of the AV-8B sensor suite in directing BOC weapons in the following priority:

(1) ARBS designations provide for the minimum TLE and should be used as the primary source for direction of BOC weapons such as JDAM.

(2) HUD designations provide for a minimization of TLE and should be used as the secondary source for direction of BOC weapons such as JDAM, provided the ARBS or AN/APG-65 radar is used to determine target elevation.

(3) MRSAR map designations do not provide for minimization of TLE and should not be used to direct a single BOC weapon against a single target designation. Further study is required to determine if the designations are accurate enough to direct multiple weapons against a single target designation.

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GLOSSARY

Acquisition Cursor. Two small parallel vertical lines on the radar display, positioned with the target designation control (TDC) to designate a target.

ADC. Air Data Computer.

A/G. Air-to-Ground. Used or occurring between aircraft and the ground, as in air-to-ground weapons delivery.

AGL. Height Above Ground Level.

AGR. Air-to-Ground Ranging. The AGR mode is selected whenever the sensor select switch is actuated forward. The AGR mode provides accurate slant range along the commanded LOS.

Airspeed. The speed of an aircraft relative to its surrounding air mass, typically qualified by true. ground, calibrated.

AN/APG-65. I-Band Pulse Doppler Radar installed in the AV-8B manufactured by Raytheon Corporation (formerly Hughes Aircraft).

AOA. Angle-of-Attack

ARBS. Angle Rate Bombing System.

A/S. Air-to-Surface. Synonymous with A/G, used to describe a mode of the radar.

BOC. Bomb-on-Coordinate

BST. Boresight.

CAS. Close Air Support. Air action against hostile targets that are in close proximity to friendly ground forces and that require detailed integration of each air mission with the fire and movement of those forces.

CEP. Circular Error Probable. An indicator of the delivery accuracy of a weapon system used as a factor in determining probable damage to a target. CEP is the radius of a circle within which half of the weapons are projected to fall.

DAS. Deep Air Support. Air action against enemy targets at such distances from friendly forces that detailed integration with fire and movement of friendly ground forces is not required.

DI. Display Index. Unit of display measure which makes up the HUD and MPCD.

DMT. Dual Mode Tracker. Tracks both EO-TV and laser designations.

DoD. Department of Defense.

DBS. Doppler beam sharpening.

EO. Electro-Optical.

EXP1, EXP2, & EXP3. AN/APG-65 expand modes are the high resolution, ground mapping modes of the surface radar.

FLIR. Forward-Looking-InfraRed.

FOM. Figure of Merit.

FOV. Field of View.

FPA. Flight path angle.

GCE. Ground Combat Element.

GPS. Global Positioning System.

HAT. Height Above Target.

HOTAS. Hands On Throttle And Stick.

HUD. Head-up Display.

IFA. In-Flight Alignment.

IFOV. Instantaneous Field of View.

INS. Inertial Navigation System.

in-video cursor. Cross-hairs used to designate on the MRSAR map.

JASM. Joint-Attack Strike Missile.

JDAM. Joint-Direct Attack Munition.

JSOW. Joint Stand-off Weapon.

LEP. Linear Error Probable.

LOS. Line of Sight. The line from the pilots eye to the target designation.

LST. Laser Spot Tracker.

MAGR. Miniaturized Airborne GPS Receiver.

MEU. Marine Expeditionary Unit.

MC. Mission Computer.

mil. A unit of angular measurement which subtends .3048 m at 304.8 m of range.

MPCD. Multi-Purpose Color Display.

MRSAR. Medium Resolution Synthetic Aperture Radar.

MSL. Mean Sea Level.

NAWC. Naval Air Warfare Center.

nm. Nautical Miles.

NVG. Night Vision Goggle.

PGM. Precision Guided Munition.

PPS. Precise Positioning Service.

rad. Radian, milliradian = 1/1000 of a radian.

radar. Radio detection and ranging. Considered to be a common use word and therefore appears in lower case throughout the thesis.

SAR. Synthetic Aperture Radar. A high resolution, ground mapping technique which takes advantage of the forward motion of the radar (aircraft movement).

SPS. Standard Positioning Service.

SR. Slant Range. The line-of-sight distance between two points not at the same level relative to a specified datum.

sweeten. The act of refining an aircraft sensor designation using HOTAS controls.

TAS. True Airspeed.

TD. Target Designation.

TDC. Target Designator Control.

TLE. Target Location Error.

TFOV. Total Field of View.

UTC. Universal Coordinated Time.

UTM. Universal Transverse Mercator.

1. INTRODUCTION

1.1 BACKGROUND

For BOC weapons the two major error sources are the target location error (not knowing exactly where the target is) and the weapon's own navigation or guidance error (inability to guide to a specified coordinate), as illustrated in Figure 1-1 [1]. For GPS weapons with perfect guidance, the second error will be bounded by GPS accuracies. Regardless of the target coordinate source, the coordinates provided to the weapon are most likely not those of the actual target location, but rather, they fall somewhere within a statistical uncertainty volume around the actual target location [1].

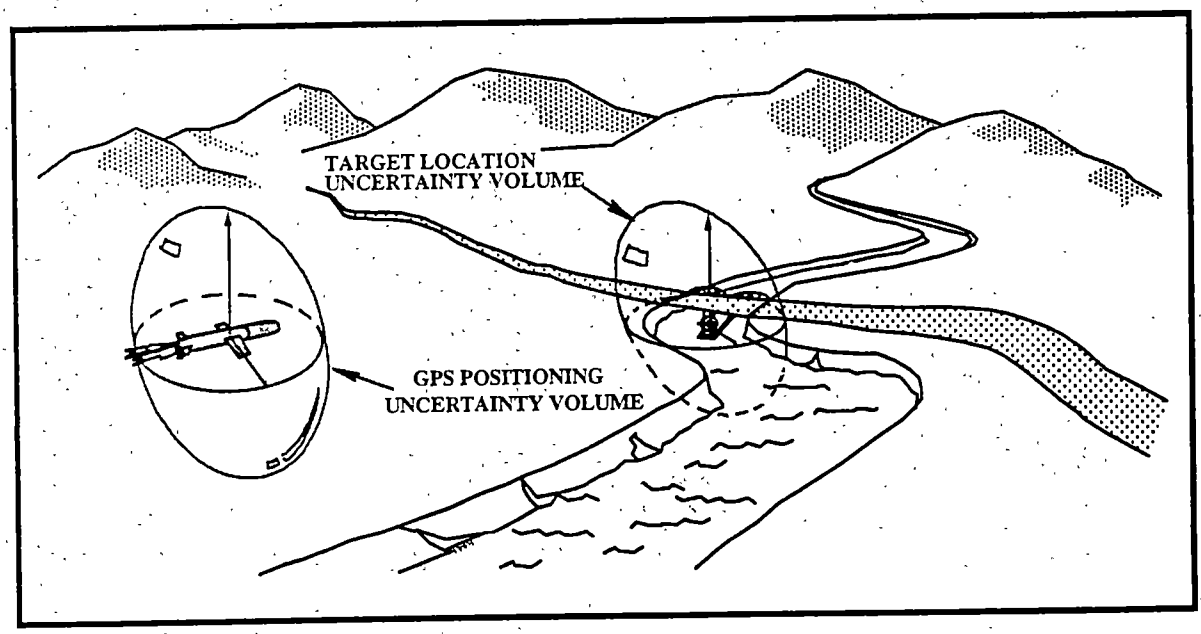


Figure 1-1
Target Location Uncertainty and GPS Positioning Uncertainty [1]

When properly integrated onto the AV-8B, BOC standoff weapons such as the JDAM, JSOW and JASM will result in increased survivability for the platform. In order to realize this increase in survivability, the AV-8B must be capable of reactively targeting these weapons on a changing battlefield using on-board aircraft software and hardware capabilities [2]. This capability, though possible in most modern day fighter-attack platforms, has yet to be accurately quantified and presented to the AV-8B user as part of the weaponeering process. Given an adequate characterization, the air-to-surface sensor suite may be found to generate a TLE outside the specified accuracy of the guided GPS munition, thus negating the destructive effect of the weapon.

The author has been involved with the software and hardware integration of precision GPS weapons onto the AV-8B from July 1997 to the present. Also, the author has participated in laboratory testing and flight simulator evaluations conducted at Boeing, St. Louis, Missouri specifically designed to aid in determining aircraft TLE. Actual flight testing of the JDAM is scheduled to begin in early 2000. Flight test to quantify TLE was conducted at the Operational Test Squadron VX-9, NAWC China Lake, California from January to March 1999. A total of 20 sorties and 26 flight hours were flown on flight test aircraft AV-8B 164549 and 162721. Both aircraft were considered to be fleet representative.

1.2 PURPOSE

For the aircraft sensor designations to be considered accurate enough for in-flight weapon targeting, TLE must fall within a specified limit. For example, the expected total circular error probable (CEP) of JDAM (13 meters) includes 7.2 meters for the effects of

TLE. CEP is defined as the value for which 50% of the impacts are within a circle centered about the point of impact.

Therefore, the purpose of this thesis is to determine a decision tree for optimum sensor use by the combat pilot, for delivery of a BOC weapon, based on aircraft TLE. An analysis of the error of three air-to-surface sensors on the AV-8B, the AN/APG-65 (σ_{APG-65}), the ARBS (σ_{ARBS}), and the HUD (σ_{HUD}), will determine which sensor is best suited for the expected attack profile.

1.3 DESCRIPTION OF THE AV-8B HARRIER

1.3.1 Aircraft.

The AV-8B is a transonic, single cockpit, single engine jet, day-night tactical fighter built by the Boeing Company, in St. Louis, Missouri. Three models of the AV-8B have been fielded over the life of the program. The base AV-8B aircraft incorporates the ARBS, HUD and GPS for day/night ground attack operations. The Night Attack version (AV-8B II), increased night time situational awareness through the addition of a digital moving map display, forward looking infra-red (FLIR) display, as well as night vision goggle (NVG) compatible lighting. The most recent AV-8B variant (AV-8B II+), builds upon the Night Attack, adding the AN/APG-65 pulse-doppler radar to the avionics suite. The three AV-8B models are between 46 – 48 feet long, with wingspans of 30 feet. The aircraft weigh approximately 16,000 pounds empty and can be loaded with fuel and ordnance to a maximum gross weight of 31,000 pounds [3].

The AV-8B weapons system is managed through a single crew station where the pilot controls aircraft flight, navigation and attack systems. Figures 1-2 depicts the crew station arrangement.

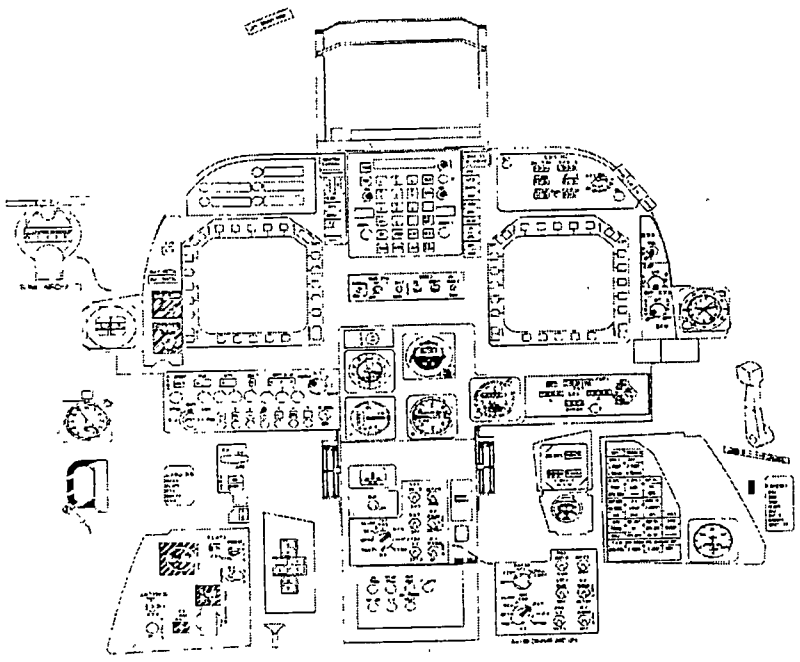


Figure 1-2
AV-8B Crew Station [3]

The AV-8B first flew in the late 1960's and began operational service in the United States in the late 1970's. The USMC operates eight AV-8B squadrons each containing sixteen aircraft and is operationally deployed aboard USN Amphibious Attack, L-Class Ships, within the continental U.S., as well as airfields abroad.

1.3.2 Sensors.

The HUD is mounted on the top of the main instrument panel (Figures 1-2, 1-3) and is used as the primary flight reference and for weapons status and delivery. The HUD displays attack, navigation, situation, and steering control information symbology by projecting symbology on a combining glass for viewing in the pilot's forward field-of-view (FOV) [4]. The HUD uses a projected velocity vector as a designating tool for both the GPS-INS and ARBS.

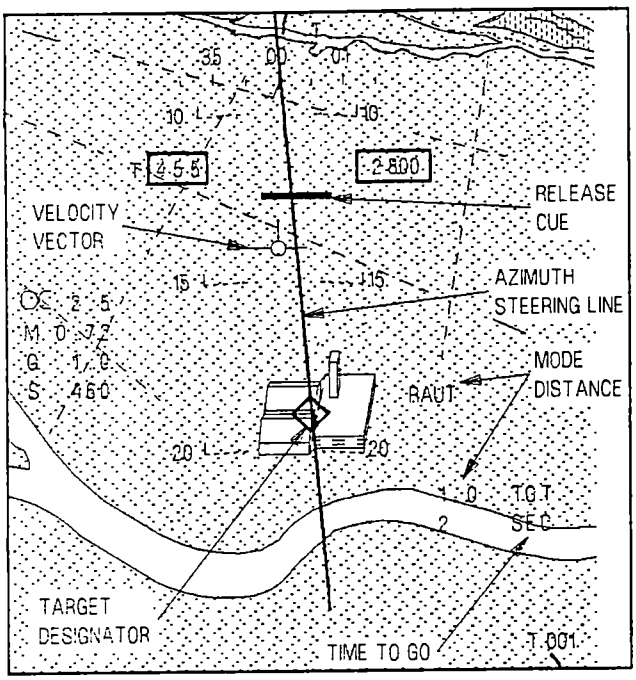


Figure 1-3
Head-Up Display [4]

The ARBS uses either reflected light images (TV mode), or reflected laser energy (Laser Spot Tracker-LST mode) to automatically lock onto and designate a target. It is flexible and accurate and provides a rapid acquisition, optical bomb delivery capability to the AV-8B aircraft. The dual mode tracker (DMT) is the heart of the AV-8B's angle rate bombing system [4]. It is located in the nose of the aircraft and is capable of tracking both TV and laser designated targets (Figure 1-4). The DMT has a field of view of 6 mrad in azimuth x 4 mrad in vertical, and provides a 6:1 magnification to the multi-purpose color display (MPCD) in the cockpit. The MPCDs are 6-inch x 6-inch color display (See Figure 1-2). The gimbal limits are $\pm$ 35° in azimuth, + 15° and –70° in elevation.

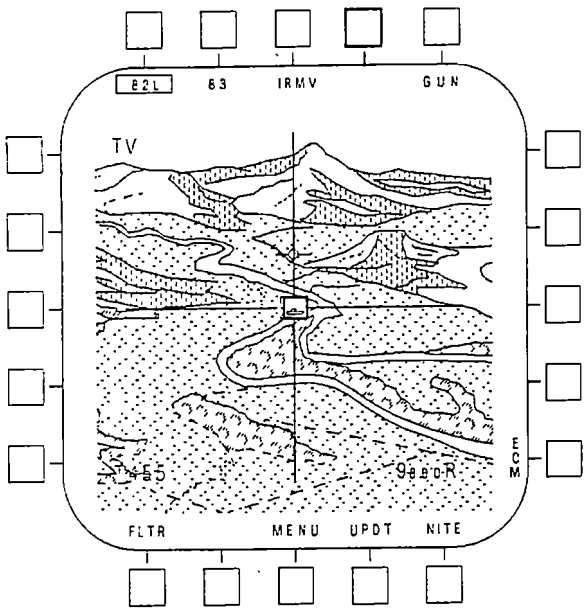


Figure 1-4
Angle Rate Bombing System [4]

The AV-8B AN/APG-65 pulse-doppler radar set is a multiple mode, search and track radar which operates in the I-band (8-10 GHz). The planar array antenna in the nose of the aircraft is 23.2 inches in diameter, offering an approximate beam-width of 3.9°. The antenna is driven by direct-coupled electric motors on a two-axis gimbal assembly. The antenna gimbal limits are $\pm$ 70° in azimuth and $\pm$ 60° in elevation (See Figure 1-5). In most cases, the pilot selects the desired mode and the optimum operating parameters are automatically selected and controlled by the radar [4].

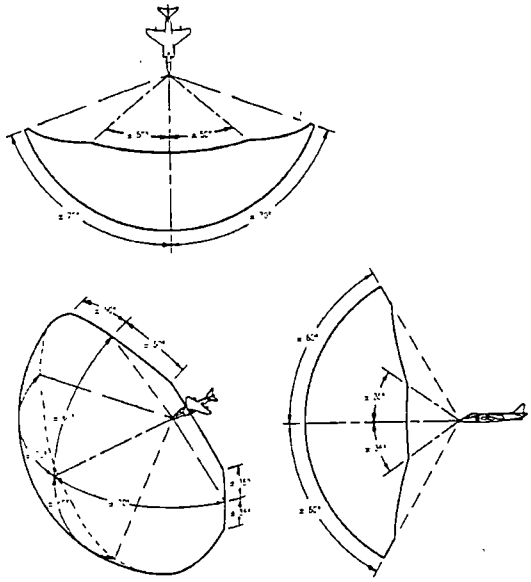


Figure 1-5
AN/APG-65 Radar Set [4]

1.3.3 Attack Profiles.

The AV-8B's mission consists primarily of Close Air Support (CAS) and Deep Air Support (DAS). The standard attack profiles utilized by the AV-8B in the release of air-to-surface weapons include diving deliveries and level to ramp down deliveries. Figure 1-6 and 1-7 are depictions of such deliveries. Diving deliveries, lasting 8-10 seconds are used when visual acquisition of the target is required to ensure safe separation from friendly elements of the Ground Combat Element (GCE). During such a delivery, the HUD can be used to direct an ARBS or GPS-INS target designation. While the HUD is a 1:1 presentation of the target designation, the ARBS video (6:1) can be used on the MPCD to further refine the target designation.

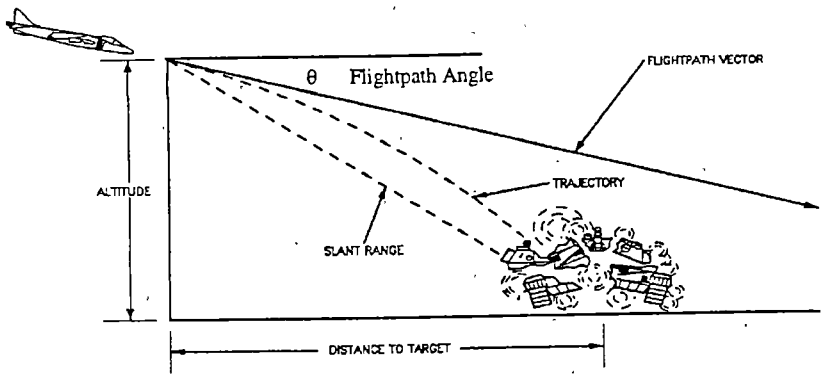


Figure 1-6
Standard Diving Attack Profile [4]

Level-to-ramp down deliveries are used to minimize exposure to the threat when the GCE is not in the immediate area. This allows the pilot a longer delivery run and permits use of the APG-65 air-to-surface (A/S) modes, assuming the target has radar signature. The A/S modes are used to validate and if necessary create target designations for fixed targets. Because of the parallax errors, the ARBS and HUD are not very accurate for long slant-range, profiles [5].

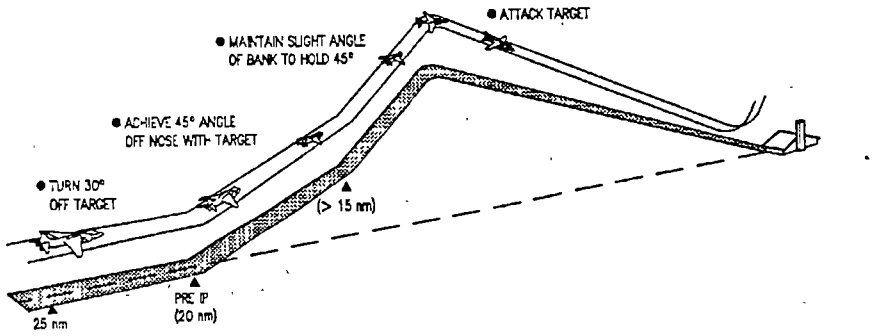


Figure 1-7
Standard Level-Ramp Down Attack Profile [4]

1.3.4 Targeting Requirements.

The AV-8B is tasked with attacking the target types listed in Table 1-1 below:

Table 1-1
AV-8B Target List [2]

Mission	Target
DAS/CAS	Command, Control, and Communications Sites, Revetments and Bunkers
DAS	Electronic Warfare and Ground-Controlled Missile Intercept Sites
DAS	Petroleum Refineries and Tank Farms
DAS/CAS	Airfields (Aircraft, Shelters, Runways, Taxiways and Maintenance Facilities)
DAS/CAS	Ships in Port and Naval Storage and Repair Facilities
DAS	Industrial Sites (Manufacturing Plants, Storage Facilities, Electrical Networks)
CAS	Troop and Equipment Formations (Truck Parks, Military Barracks)
CAS	Tanks, Armored Personnel Carriers, Artillery and Trucks

The number of weapons required to demobilize or kill a target is in part determined by the accuracy of the weapon itself. Figure 1-8 depicts the typical accuracy required from a single weapon to adequately demobilize or kill several types of targets using conventional weapons.

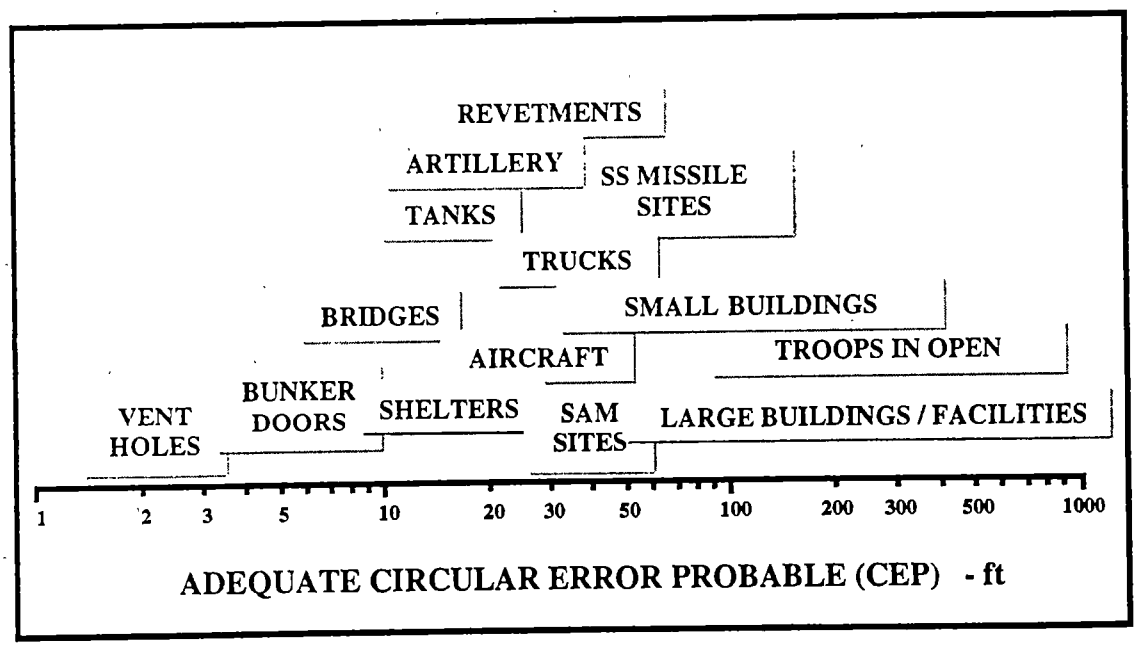


Figure 1-8
Circular Error Probable Accuracy Requirements [1]

1.4 SCOPE OF THESIS

1.4.1 Objectives.

While some point targets will require terminally guided weapons, and/or a dispersed pattern of multiple weapons to achieve the desired kill criteria, it is more likely that the typical targets engaged by the AV-8B can be attacked using GPS guided weapons.

Therefore, the objective of this thesis is to describe a sensor decision tree, through which the AV-8B air-to-ground (A/G) sensor suite can be used to employ GPS-guided weapons to their optimum effects. Specific objectives are to quantify, using mathematical analysis and laboratory and flight empirical data, the TLE resulting from:

(1) Aircraft Position Error (See Chapter 2)
(2) Operator Error (See Chapter 3)
(3) AV-8B Sensor Error (See Chapter 4).

This thesis describes the target location error associated with autonomously generated target coordinates using the AV-8B air-to-surface sensor suite. In this study, total TLE is defined in terms of aircraft position error ($\sigma_{a/c}$), operator error (σ_{op}), and sensor error (σ_{sens}) using the following expression:

$$\sigma_{TLE} = \sqrt{(\sigma_{a/c})^2 + (\sigma_{op})^2 + (\sigma_{sens})^2}.$$

The standard deviations $\sigma_{a/c}$, σ_{op} and σ_{sens} are the one-sigma errors derived from individual measurement of each contributor and are defined in Chapters 2, 3 and 4 respectively, as well as Appendix A.

Recommendations for minimizing each contributor to TLE are made during each respective Target Location Error Analysis Section and as part of the final conclusions and recommendations.

1.4.2 Statistical Analysis.

Standard Department of Defense (DoD) publications utilize CEP to define TLE allowable for ground targets, as discussed in Section 1.2 for JDAM. For horizontal targets, the targeting error can be given in terms of cross-range and down-range components [6]. For vertical targets, the targeting error is specified relative to the plane normal to the weapon heading, in terms of vertical and cross-range error. This thesis will assume tactical size point targets with minimal height are being attacked and therefore, quantify vertical errors in terms of linear error probable (LEP). 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 in range, depending on the sensitivity of the horizontal CEP to that error.

To conduct an adequate characterization of the AV-8B air-to-ground sensor suite, an understanding of its positional, display and designation accuracies is required. A conceptual analysis of the standard deviation of each TLE contributor from the aircraft axes to the ground plane provides for a sufficient understanding of the total TLE. The analysis utilizes previous flight test and laboratory data to generate expected TLE for a single point source target in the horizontal ground plane. Vertical TLE (LEP) are resolved to effects on the horizontal TLE CEP.

The conceptual analysis was validated via flight test using all three sensors (See Chapter 5). Fifty aircraft-target designations were made using each sensor over multiple sorties. Target designations were compared with a surveyed location to derive total TLE. The flight test TLE was compared with that of analysis to refine the sensor decision tree.

The statistical measure of standard deviation calculated to a one-sigma (σ) accuracy of 68% supports the stated objective [7]. Standard DoD statistical definitions and formulas used during the study are contained in Appendix A.

1.4.3 Assumptions.

During the course of the study, general and specific assumptions are made. The following delineate the general assumptions. Specific assumptions are detailed during the analysis of each error source.

1. Flight test aircraft, laboratory equipment and sensors are operationally representative.

2. The pilots who conducted the test were suited in physical size and weight for the crew station from which they make the target designations and were considered equally trained.

3. Statistically significant samples of pilots and aircraft data were not available and the aircraft were not instrumented to allow an analysis of sensor sensitivity.

4. All error distributions are considered to be normal (i.e. Gaussian).

5. Conceptual error analysis tables are valid for the moment of designation only, i.e. constant squint angles, line-of-sight (LOS) angles, flight path angles and slant ranges, and are included to indicate error trends with respect to aircraft, operator and sensor error.

6. Small angle approximations are made with respect to mils vs. milliradians. A mil represents an angular measurement, which spans 1 foot at 1000 feet. A milliradian is an angular measurement equal to 1/1000 of a radian. At small angles, the two quantities are treated as equivalent.

7. CEP and LEP calculations use the approximations contained in Appendix A. The equations used are from the Integrated Multi-service Test and Evaluation Master Plan for NAVSTAR GPS and are considered DoD standard approximations [6].

2. AIRCRAFT POSITION ERROR

2.1 GPS-INS INTEGRATION

The AV-8B 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. Correction signals from the accelerometers and computer provide constant leveling. Correct initial condition data is essential to INS performance. The INS was first integrated onto the AV-8B during the early 1980's. The currently fielded INS is the Litton ASN-139 specified to a position accuracy of 1 nm/hour CEP.

The AV-8B GPS integration occurred in 1993 and consists of the GPS antenna and the Miniaturized Airborne GPS Receiver (MAGR). The GPS antenna is a fixed radiation pattern low profile antenna providing omni-directional coverage above 10^{o} elevation from its surface. The MAGR is a five-channel, dual frequency receiver designed for highly maneuverable aircraft. The first four channels are reserved for reception of satellite data, while the fifth channel designates the next satellite to be acquired [8]. It receives ranging codes and a navigation message from the NavStar satellites through the GPS antenna. The MAGR provides Universal Coordinated Time (UTC), aircraft position, ground-track, ground speed and altitude data to the mission computer (MC). Two levels of navigation are provided by the GPS, the precise positioning service (PPS) and the standard positioning service (SPS). This thesis assumes PPS capability is enabled for the AV-8B pilot and thus PPS accuracies are achievable. The PPS is specified to provide a 9.2-meter horizontal accuracy (CEP) and 18.7-meter vertical accuracy (LEP).

The position and velocity calculations are based on the WGS-84 geodetic datum (earth model). WGS-84 is a very precise model, providing a common grid system for transformations into other coordinate systems or map datums [9].

The three sources the AV-8B utilizes for determining and maintaining aircraft present position are, in order of priority: INS, GPS and air data computer (ADC). At power-up, the aircraft will initialize to ADC position keeping. When the GPS completes initialization, the position-keeping mode will automatically upgrade from ADC to GPS. When the INS present position becomes valid, the position keeping mode will automatically upgrade from either ADC or GPS to INS [4]. This is done as the velocities from the INS provide for a smoother navigation system over time with varied flight conditions, than the GPS. However, at a given instant in time, the GPS will typically indicate a more accurate aircraft position. The MC automatically upgrades or degrades to the best available mode when the better mode becomes available or in the event the current source is deemed erroneous or unavailable. Selecting inflight align (IFA) on the INS causes the navigation system to enter into tightly-coupled mode whereby the GPS is aided by ADC and INS data, continually returning corrections to the INS platform.

The alteration between GPS and INS position keeping is based on a figure of merit (FOM) which is a measure of an estimated three-dimensional position error generated by the MAGR based on the number of satellites being tracked and health of the signal.

Aircraft computed GPS altitude (mean sea level – MSL), when selected by the pilot, is used in conjunction with sensor inputs to derive height above target (HAT, above ground level – AGL). GPS altitude is considered the second most accurate source of aircraft altitude following radar altimeter altitude. Given that the radar altimeter is valid

up to 5000 feet AGL and the attack profiles occur well above that, this thesis will assume GPS is being used as the primary aircraft altitude source.

2.2 ERROR ANALYSIS

2.2.1 Derivation.

This section defines the singular effects of the aircraft vertical and horizontal position error on TLE. The aircraft is assumed to be axially aligned with the target at the time of designation, simplifying the analysis of down-range and cross-range errors.

The AV-8B calculates its earth fixed coordinate to within current PPS accuracies. When the aircraft is tasked to determine a target location, it utilizes aircraft present position and altitude as the truth source to generate an earth fixed target coordinate. Any error associated with aircraft present position and altitude will then contribute to the generated target coordinate error. Figure 2-1 depicts the AV-8B at an earth fixed coordinate (x, y, z), with its associated respective position errors ($\sigma_{x\ a/c}$, $\sigma_{y\ a/c}$, $\sigma_{z\ a/c}$).

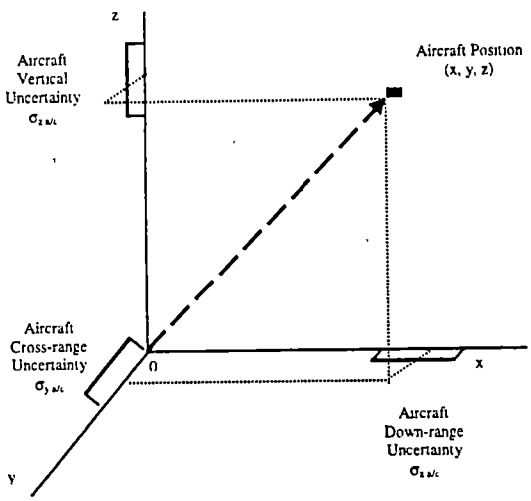


Figure 2-1
AV-8B Position Uncertainty

The aircraft position uncertainty can be stated by the following expression (See Appendix A for derivation):

$$\sigma_{a/c} = \sqrt{(\sigma_{x\,a/c})^2 + (\sigma_{y\,a/c})^2 + (\sigma_{z\,a/c})^2}$$

The effect of a singular uncertainty in aircraft position, results in a linear translation of error to the aircraft generated target coordinate or TLE. The translation of error in each axis is depicted in Figures 2-2, 2-3 and 2-4. Assuming that slant range (SR) is known and fixed from an aircraft sensor, the aircraft vertical position error maps directly to an error in the vertical position of the target, as illustrated in Figure 2-2.

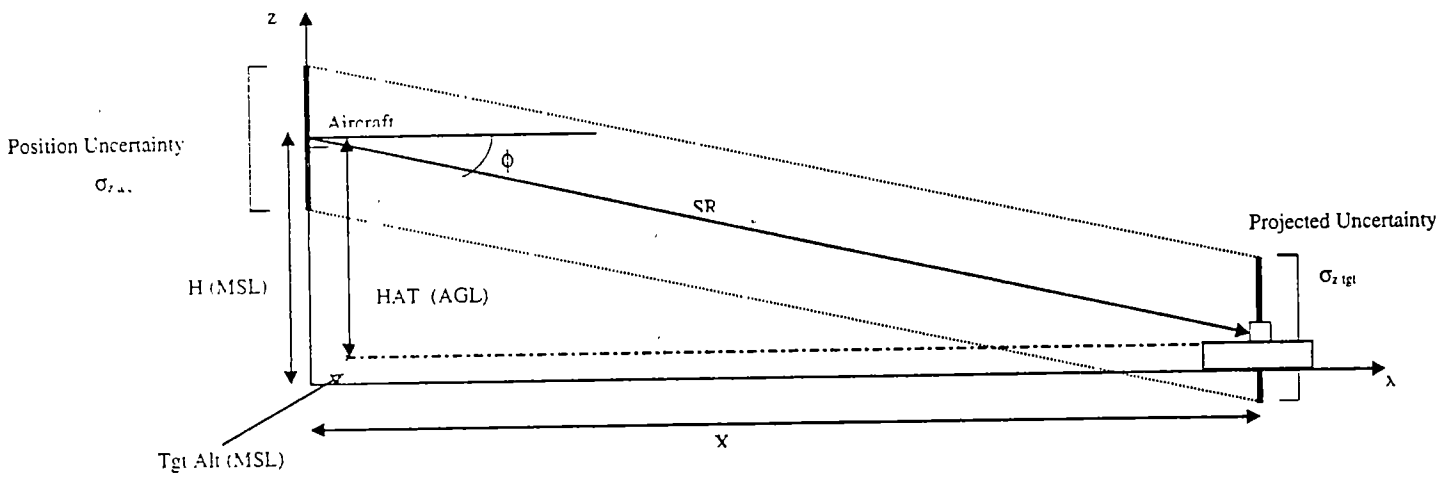


Figure 2-2
Vertical Aircraft Error Projected to Vertical Target Error

Given H as the GPS derived aircraft altitude with standard deviation $\sigma_{z\,a/c}$ and an aircraft sensor derived height above target, target altitude is given by:

$$\text{TGT ALT (MSL)} = \text{H (MSL)} - \text{HAT (AGL)}$$

$$\therefore \sigma_{z\,tgt} = \sigma_{z\,a/c} \text{ for fixed HAT.}$$

The effects of a horizontal aircraft position error can be similarly addressed.

As illustrated in Figures 2-3 and 2-4, for a down-range or cross-range aircraft position uncertainty, the errors transpose linearly to the aircraft generated target coordinate.

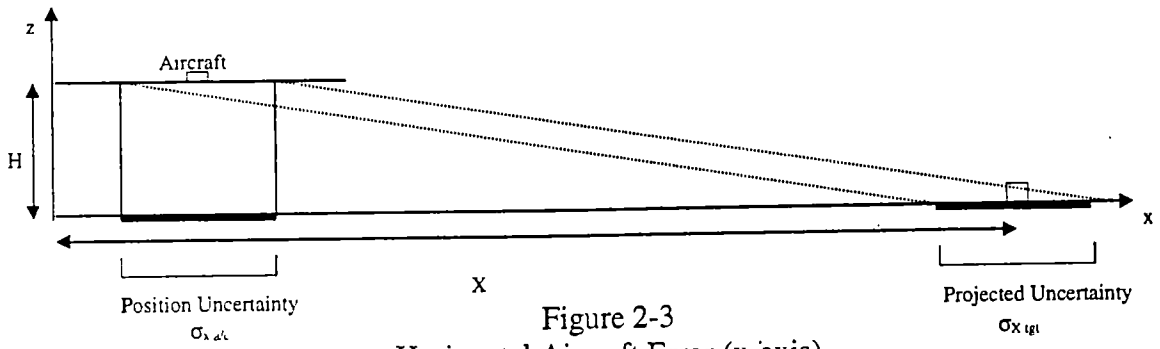


Figure 2-3
Horizontal Aircraft Error (x-axis)
Projected to Horizontal Target Error (Down-range)

$$\sigma_{x\ tgt} = \sigma_{x\ a/c.}$$

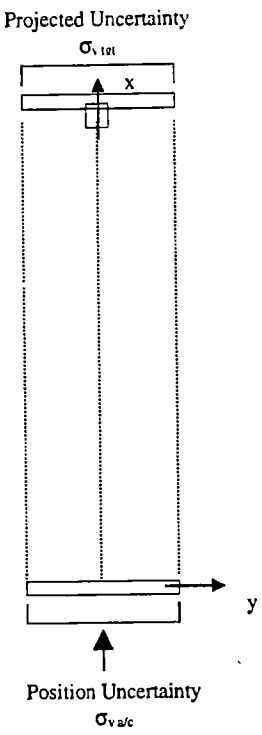


Figure 2-4
Horizontal Aircraft Error (y-axis)
Projected to Horizontal Target Error (Cross-range)

$$\sigma_{y\ tgt} = \sigma_{y\ a/c.}$$

The total effect of an aircraft position error, $\sigma_{a/c}$ on the generated target coordinate can be summarized by the following expressions:

$$\sigma_{x\,tgt} = \sigma_{x\,a/c} \quad \sigma_{y\,tgt} = \sigma_{y\,a/c} \quad \sigma_{z\,tgt} = \sigma_{z\,a/c}.$$

$$\therefore \sigma_{tgt\,a/c} = \sqrt{(\sigma_{x\,tgt})^2 + (\sigma_{y\,tgt})^2 + (\sigma_{z\,tgt})^2}$$

2.2.2 Test Results.

GPS hardware and software integration testing was conducted on the AV-8B during January 1994. The aircraft generated position and altitude of the MAGR and INS system were characterized for position keeping accuracy against a differential GPS truth source. Table 2-1 details the culmination of seven flights totaling 331 minutes of data within the AV-8B operational flight envelope.

Table 2-1
AV-8B Miniaturized Airborne GPS Receiver
Inertial Navigation System Integration[1, 2] [10]

Flights = 7	GPS Position Keeping	INS Position Keeping
Flight Duration (331min)	Std Deviation (m)	Std Deviation (m)
$\sigma_{x\,a/c}$	2.44	4.56
$\sigma_{y\,a/c}$	3.80	5.48
$\sigma_{z\,a/c}$	2.35	15.42
$\sigma_{a/c}$	5.09	16.99

1. AV-8B GPS Integration Test Results, 11/01/94
2. Differential GPS Truth Source

Flight test results indicate a more accurate aircraft GPS position, when compared with the INS position. This is in keeping with the GPS-INS software integration completed for the aircraft, which uses the GPS to update the INS position continuously. As discussed in the integration section, the INS may at times be more accurate, depending on the state of the aircraft inputs to the MAGR, satellites being tracked and the aircraft flight conditions.

2.3 TARGET LOCATION ERROR ANALYSIS

The singular effects of aircraft position error, $\sigma_{a/c}$ on the generated target coordinate, σ_{tgt} are: $\sigma_{x\,tgt} = \sigma_{x\,a/c}$ $\sigma_{y\,tgt} = \sigma_{y\,a/c}$ $\sigma_{z\,tgt} = \sigma_{z\,a/c}$.

From Appendix A, the equations for CEP and LEP are:

$$CEP_{tgt} = 0.5887 * (\sigma_{x\,tgt} + \sigma_{y\,tgt}) \text{ meters}$$

$$LEP_{tgt} = 0.6745 * \sigma_{z\,tgt} \text{ meters}$$

Utilizing the flight test results, the TLE due to aircraft position error is known. Table 2-2 details the errors in terms of CEP and LEP.

Table 2-2
Target Location Error Due to Aircraft Position Uncertainty

GPS Position Keeping (m)					INS Position Keeping (m)				
$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{z\,tgt}$	LEP_{tgt}	CEP_{tgt}	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{z\,tgt}$	LEP_{tgt}	CEP_{tgt}
2.44	3.80	2.35	1.59	3.67	4.56	5.48	15.42	10.40	5.91
$\sigma_{tgt} = 5.09$					$\sigma_{tgt} = 16.99$				

The TLE in the vertical and the horizontal ground plane due to aircraft positional errors are expressed in terms of LEP and CEP respectively. The CEP for GPS and INS position keeping results, indicate an error within the TLE allocated for JDAM. The sensitivity of the CEP portion of the TLE to the LEP will be dependent on the magnitude of the LEP and the weapon impact angle (See Figure 2-5).

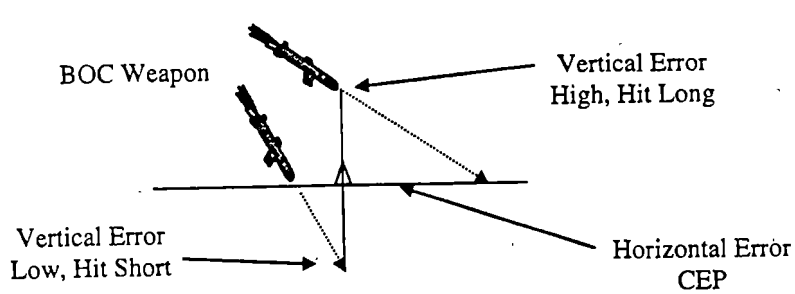


Figure 2-5
Horizontal Error Sensitivity to Vertical Error

The greater the LEP or the lower the impact angle, the greater the probable effect on the horizontal TLE. This sensitivity will be more thoroughly discussed in the analysis of the flight test data in Chapter 5.

Given knowledge of the AV-8B aircraft GPS and INS position keeping accuracies and the affects on the TLE, it can be concluded that either is singularly accurate enough for on-board target coordinate generation. The target location error associated with aircraft position error is not a degradation to the mission effectiveness of the AV-8B aircraft with GPS based weapons. **If flight conditions permit, GPS position keeping should be selected for creation of a target coordinate from an on-board sensor provided PPS capabilities are enabled.** Finally, use of GPS position keeping will provide for the lowest addition to TLE.

3. OPERATOR ERROR

3.1 OPERATOR-DISPLAY INTEGRATION

The AV-8B has a single crew station from which the pilot accomplishes all tasks involving aircraft flight and weapon systems employment. The pilot sits in the cockpit elevated to design eye. Design eye in the AV-8B is a specific sitting height, which places the pilot's eyes at the optimum location to view the entire HUD presentation. Design eye was developed through crew station geometry studies using an average pilot as a model. The pilot is ergonomically fit to the cockpit by meeting specific anthropometric measurement criteria. Design eye permits adequate viewing of all aircraft controls and displays and is referenced from the aircraft zero sight line (Figure 3-1). For the purposes of this thesis, the pilot is seated at design eye and there are considered to be no pilot to aircraft display interface issues, which prevent accomplishment of all required tasks.

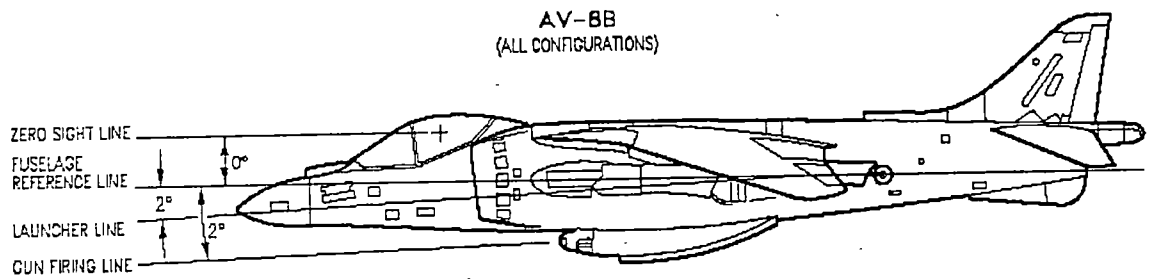


Figure 3-1
Zero Sight Line [3]

3.1.1 Hands on Throttle and Stick (HOTAS).

The AV-8B utilizes HOTAS functionality to decrease pilot workload within the cockpit. The HOTAS controls enable pilot operation of the weapon system sensors and displays without removing the hands from the control stick and throttle (Figure 3-2). The

flight control stick and throttle have 17 switches, actuated with the fingers and thumb of the pilot's hands while he controls the aircraft flight path and power. The switches are programmed via software to enable 52 functions, depending on the selected avionics system mode.

The sensor select switch on the control stick has various A/G functions depending on the model of AV-8B (AV-8B II or AV-8B II+), current sensor mode and the weapons loaded on the aircraft. It permits selection of the air-to-surface radar, ARBS or HUD-INS sensor mode.

The Throttle Designator Control (TDC) is a two-axis force transducer with a 0.20-inch displacement and a discrete action switch. The TDC is a mouse-like control, providing motion to the acquisition cursor and enabling various modes of the radar, depending on the selected operation (See Figure 3-3). The TDC incorporates both "action" and "no action slewing." Slewing is the action of designating a target on the display and moving it. Slewing without the TDC pressed (no action slewing) is used primarily for sensor control and sweetening of target track. Sweetening is any pilot action taken to refine the sensor designation. Action slewing (TDC pressed) is used primarily in target acquisition and target designation [4]. The acquisition cursor is represented by two small vertical lines positioned by the radar set in response to TDC slewing. The cursor is used in conjunction with the TDC for target designation. A target designation (TD) diamond is displayed in the HUD for all visual designations, within the HUD FOV.

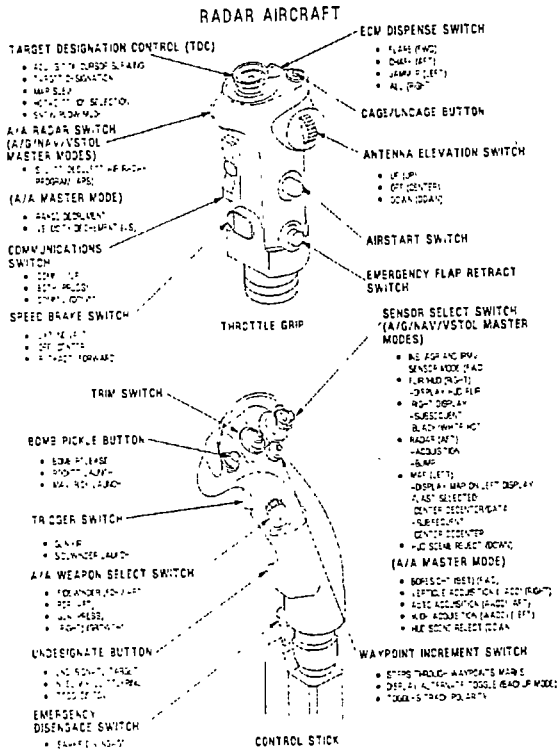


Figure 3-2
Hands on Throttle and Stick [4]

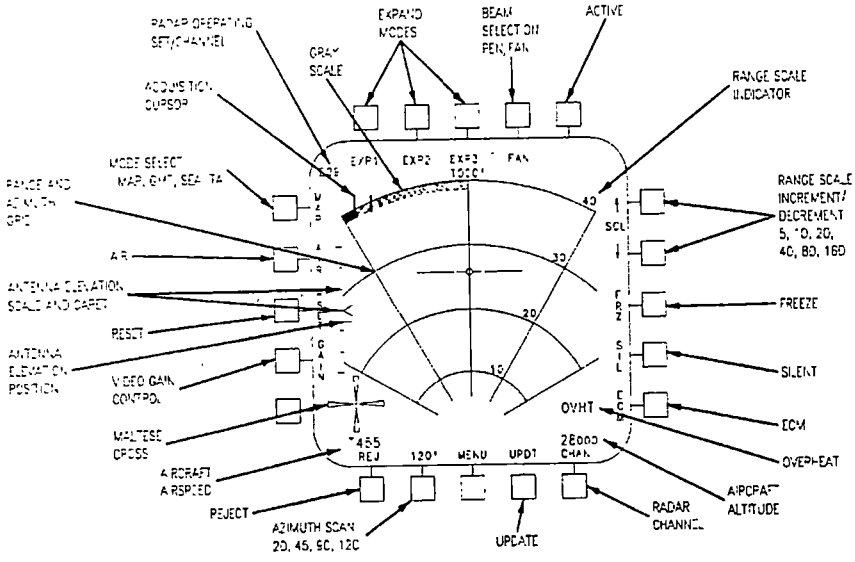


Figure 3-3
Air-to-Ground Radar Options [4]

3.1.2 Head-Up Display (HUD).

The HUD is composed of two combining glasses onto which collimated symbology is projected into the pilot's FOV (Figure 3-4). The display is referenced to the aircraft body axis, mounted forward of the pilot at design eye. The HUD is two-dimensional (2-D) projection normal to the aircraft longitudinal axis and overlays the pilots three-dimensional (3-D) view of the outside world. The projection subtends different footprints on the ground, based on flight path angle and slant range. The HUD has a 22° total-field-of-view (TFOV) and a 16° x 20° instantaneous field-of-view (IFOV). When seated at design eye, the pilot can view the IFOV without movement of the head, and the TFOV with minimal movement.

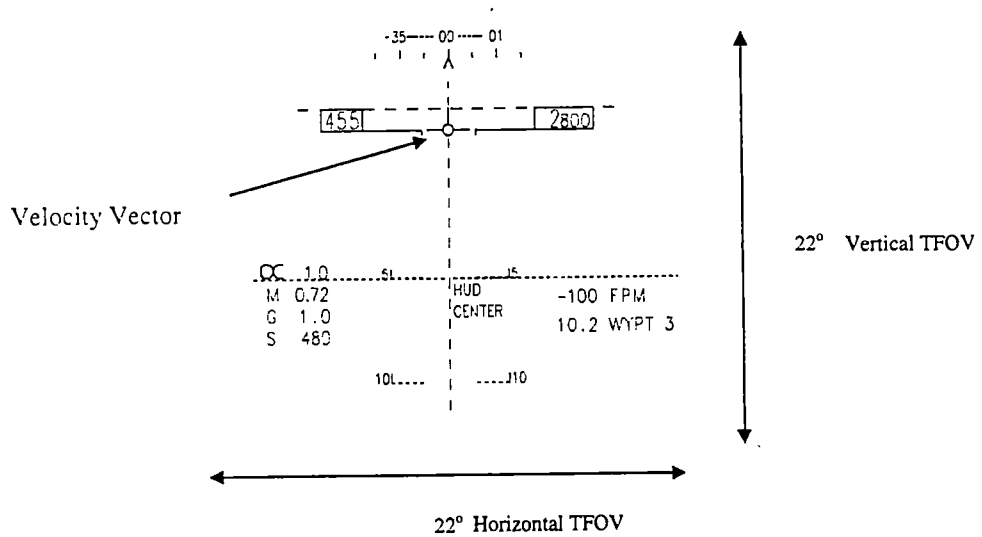


Figure 3-4
Head-Up Display FOV & Design Eye Perspective [3]

Symbols are projected to the display based on an (x, y) coordinate system within the HUD reference frame. The TFOV display is made up of 1024 x 1024 display indexes or DI, which can be likened to pixels.

One of the symbols projected to the HUD is the velocity vector, to aid in aircraft attitude and flight path control. The velocity vector provides the pilot with an outside world reference with regard to actual aircraft flight path, representing the point towards which the aircraft is flying. INS velocities normally position the velocity vector. When these are invalid, filtered values of ADC true airspeed (TAS) and ADC angle-of-attack (AOA) are used to determine all velocities and therefore position of the velocity vector. Once velocity is calculated, aircraft ground speed, waypoint steering and flightpath angle are derived and distributed for display on the HUD [4].

As it is referenced from the aircraft body-axis to the outside world, the velocity vector provides the pilot a rapid means of designating a target on the ground to produce weapons employment calculations.

3.1.3 Multi-Purpose Color Display (MPCD).

The AV-8B integrates two MPCDs which are mounted forward of the pilot's knees within the cockpit (Figure 1-2, Section 1.3.1). Each MPCD has the capability to display color moving map information, ARBS and FLIR information and other tactical data pages. The MPCDs are surrounded by twenty push-tiles, which are used by the aircrew to interface with and control the aircraft and weapon systems. The legends and respective functions assigned to the push-tiles vary according to the display format selected.

Symbols are projected to the display based on a 2-D (x, y) coordinate system referenced to the aircraft body-axis. The MPCD is made up of 1024 x 1024 DI. The amplification represented by the MPCD is dependent on the sensor being displayed. The radar Expand 3 (EXP3) MRSAR map presents a fixed 2-D 1.2 nm x 1.2 nm ground

patch, displayed within 256 x 256 DIs on the MPCD. The ARBS 6 mrad x 4 mrad FOV is displayed within an 84 x 64 DI designation box with a 6:1 magnification.

3.2 ERROR ANALYSIS

3.2.1 Derivation.

This section defines the conceptual analysis of the singular effects of the operator pointing error as it contributes to the target location error. The pointing error is the summation of any operator-display parallax, display resolution and operator-display designation errors. The operator error can be stated with the expression (See Appendix A for derivation):

$$\sigma_{op} = \sqrt{(\sigma_{x\,op})^2 + (\sigma_{y\,op})^2}$$

where, $\sigma_{x\,op}$ equals the induced pointing error in display range and $\sigma_{y\,op}$ equals the pointing error in display cross-range, over multiple designations. When the pilot interfaces with the controls and displays to create a system designation, a radius of error in the horizontal ground plane is induced. The magnitude of the TLE that results from operator error will be a function of the accuracy of the designation symbol placement on the display, the amplification of the sensor represented and the footprint that the sensor subtends in the ground plane at the time of designation. An operator-display pointing error may effect the aircraft derived target altitude, depending on the sensor used to derive HAT (see Chapter 4).

HUD Error

Figure 3-5 depicts the AV-8B HUD, with a single DI target located at HUD position (x, y). The designation diamond contains a centering 2 DI dot, which is inaccurately positioned on the HUD over multiple designations by the pilot, at some standard

deviation ($\sigma_{x\,op}$, $\sigma_{y\,op}$) from the true target location. Because the target is a specific two-dimensional point in the ground plane with unknown vertical height, represented on a two-dimensional display, operator pointing error result in a radius of error in the ground plane. Error in the vertical is unknown.

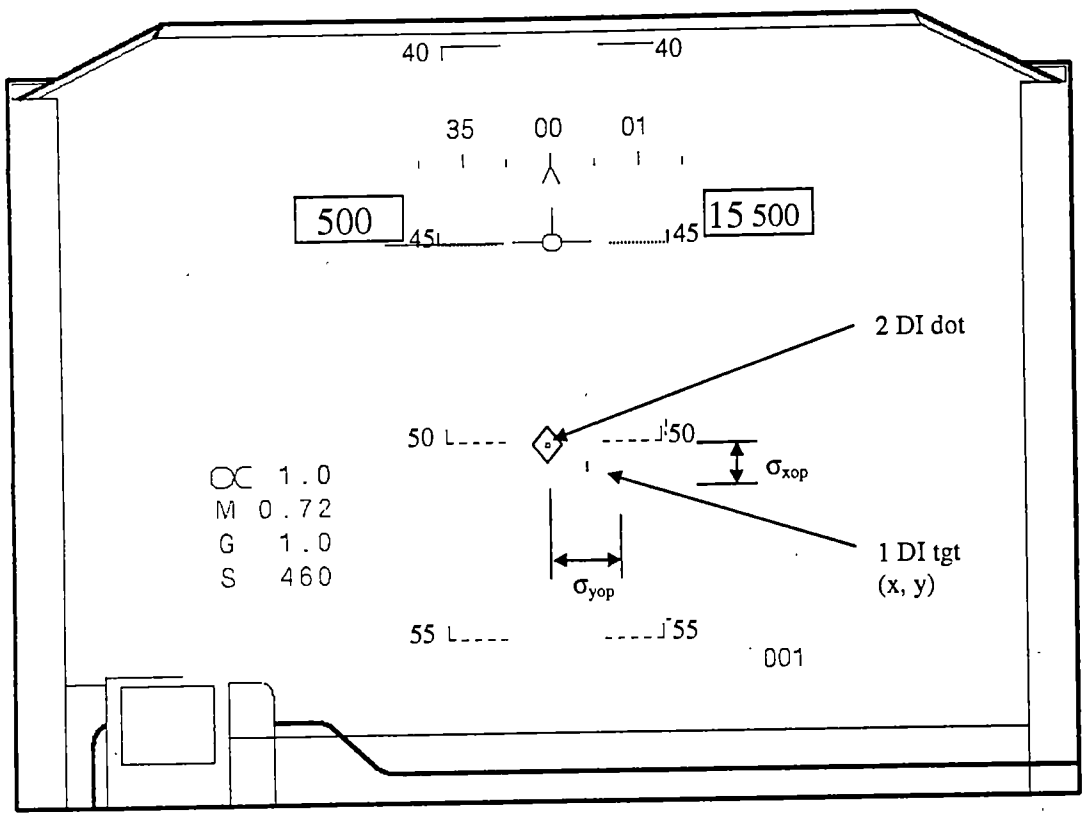


Figure 3-5
Head-Up Display Operator Error

To derive the effect of the HUD designation error on TLE, the standard deviations must be resolved to the ground plane, accounting for aircraft flight path angle and the slant range to target at the time of designation. Given the relationship: 1 mil = .3048 m at 304.8 m SR, the effects of slant range in a single plane, are illustrated by the following depiction (Figure 3-6).

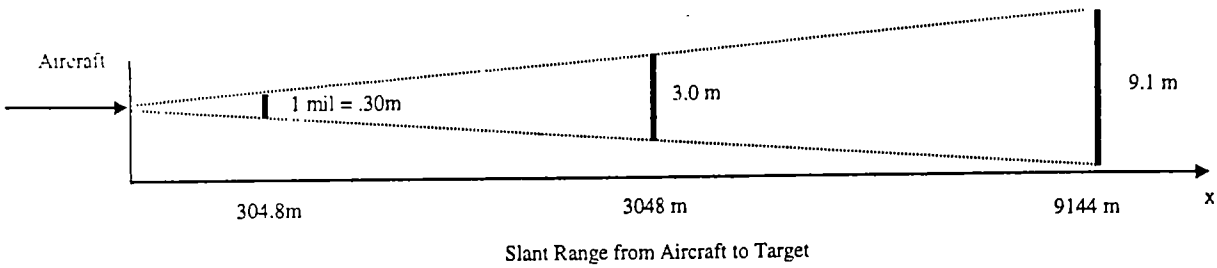


Figure 3-6
Slant Range Effects on Display Error

This expression holds for all axes. As shown, a single mil error at the aircraft, will equate to a 9.1m error at 9144 m of slant range. Recalling that the HUD is a 1024 x 1024 DI display, the total FOV of 22° can be resolved to 46.55 DI/Degree or 2.65 DI/mil (1° = 17.54 mil). The next step is to account for the aircraft flight path-angle (See Figure 3-7).

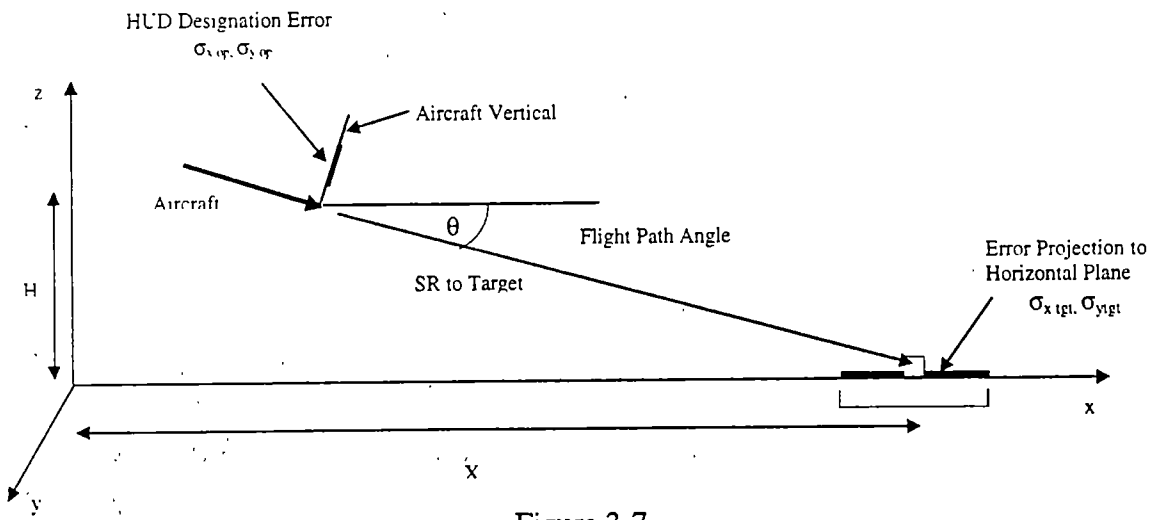


Figure 3-7
Head-Up Display Designation Error Projection

The projection of the HUD error to the ground plane can be quantified by the following relationships (See Appendix A for derivation):

$$\sigma_{x\,tgt} = \sigma_{x\,op}(SR/304.8\text{ m})(.3048\text{ m})\cos(\theta)/(2.65\text{ DI/mil})\text{ meters}$$
$$\sigma_{y\,tgt} = \sigma_{y\,op}(SR/304.8\text{ m})(.3048\text{ m})/(2.65\text{ DI/mil})\text{ meters}$$

Table 3-1 contains the effects on TLE of a conceptual 1 and 2 DI error in the x, y-axis on the HUD over a range of flight path angles and slant ranges.

Table 3-1
Target Location Error Due to Head-Up Display Operator Error[1]

1 DI Error	$\sigma_{x\,tgt}$ Down-range Error (m)/ $\sigma_{y\,tgt}$ Cross-range Error (m)											
Slant Range	1524 m		3048 m		4572 m		6096 m		7620 m		9144 m	
Flight Path	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$
10°	0.56	0.57	1.13	1.15	1.70	1.72	2.27	2.30	2.83	2.88	3.40	3.45
30°[2]	0.50	0.57	0.99	1.15	1.49	1.72	1.99	2.30	2.49	2.88	2.99	3.45
45°[2]	0.41	0.57	0.81	1.15	1.22	1.72	1.63	2.30	2.03	2.88	2.44	3.45
60°	0.29	0.57	0.58	1.15	0.86	1.72	1.15	2.30	1.44	2.88	1.73	3.45
2 DI Error	$\sigma_{x\,tgt}$ Down-range Error (m)/ $\sigma_{y\,tgt}$ Cross-range Error (m)											
Slant Range	1524 m		3048 m		4572 m		6096 m		7620 m		9144 m	
Flight Path	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$
10°	1.13	1.15	2.26	2.30	3.39	3.45	4.53	4.60	5.66	5.75	6.79	6.90
30°[2]	0.99	1.15	1.99	2.30	2.99	3.45	3.98	4.60	4.98	5.75	5.98	6.90
45°[2]	0.81	1.15	1.63	2.30	2.44	3.45	3.25	4.60	4.07	5.75	4.88	6.90
60°	0.58	1.15	1.15	2.30	1.73	3.45	2.30	4.60	2.88	5.75	3.45	6.90

1 Conceptual Data
2 Standard Attack Profile Designation/Release Values

Overall, as flight path angle increases, the effects of an operator range error are reduced, while the cross-range error remains unaffected. An increase in operator error or slant range to target will incur a linear increase in targeting error.

MPCD Error MRSAR Map

Figure 3-8 depicts the AV-8B MPCD displaying an EXP3 map, with a single DI target at MPCD position (x, y). The in-video cursor is positioned at some delta from the target location. The resultant display standard deviations over multiple designations are ($\sigma_{x\,op}$, $\sigma_{y\,op}$). As with the HUD, the MRSAR map represents a ground plane target with unknown height, on a two-dimensional display. Further, the MRSAR map will represent a target with significant height as a larger return in both the x and y display axes. The shape of the return will be dependent on the doppler frequency returned to the range cell

for display. Given an unresolved target on the display (i.e. an undefined shape), the operator is left with little choice, but to designate at the apparent centroid. The current AV-8B radar software calculates target elevation using air-to-ground ranging (See Chapter 4).

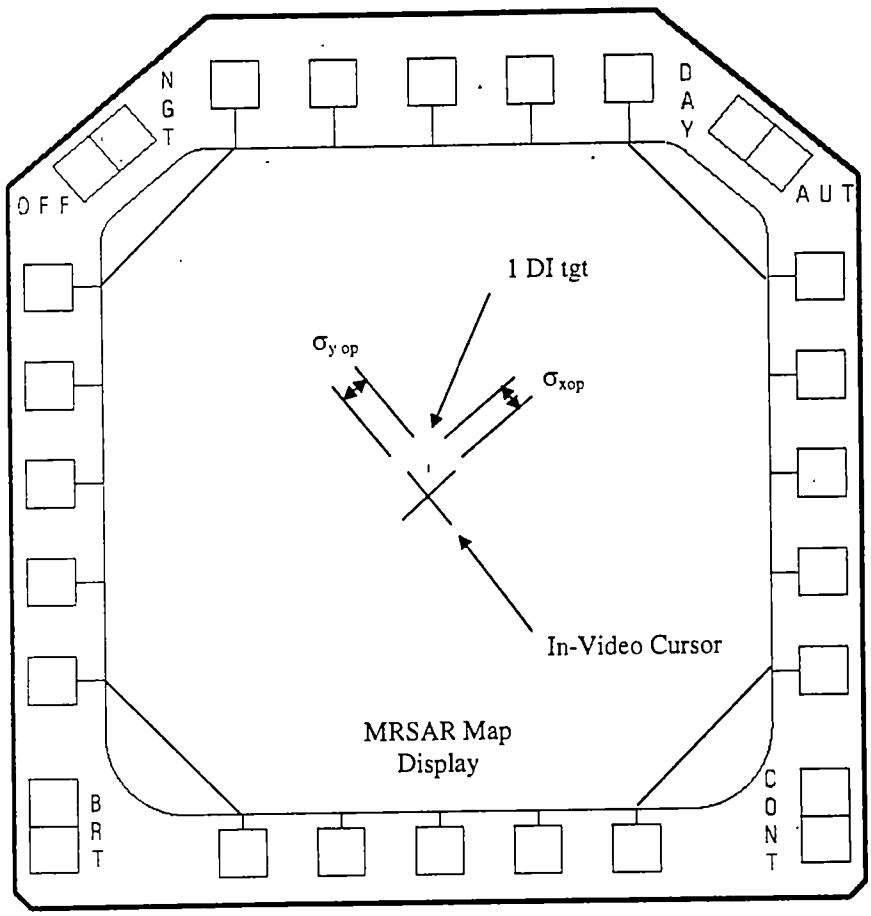


Figure 3-8
Medium Resolution Synthetic Aperture Radar Map
Multi-Purpose Color Display Operator Error

To derive the effect of the MPCD designation error on the target coordinate, the standard deviations must be resolved from the aircraft coordinate system, to the ground plane in down-range and cross-range errors accounting for squint angle at the time of designation (See Figure 3-9). Given the relationship of a 1.2 nm x 1.2 nm MRSAR

ground plane map, displayed within a 256 x 256 DI box, a ground distance per DI can be computed as 8.68 meters/DI.

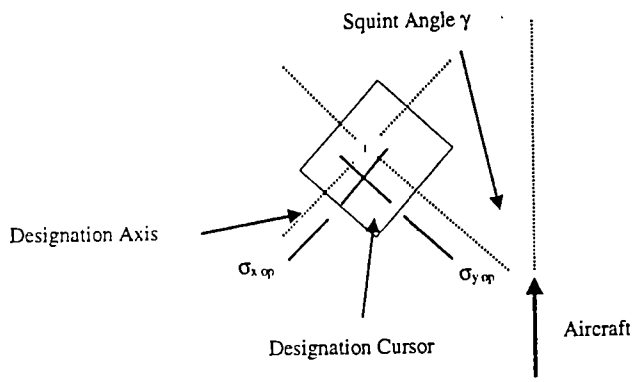


Figure 3-9
Medium Resolution Synthetic Aperture Radar
Display Error

The following relationships apply (See Appendix A for derivation):

$$\sigma_{x\,tgt} = (\sigma_{x\,op}\cos(\gamma) + \sigma_{y\,op}\sin(\gamma))(8.68\ \text{m/DI})\ \text{in meters}$$
$$\sigma_{y\,tgt} = (\sigma_{x\,op}\sin(\gamma) + \sigma_{y\,op}\cos(\gamma))(8.68\ \text{m/DI})\ \text{in meters}$$

Table 3-2 lists the conceptual operator TLE associated with an EXP3 MRSAR map over range of squint angles commonly encountered during radar mapping.

Table 3-2
Target Location Error Due to
Medium Resolution Synthetic Aperture Radar Map Operator Error[1]

Operator Error	$\sigma_{x\,tgt}$ Down-range Error (m)/ $\sigma_{y\,tgt}$ Cross-range Error (m)											
Squint Angle	10°		20°		30°[2]		40°[2]		50°[2]		60°	
DI Error	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$
1	10.0	10.0	11.1	11.1	11.9	11.9	12.2	12.2	12.2	12.2	11.9	11.9
2	20.1	20.1	22.3	22.3	23.7	23.7	24.5	24.5	24.5	24.5	23.7	23.7

1. Conceptual Data
2. Standard Attack Profile Designation/Release Values

The results are what should be expected given the resolution of the display (8.68 m/DI). Even a single DI error in designation will incur TLE on the order of 11-12 meters. As the squint angle increases up to 45°, both $\sigma_{x\,op}$ and $\sigma_{y\,op}$ level off in error. A linear increase in

TLE occurs with increase in designation error. The MRSAR technique requires increasing squint angle to improve resolution of the target and is optimized at 30°-50°. The minimization of MRSAR MPCD TLE will therefore require a balance of squint angle and designation accuracy (resolution dependent).

MPCD Error ARBS

Figure 3-10 depicts the AV-8B MPCD with an ARBS TV displayed target. As the aircraft tracks towards the target, the ARBS maintains lock. Although the ARBS is locked onto the target, it is not always centered on the target, and thus an operator induced pointing error induces TLE during designation. This typically occurs when the TV does not have contrast within the designation box to lock and the auto gate takes over acquiring the nearest trackable part of the target. The resultant standard deviations are $(\sigma_{x\,op}, \sigma_{y\,op})$.

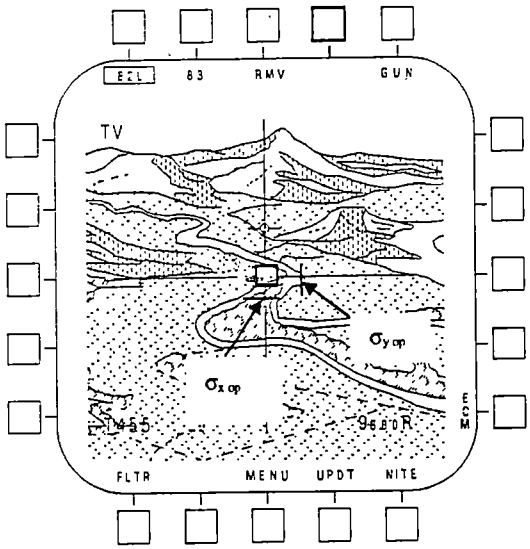


Figure 3-10
Angle-Rate Bombing System
Designation Error [4]

To derive the effect of an off-centroid track, MPCD designation error on the target coordinate, the errors must be resolved from the aircraft coordinate system, to the ground plane in down-range and cross-range errors, accounting for LOS and SR at the time of designation. Given the 6:1 amplified 6 mrad x 4 mrad FOV displayed within a 84 x 64 DI auto gate box on the MPCD, a useful ratio of 14 DI/mil azimuth and 16 DI/mil (assuming mils = mrad at small angles) vertical can be computed. Figure 3-11 provides a zoomed in view of the error.

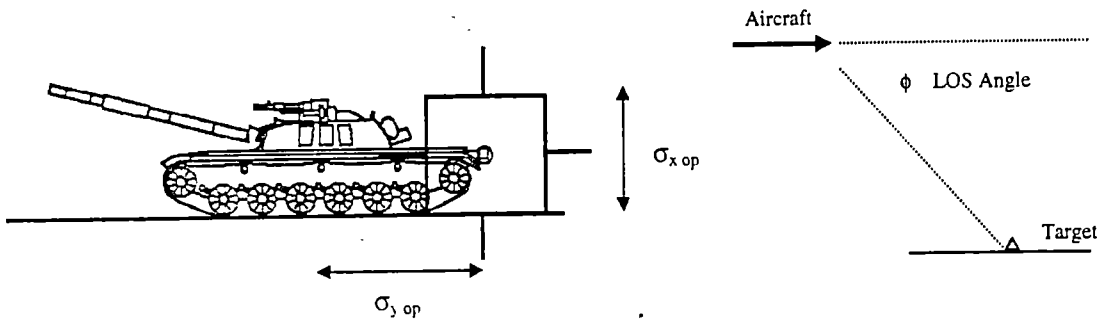


Figure 3-11
Target Location Error
Due to Angle-Rate Bombing System Off Target Designation

The following relationships apply (See Appendix A for derivation):

$$\sigma_{xtgt} = 6*\sigma_{x\,op}(SR/304.8\text{ m})(.3048\text{ m})\cos(\phi)/(16\text{ DI/mil})\text{ meters}$$
$$\sigma_{ytgt} = 6*\sigma_{y\,op}(SR/304.8\text{ m})(.3048\text{ m})/(14\text{ DI/mil})\text{ meters}$$

Table 3-3 lists some conceptual operator errors of 1 and 2 DI associated with an ARBS designation over multiple LOS angles.

Table 3-3

Target Location Error Due to Angle-Rate Bombing System Operator Error[1]

1 DI Error	$\sigma_{x\,tgt}$ Down-range Error (m)/ $\sigma_{y\,tgt}$ Cross-range Error (m)											
Slant Range	1524 m		3048 m		4572 m		6096 m		7620 m		9144 m	
LOS	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$
10°	0.56	0.65	1.13	1.31	1.69	1.96	2.25	2.61	2.81	3.27	3.38	3.92
30°[2]	0.49	0.65	0.99	1.31	1.48	1.96	1.98	2.61	2.47	3.27	2.97	3.92
45°[2]	0.40	0.65	0.81	1.31	1.21	1.96	1.62	2.61	2.02	3.27	2.42	3.92
60°	0.29	0.65	0.57	1.31	0.86	1.96	1.14	2.61	1.43	3.27	1.71	3.92
2 DI Error	$\sigma_{x\,tgt}$ Down-range Error (m)/ $\sigma_{y\,tgt}$ Cross-range Error (m)											
Slant Range	1524 m		3048 m		4572 m		6096 m		7620 m		9144 m	
LOS	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$
10°	1.13	1.31	2.25	2.61	3.38	3.92	4.50	5.23	5.63	6.53	6.75	7.84
30°[2]	0.99	1.31	1.98	2.61	2.97	3.92	3.96	5.23	4.95	6.53	5.94	7.84
45°[2]	0.81	1.31	1.62	2.61	2.42	3.92	3.23	5.23	4.04	6.53	4.85	7.84
60°	0.57	1.31	1.14	2.61	1.71	3.92	2.29	5.23	2.86	6.53	3.43	7.84

1 Conceptual Data
2 Standard Attack Profile Designation/Release Values

Similar to the HUD, the ARBS designation TLE increases with slant range. The range error decreases with an increase in LOS angle. An increase in designation error results in a linear increase in cross-range or down-range error.

3.2.2 Test Results.

Laboratory testing was conducted during the weeks of 22 February and 1 March 1999. Actual AV-8B controls and displays were used to conduct the test. A single DI target was displayed first on the HUD and then on the MPCD. The pilot was given 5 seconds to make the designation. After the initial designation was made, no sweetening was permitted to simulate the higher workload of designations in flight. The error in the (x, y) display axes were measured from the target. Table 3-4 lists the mean error and standard deviation in each axis from the laboratory testing.

Table3-4

AV-8B Operator-Display Error [11] [1,2]

Samples = 30	Head-Up Display Error		MPCD Error	
Display Error x-axis/y-axis	Mean (DI)	Std Deviation (DI)	Mean (DI)	Std Deviation (DI)
$\sigma_{x\ op}$	0.23	1.14	1.66	0.75
$\sigma_{y\ op}$	1.06	1.36	1.43	0.84
σ_{op}	1.77		1.12	

1 AV-8B Operator Display Error Laboratory Test Results, 02/15/99-03/01/99.
2 3 Target Locations, 10 Samples per Target

3.3 TARGET LOCATION ERROR ANALYSIS

Total operator pointing error can be expressed by the following relationship (See Appendix A for derivation):

$$\sigma_{tgt} = \sqrt{(\sigma_{x\ tgt})^2 + (\sigma_{y\ tgt})^2}$$

The effects of operator error on the generated target coordinate, σ_{tgt} are (See Appendix A for derivation):

HUD:

$$\sigma_{x\ tgt} = \sigma_{x\ op}(SR/304.8\ m)(.3048\ m)\cos(\theta)/(2.65\ DI/mil)\ meters$$
$$\sigma_{y\ tgt} = \sigma_{y\ op}(SR/304.8\ m)(.3048\ m)/(2.65\ DI/mil)\ meters$$

MPCD:

MRSAR Map:

$$\sigma_{x\ tgt} = (\sigma_{x\ op}\cos(\gamma) + \sigma_{y\ op}\sin(\gamma))(8.68\ m/DI)\ meters$$
$$\sigma_{y\ tgt} = (\sigma_{x\ op}\sin(\gamma) + \sigma_{y\ op}\cos(\gamma))(8.68\ m/DI)\ meters$$

ARBS:

$$\sigma_{x\ tgt} = 6*\sigma_{x\ op}(SR/304.8\ m)(.3048\ m)\cos(\phi)/(16\ DI/mil)\ meters$$
$$\sigma_{y\ tgt} = 6*\sigma_{y\ op}(SR/304.8\ m)(.3048\ m)/(14\ DI/mil)\ meters$$

From Appendix A, the equation for CEP approximation is:

$$CEP_{xy} = 0.5887 * (\sigma_{x\ tgt} + \sigma_{y\ tgt})\ meters$$

Utilizing the laboratory test results in Table 3-4, and a range of AV-8B attack profile flight path angles, LOS angles and slant ranges, the effect on the aircraft TLE expressed in CEP can be calculated. Table 3-5 details the results of these calculations.

Table 3-5
Target Location Error Due to Operator Error[1]

HUD						
Slant Range	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
Flight Path	CEP	CEP	CEP	CEP	CEP	CEP
10°	0.84	1.69	2.53	3.38	4.22	5.07
30°[2]	0.80	1.60	2.39	3.19	3.99	4.79
45°[2]	0.74	1.47	2.21	2.95	3.68	4.42
60°	0.66	1.31	1.97	2.62	3.28	3.94
MPCD - MRSAR						
Squint Angle	10°	20°	30°	40°	50°	60°
CEP	9.46	10.47	11.16	11.51	11.51	11.16
MPCD - ARBS						
Slant Range	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
LOS	CEP	CEP	CEP	CEP	CEP	CEP
10°	0.57	1.15	1.72	2.30	2.87	3.45
30°[2]	0.54	1.09	1.63	2.18	2.72	3.27
45°[2]	0.50	1.01	1.51	2.02	2.52	3.02
60°	0.45	0.90	1.35	1.81	2.26	2.71

1 AV-8B Operator Display Error Laboratory Test Results, 02/15/99-03/01/99.
2 Standard Attack Profiles Slant-Ranges and Line of Sight.

Generally, the HUD and ARBS operator interface provides for the least addition to TLE, falling within the requirement specified for JDAM. The standard attack profiles where HUD designations are valid include 30° - 45° dives with targeting occurring at 3048-4572 meters. **Therefore, the pilot should finalize, i.e. sweeten the HUD or ARBS designation when the flight path angle has increased to 30° - 45° and slant range has decreased to the minimum possible prior to release.**

Due to the resolution of the MRSAR map (1.2 nm x 1.2 nm), even a small DI error results in an 11m error, well outside the TLE requirements for a single JDAM. Additionally, the MRSAR technique requires LOS and squint angles of 30° - 50° to produce good resolution maps, though CEP actually decreases with decreases in squint angle. As this does not optimize the map resolution, the designation error would increase. **Therefore, the operator should optimize the MRSAR map by increasing**

squint angle while minimizing addition to TLE by accurately placing the designation symbol in range. A possible solution to the TLE associated with MRSAR maps would be to drop more than one weapon. This would improve the weapon's effects on target. Further study would be required with respect to weapon effectiveness to validate this solution.

4. AV-8B SENSOR ERROR

4.1 SENSOR INTEGRATION

In computed weapons delivery, the speed and accuracy of the aircraft mission computer is used to solve the heart of the release solution, the bombing triangle. The bombing triangle is subject to continuous change as the aircraft moves toward the target. The data used in these computations are obtained from the various sensors, pre-programmed data, and pilot inputs (Figure 4-1). The common factor that affects the ability of all sensors to derive target coordinates is pointing accuracy. The total pointing accuracy error will be a summation of aircraft position error (Chapter 2), operator-display error (Chapter 3) and sensor error (Chapter 4). Any sensitivity in pointing accuracy will directly affect the solution for HAT, SR and down range travel.

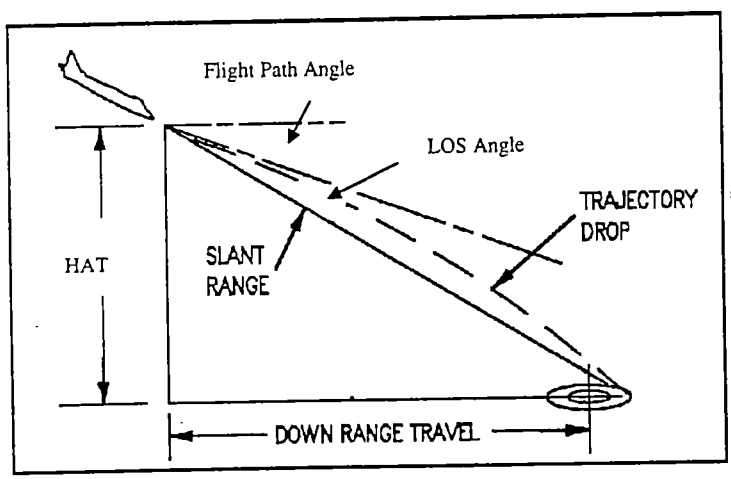


Figure 4-1
Bombing Triangle [4]

To obtain a target position solution, normally two of the quantities illustrated (HAT, LOS angle, slant-range and DRT) need to be derived by a sensor to solve the remainder of the bombing triangle problem.

4.1.1 Head-Up Display – Inertial Navigation System.

A HUD-INS designation is a visual designation requiring the target to be in the HUD TFOV and the INS sensor mode selected. When the TDC is pressed, the TD diamond appears on the HUD initialized at the velocity vector. It is ground stabilized and may be slewed via the TDC (See Figures 3-2, 3-5). However, the preferred method is to steer the aircraft to overlay the velocity vector on the target and when they are coincident, tap the TDC (press/release) to designate. The intersection of the target and the ground should be designated to avoid entering false range information.

HUD designation height above target calculations will be made using the pilot selected source for altitude. For aircraft equipped with radar, HAT will be computed using AGR. Aircraft without a radar and restricted from use of ARBS (due to night-time or smoke on the battlefield) will use aircraft GPS altitude minus a pilot estimate of the target elevation, to derive HAT. This requires the pilot to have some knowledge of the target area to provide an accurate estimate.

4.1.2 Angle-Rate Bombing System.

The ARBS is a mechanical target tracking system, which utilizes rate of change of the LOS angle between the aircraft and target to compute slant range (Figure 4-2). The dual mode tracker performs the angle rate calculations using aircraft motion relative to the target to kinematically calculate target range and from this, the target coordinates.

The height above target calculations are also computed using the angle rate computation. However, the target LOS angle and associated LOS angular rate data require mission computer input along with air data and attitude information to compute height above target. Height above target is independent of the designation position. If the designation is long or short of the target, calculated HAT will not be affected as long as designated altitude equals target altitude. Thus, two of the triangle quantities are obtained and target ranges are computed.

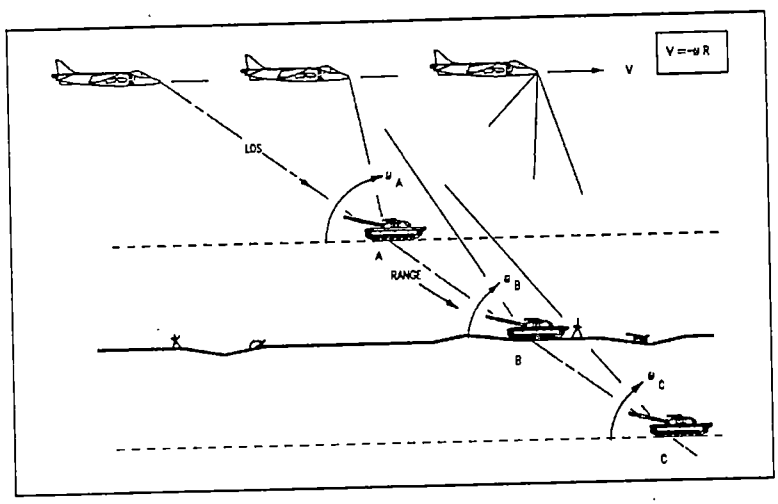


Figure 4-2
Angle-Rate Bombing System [4]

4.1.3 AN/APG-65 Medium Resolution Synthetic Aperture Radar Map.

The EXP3 MRSAR mode utilizes synthetic aperture radar (SAR) processing techniques to look at a small fixed range perimeter area (1.2 nm x 1.2 nm) as depicted in Figure 4-3. EXP3 takes advantage of the forward motion of the radar (aircraft velocity) to synthesize the equivalent of a very long side-looking array antenna from the radar returns received over a period of several seconds or more. EXP3 is specified to provide a 30' x 30' resolution. The EXP3 mode of the radar can effectively be used to designate

radar resolvable point targets to create INS coordinates and weapon solution computations for the bombing triangle.

On radar aircraft, the AGR mode is the primary source for height above target information. The MC uses the radar slant range and LOS angles to compute height above target for the weapon delivery solution.

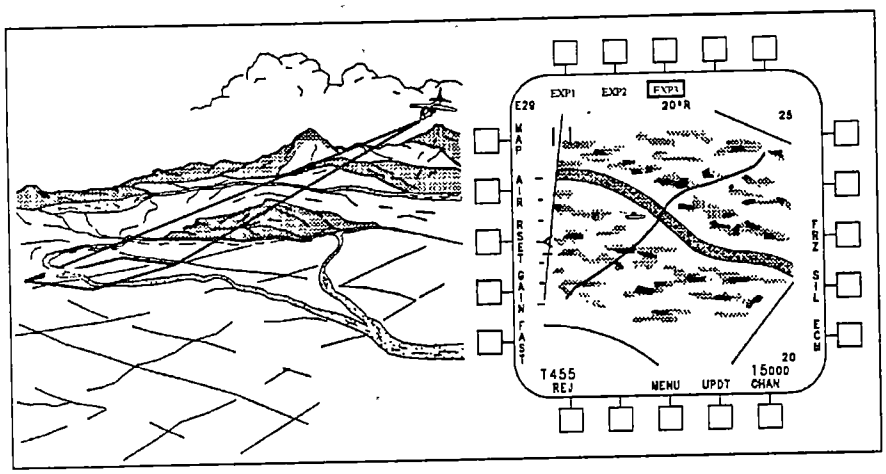


Figure 4-3
EXP3 Medium Resolution Synthetic Aperture Radar Display [4]

4.2 ERROR ANALYSIS

4.2.1 Derivation.

This section defines the singular effects of sensor pointing error as it contributes to the target location error. Sensor error can be stated with the following expression (See Appendix A for derivation):

$$\sigma_{sens} = \sqrt{(\sigma_{x\,sens})^2 + (\sigma_{y\,sens})^2}$$

where $\sigma_{x\,sens}$ equals the standard deviation in down-range error, $\sigma_{y\,sens}$ equals the standard deviation in cross-range error. Any error in the horizontal plane may effect the derived HAT, depending on the sensor used. Although each sensor is different, they all attempt to solve the bombing triangle, and are therefore subject to similar sensitivities. The

conceptual analysis described here will discuss the singular pointing errors associated with each sensor.

HUD Error

The major error occurring with HUD-INS designations results from the projection of the HUD not boresighted (BST) to the aircraft design eye position. Head-Up Display projectors are changed at times due to failure or other maintenance action. The procedure does not always include boresighting the display to the design eye position. If this occurs, the projection from which the pilot views and designates on the HUD will not overlay the intended position on the ground. An example of boresight corrections would be an adjustment of 2 mils in pitch (x-axis) and 2 mils in yaw (y-axis). Figure 4-4 depicts the sensor error as it propagates to the ground plane, down and cross track calculations.

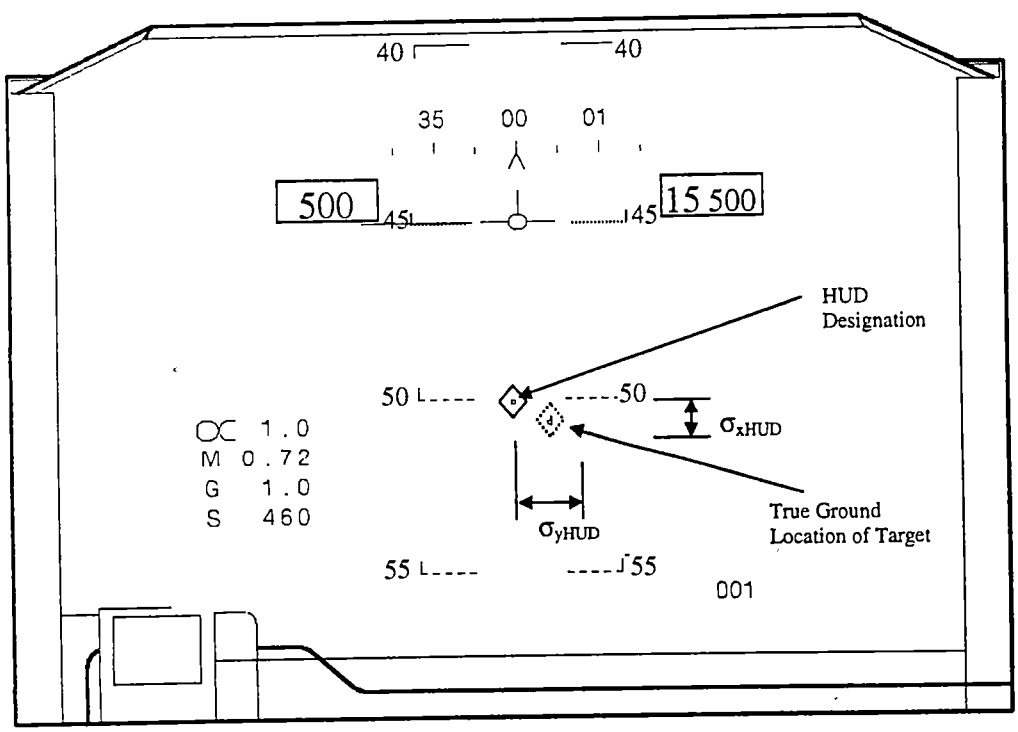


Figure 4-4
Head-Up Display Boresight Error

To derive the effect of the HUD boresight error, the uncertainties must be resolved to the ground plane, accounting for the aircraft flight path angle and slant range to target at time of designation. Again, given the relationship: 1 mil = .3048 m at 304.8 meters SR, the effects of slant range and FPA at the time of designation can be calculated. The boresight of the HUD error resolved in the ground plane can be quantified by (See Appendix A for derivation):

$$\sigma_{x\,tgt} = \sigma_{x\,HUD}(SR/304.8\text{ m})(.3048\text{ m})\cos(\theta)\text{ meters}$$
$$\sigma_{y\,tgt} = \sigma_{y\,HUD}(SR/304.8\text{ m})(.3048\text{ m})\text{ meters}$$

Table 4-1 contains the effects on TLE of a 2 x 2 mil boresight error in the x, y-axis on the HUD over a range of flight path angles and slant ranges.

Table 4-1
Target Location Error Due to Head-Up Display Boresight Error[1]

2 x /2 y Error (mils)	$\sigma_{x\,tgt}$ Down-range Error (m)/ $\sigma_{y\,tgt}$ Cross-range Error (m)											
Slant Range	1524 m		3048 m		4572 m		6096 m		7620 m		9144 m	
Flight Path	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$
10°	3.00	3.05	6.00	6.10	9.01	9.14	12.0	12.2	15.0	15.2	18.0	18.3
30°[2]	2.64	3.05	5.28	6.10	7.92	9.14	10.6	12.2	13.2	15.2	15.8	18.3
45°[2]	2.16	3.05	4.31	6.10	6.47	9.14	8.62	12.2	10.8	15.2	12.9	18.3
60°	1.52	3.05	3.05	6.10	4.57	9.14	6.10	12.2	7.62	15.2	9.15	18.3

1. Conceptual Data
2 Standard Attack Profile Designation/Release Values

Similar to the operator error, the effects of HUD boresight errors are reduced as the flight path angle increases and the slant range decreases. The dive angles and slant ranges at which the target designation will be made indicate greater error than desired for BOC weapons.

When the pilot uses the HUD without the ARBS or radar to create the target designation, he must have knowledge of the target area and include an estimate for target elevation. If possible, the ARBS or radar will always be used to aid in defining the target

elevation thus eliminating a possible pilot entered altitude error. The sensitivity of the designation and weapons solution to an error in target elevation will be dependent on the radius of error already resident in the ground plane. An example of this would be if the BOC weapon navigated to the target with a ranging error of 3.5 meters. The weapon could err 3.5 meters in target elevation with an impact angle of 45°, and have minimal effect on TLE. The effect of target elevation will be further discussed in Chapter 5.

MPCD ARBS Error

The ARBS determines target location by pointing the DMT. Errors are induced if the sensor pointing angles have some uncertainty in position. Similar to the HUD, ARBS are changed at times due to failure or other maintenance action. The replacement procedure does not include assessing the new systems pointing accuracy. If sensitivity in pointing accuracy is resident in the system, the projection the pilot views and utilizes to designate targets on the MPCD or HUD will not overlay the intended position on the ground. As the ARBS moves both in azimuth and in elevation, any error in either will induce an associated error in down-range and cross-range coordinate calculation. Figure 4-5 depicts this sensor error as it propagates to the ground plane.

To derive the effect of ARBS pointing error, the uncertainties must be resolved to the ground plane, including the aircraft to target LOS angle and the slant range to target at the time of designation. The projection of the ARBS pointing error to the ground plane can be quantified by the following relationships (See Appendix A for derivation):

$$\sigma_{x\,tgt} = \sigma_{x\,ARBS}(SR/304.8\text{ m})(.3048\text{ m})\cos(\phi)\text{ meters}$$
$$\sigma_{y\,tgt} = \sigma_{y\,ARBS}(SR/304.8\text{ m})(.3048\text{ m})\text{ meters}$$

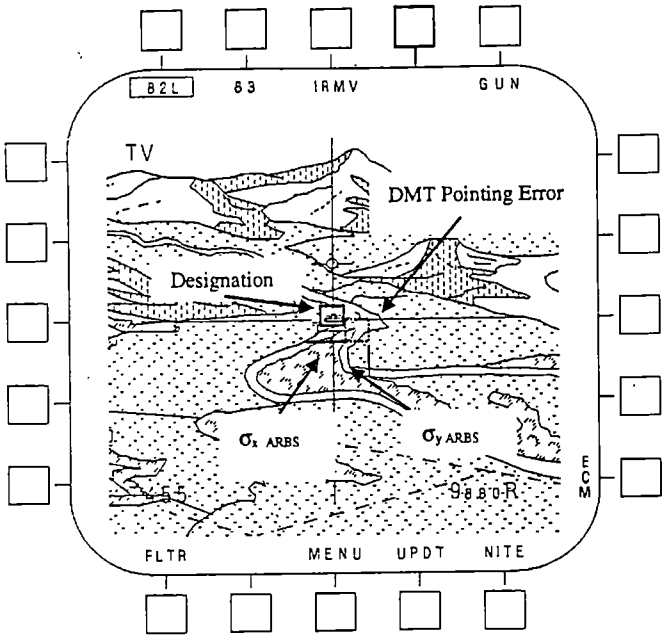


Figure 4-5
Angle-Rate Bombing System Pointing Angle Error [4]

Table 4-2 contains the effects on TLE of a 2 mil x 2 mil pointing error in the x, y-axis of the ARBS over a range of LOS angles and slant ranges.

Table 4-2
Target Location Error Due to Angle-Rate Bombing System Pointing Angle Error[1]

2 x/2 y mil Error	$\sigma_{x\,tgt}$ Down-range Error (m)/ $\sigma_{y\,tgt}$ Cross-range Error (m)											
Slant Range	1524 m		3048 m		4572 m		6096 m		7620 m		9144 m	
LOS	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$
10°	3.00	3.05	6.00	6.10	9.01	9.14	12.0	12.2	15.0	15.2	18.0	18.3
30°[2]	2.64	3.05	5.28	6.10	7.92	9.14	10.6	12.2	13.2	15.2	15.8	18.3
45°[2]	2.16	3.05	4.31	6.10	6.47	9.14	8.62	12.2	10.8	15.2	12.9	18.3
60°	1.52	3.05	3.05	6.10	4.57	9.14	6.10	12.2	7.62	15.2	9.15	18.3

1. Conceptual Data
2 Standard Attack Profile Designation/Release Values

The effects of ARBS pointing angle errors are similar to those of the HUD, greatly increasing with slant range and decreasing with LOS angle increases.

The heights above target calculations for ARBS designations are made using the ARBS computation. HAT accuracy is dependent on designation placement. If an off-

target designation is made and the elevation is the same as the target location, no increase in TLE due to target height is incurred. The effects of an error in target altitude are further discussed in Chapter 5.

MRSAR Mapping Error

It is important for the pilot to realize that although EXP3 provides improved resolution it is synthetically created and subject to pointing errors created by erroneous inputs. The complexities of MRSAR techniques and the associated errors are outside the scope of this thesis. However, generalizations with respect to some of the error sources can be made. For example, a velocity error will effect SAR mapping by causing radar map generation error and target designation drift error. If this occurs, the MRSAR display will not overlay the position on the ground where the target is actually located and thus, the pilot will create the designation in the wrong location [12]. The amount the designation is off is a function of the magnitude of velocity error and the time the pilot takes to designate (approximately 5 seconds). For the purpose of this conceptual analysis, a 1kt and 5 kt error will be examined. Figure 4-6 depicts this sensor error.

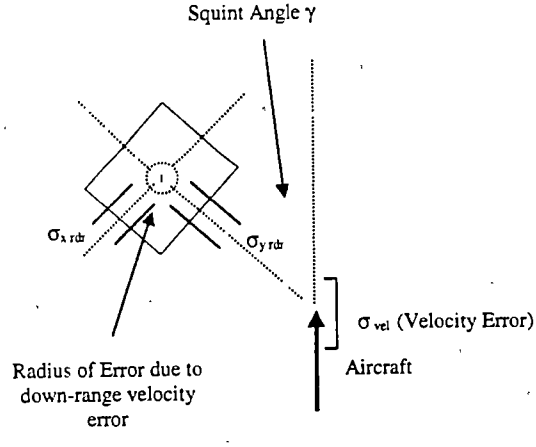


Figure 4-6
Radar Mapping Error

To derive the effect of the MPCD mapping error on the target coordinate, the standard deviations must be resolved from the aircraft coordinate system, to the ground plane in down-range and cross-range errors. Similar to the operator error (Section 3.2), squint angle at the time of designation, must be accounted for. The following relationships apply for a constant aircraft velocity error (See Appendix A for derivation):

$$\sigma_{x\,rdr} = \sigma_{vel}\cos(\gamma)(time)$$
$$\sigma_{y\,rdr} = \sigma_{vel}\sin(\gamma)(time)$$

$$\sigma_{x\,tgt} = \sigma_{x\,rdr}\cos(\gamma) + \sigma_{y\,rdr}\sin(\gamma) \text{ meters}$$
$$\sigma_{y\,tgt} = \sigma_{x\,rdr}\sin(\gamma) + \sigma_{y\,rdr}\cos(\gamma) \text{ meters}$$

Table 4-3 details the expected TLE associated with an EXP3 MRSAR map over a range of squint angles and two conceptual velocity errors.

Table 4-3
Target Location Error Due to Radar Mapping Error[1]

Radar Map Error	$\sigma_{x\,tgt}$ Down-range Error (m)/ $\sigma_{y\,tgt}$ Cross-range Error (m)											
Squint Angle	10°		20°		30°[2]		40°[2]		50°[2]		60°	
Vel Error	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$	$\sigma_{x\,tgt}$	$\sigma_{y\,tgt}$
1	2.57	0.88	2.57	1.65	2.57	2.23	2.57	2.53	2.57	2.53	2.57	2.23
5	12.9	4.40	12.9	8.27	12.9	11.1	12.9	12.7	12.9	12.7	12.9	11.1

1 Conceptual Data
2 Standard Attack Profile Designation/Release Values

Radar mapping errors increase linearly with the velocity error. Understanding the sensitivity of this error to an increase in aircraft forward velocity can be used to mitigate its effects. Any increase in forward airspeed will reduce the percentage of uncertainty to total velocity, thus decreasing mapping errors and TLE. The squint angles used during the standard attack profiles indicate minimal effect on the mapping error. An increase in squint angle is required to obtain the best resolution map, which should also help reduce

mapping errors. Additionally, increased aircraft forward velocity will also increase map resolution and therefore reduce mapping error.

The height above target calculations for the radar designations will be made using the air-to-ground ranging computation. HAT accuracy will be dependent on designation placement. The most significant radar object within the beam width of the radar will be used for calculation of target elevation. If an off-target designation is made and the elevation is the same as the target location, no increase in TLE due to target height will occur. The sensitivity of the horizontal TLE to vertical TLE will be further discussed in Chapter 5.

4.2.2 Test Results.

An example of boresight and pointing angle corrections would be those made for the test aircraft. The adjustments for the HUD and ARBS listed in Table 4-4 were made prior to the test flights. Though not a statistically significant representation of boresight or pointing error corrections, they provide an example from which to discuss a system error. Additionally, Table 4-4 contains the mean down-range velocity error measured from a differential GPS truth source, from the 331 minutes of GPS-INS testing discussed in Chapter 2.

Table 4-4
AV-8B Sensor Error[1]

Sensor Error	HUD (mrad)	ARBS (mrad)	Aircraft (kts)
$\sigma_{x\ sens}$	3.54	1.55	NA
$\sigma_{y\ sens}$	2.02	1.05	NA
Velocity	NA	NA	1.80

1 Boresight/Pointing Angle and Velocity Test Data

4.3 TARGET LOCATION ERROR ANALYSIS

Sensor pointing error can be expressed by the following relationship:

$$\sigma_{sens} = \sqrt{(\sigma_{x\,sens})^2 + (\sigma_{y\,sens})^2}$$

The effects of sensor error on the generated target coordinate location error, σ_{tgt} are:

HUD:

$$\sigma_{x\,tgt} = \sigma_{x\,HUD}(SR/304.8\ m)(.3048\ m)\cos(\theta)\ meters$$
$$\sigma_{y\,tgt} = \sigma_{y\,HUD}(SR/304.8\ m)(.3048\ m)\ meters$$

MPCD:

ARBS:

$$\sigma_{x\,tgt} = \sigma_{x\,ARBS}(SR/304.8\ m)(.3048\ m)\cos(\phi)\ meters$$
$$\sigma_{y\,tgt} = \sigma_{y\,ARBS}(SR/304.8\ m)(.3048\ m)\ meters$$

MRSAR Map:

$$\sigma_{x\,tgt} = \sigma_{x\,rdr}\cos(\gamma) + \sigma_{y\,rdr}\sin(\gamma)\ meters$$
$$\sigma_{y\,tgt} = \sigma_{x\,rdr}\sin(\gamma) + \sigma_{y\,rdr}\cos(\gamma)\ meters$$

From Appendix A. the equation for CEP approximation is:

$$CEP_{xy} = 0.5887 * (\sigma_{x\,tgt} + \sigma_{y\,tgt})\ meters$$

Utilizing the boresight/pointing angle corrections, the velocity error test results in Table 4-4 and a range of AV-8B attack profile flight path angles, LOS angles and slant ranges, the effect on the aircraft TLE expressed in CEP can be calculated. Table 4-5 details the results of these calculations.

Generally, the ARBS and MRSAR map provide for the lowest addition to aircraft TLE. The standard attack profiles where ARBS designations are valid include 30° - 45° dives with targeting occurring at 3048-4572 meters. The MRSAR mapping occurs at 30° - 50° squint angle and 3-6 nm from the target.

Table 4-5
Target Location Error Due to Sensor Error

HUD						
Slant Range	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
Flight Path	CEP (m)	CEP (m)	CEP (m)	CEP (m)	CEP (m)	CEP (m)
10°	4.94	9.88	14.82	19.76	24.70	29.64
30°[1]	4.56	9.13	13.69	18.25	22.81	27.38
45°[1]	4.06	8.12	12.17	16.23	20.29	24.35
60°	3.40	6.80	10.20	13.60	17.00	20.40
MPCD - MRSAR						
Squint Angle	10°	20°	30°[1]	40°[1]	50°[1]	60°
CEP (m)	3.66	4.48	5.09	5.41	5.41	5.09
MPCD - ARBS						
Slant Range	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
LOS	CEP (m)	CEP (m)	CEP (m)	CEP (m)	CEP (m)	CEP (m)
10°	2.30	4.61	6.91	9.21	11.51	13.82
30°[1]	2.14	4.28	6.42	8.55	10.69	12.83
45°[1]	1.92	3.84	5.76	7.68	9.60	11.51
60°	1.63	3.27	4.90	6.53	8.16	9.80

1 Standard Attack Profiles Slant-Ranges and Line of Sight.

The operator should attempt to maximize line of sight angle or minimize slant range to the target during the attack profile, to minimize TLE induced by ARBS pointing errors. Given the MRSAR technique, which requires LOS and squint angles of 40° - 50° to produce adequate resolution maps, TLE due to velocity error can be reduced by increasing forward velocity. **The operator should optimize the MRSAR map by increasing squint angle and forward velocity, thus reducing TLE.** All sensors would benefit from having a sensitivity analysis and boresight performed to help characterize and reduce the effects of pointing and velocity errors. **Prior to use for BOC weapon designations, the sensors should be analyzed for pointing accuracy to minimize the TLE.**

5.0 FLIGHT TEST

5.1 SENSOR DESIGNATIONS

The conceptual analysis was validated via flight test using all three sensors. Figure 5-1 depicts the operationally representative ramp-down to diving attack profile used. Fifty aircraft-target designations were made using each sensor, over multiple sorties. During each attack the 10-digit Universe Transverse Mercator (UTM) grid coordinate was recorded, as well as the target elevation for comparison with the surveyed target location. The recorded coordinate was divided into three parts, Easting, Northing and elevation relative to an earth-fixed coordinate system. Flights were conducted at various times, during daylight hours with GPS PPS available. No flights were conducted with INS only. There were no aircraft system anomalies noted for any of the flights. Each individual sortie data are located in Appendix B.

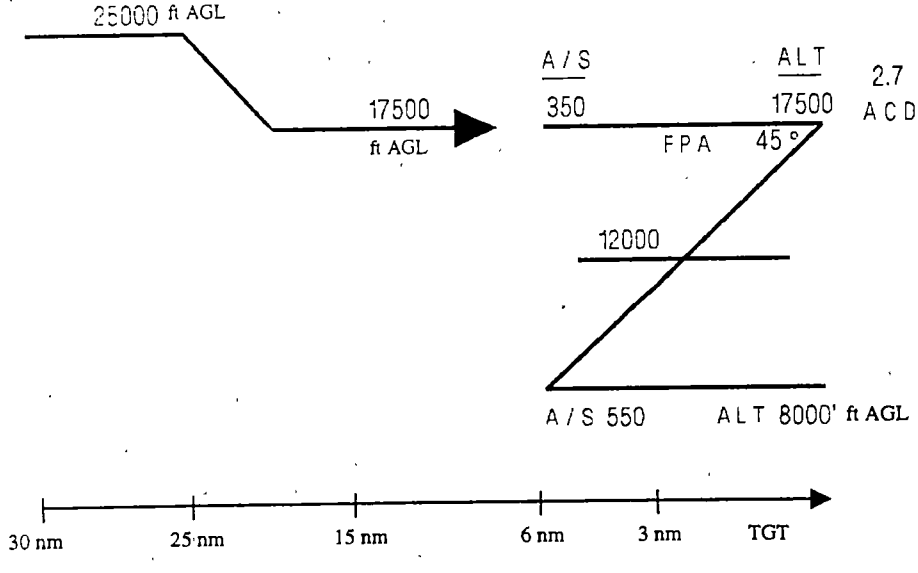


Figure 5-1
Attack Profile [5]

5.1.1 Head-Up Display – Inertial Navigation System.

Fifty HUD designations were made over five flights using a diving attack profile. Twenty-five of the designations used AGR for the altitude calculations and twenty-five designations used ARBS for the altitude calculation. Table 5-1 summarizes the TLE flight test results calculated to 1-sigma accuracy and the CEP/LEP approximated to 50% accuracy.

Table 5-1
Target Location Error Due to Head-Up Display Designations [13,14] 1,2

Flights = 10	HUD (AGR)		HUD (ARBS)	
Flight Path	Mean (m)	Std Deviation (m)	Mean (m)	Std Deviation (m)
$\sigma_{x\ tgt}$	7.57	4.09	6.92	4.57
$\sigma_{y\ tgt}$	8.13	4.03	6.94	3.85
$\sigma_{z\ tgt}$	5.15	2.94	9.86	5.53
CEP_{tgt}	4.78		4.96	
LEP_{tgt}	1.98		3.73	

1 Pseudo Data
2 Standard Attack Profile Designation/Release Values

5.1.2 Angle-Rate Bombing System.

Fifty ARBS designations were made over five flights using a diving attack profile. Designation and slewing were permitted until the checkpoint altitude of 12,000 feet AGL. The tolerance on the dive deliveries was $\pm 2^{\circ}$ flight path angle to ensure consistent slant range to target and designation accuracy. Table 5-2 summarizes the TLE flight test results calculated to 1-sigma accuracy and the CEP/LEP approximated to 50% accuracy.

5.1.3 AN/APG-65 Medium Resolution Synthetic Aperture Radar Map.

Fifty MRSAR map designations were made over ten flights using a standard level-ramp down attack profile. The profile was started at 30 nm and 25,000 feet MSL. A shallow ramp-down was begun at 25 nm to prevent gimbaling of the radar in the vertical

axis. Squint angle was gradually increased to 45° at 6 nm range. At 6 nm and 17,500 feet AGL. the MRSAR map was frozen and the aircraft turned nose on to the target. At 3 nm the aircraft rolled in on the target and selected AGR to calculate the HAT and derive target elevation. Table 5-2 summarizes the TLE flight test results calculated to 1-sigma accuracy and the CEP/LEP approximated to 50% accuracy.

Table 5-2
Target Location Error Due to Angle-Rate Bombing System/Medium Resolution Synthetic Aperture Radar Maps Designations [13, 14] [1,2]

Flights = 10	MPCD (ARBS)		MPCD (MRSAR Map)	
Flight Path	Mean (m)	Std Deviation (m)	Mean (m)	Std Deviation (m)
$\sigma_{x\ tgt}$	2.53	1.43	12.70	9.09
$\sigma_{y\ tgt}$	2.40	1.46	14.73	8.85
$\sigma_{z\ tgt}$	5.32	3.06	5.08	2.88
CEP_{tgt}	1.70		10.56	
LEP_{tgt}	2.06		1.94	

1 Pseudo Data
2 Standard Attack Profile Designation/Release Values

5.2 ERROR ANALYSIS

The total TLE was defined in terms of aircraft position error ($\sigma_{a/c}$), operator error (σ_{op}), and sensor error ($\sigma_{sens} = \sigma_{APG\text{-}65}, \sigma_{ARBS}, \sigma_{HUD}$) using the following expression (See Appendix A for derivation):

$$\sigma_{TLE} = \sqrt{(\sigma_{a/c})^2 + (\sigma_{op})^2 + (\sigma_{sens})^2}.$$

The standard deviations $\sigma_{a/c}$, σ_{op} and σ_{sens} are the 1-sigma errors derived from individual analysis of each contributor, composed of an error in each axis σ_x, σ_y and σ_z. The computational and laboratory analysis results from Chapters 2-4 for all three error sources and sensors are summarized in Table 5-3 for a 45° dive and 3048 m of slant range. The MRSAR Map results are from a 40° squint angle approach to the target.

Table 5-3
Summary of Ground Analysis Results

Error Source	Aircraft		Operator			Sensor		
Sensor / Error	GPS (m)	INS (m)	HUD (m)	ARBS (m)	Radar (m)	HUD (m)	ARBS (m)	Radar (m)
$\sigma_{x\ tgt}$	2.44	4.56	.93	.61	9.22	7.63	3.32	4.63
$\sigma_{y\ tgt}$	3.80	5.48	1.57	1.10	10.33	6.16	3.2	4.56
$\sigma_{z\ tgt}$	2.35	15.42	NA	NA	NA	NA	NA	NA

From the information in Table 5-3, the CEP and LEP by sensor can be calculated using the following expressions (See Appendix A for derivation):

$$\sigma_{x,y,z\ tgt} = \sqrt{(\sigma_{tgt\ a/c})^2 + (\sigma_{tgt\ op})^2 + (\sigma_{tgt\ sens})^2} \quad \text{by axis respectively,}$$

$$CEP = 0.5887 * (\sigma_x + \sigma_y),$$

$$LEP = 0.6745 * \sigma_z.$$

A comparison of ground analysis with flight test is delineated in Table 5-4.

Table 5-4
Ground Analysis vs. Flight Test Results

Sensor	HUD Designations (AGR/ARBS HAT)			ARBS Designations (ARBS HAT)		MRSAR Map Designations (AGR HAT)	
TLE (GPS)	Ground Test (m)	Flight Test Results (m) [1]		Ground Test (m)	Flight Test Results (m) [1]	Ground Test (m)	Flight Test Results (m) [1]
CEP	9.11	4.78	4.96	5.45	1.70	13.26	10.56
LEP	1.58	1.98	3.73	1.58	2.06	1.58	1.94
TLE (INS)	Ground Test (m)	Flight Test Results (m) [1]		Ground Test (m)	Flight Test Results (m) [1]	Ground Test (m)	Flight Test Results (m) [1]
CEP	10.2	4.78	4.96	7.13	1.70	14.03	10.56
LEP	10.40	1.98	3.73	10.40	2.06	10.40	1.94

1. Pseudo Data

Overall, the flight test data indicate a smaller horizontal TLE (CEP) than the ground analysis test evaluations. Optimally, the pilot will be minimizing all three-error sources during actual flight. Though no direct correlation from this study can be made, the in-flight targeting errors could tend to offset each other, thus reducing TLE from that of the ground test analysis.

Because the vertical TLE (LEP) could not be computed during the ground analysis (other than GPS/INS position keeping errors in Chapter 2), an accurate comparison to flight test LEP cannot be made. However, for GPS position keeping enabled, the order of magnitude is similar to the flight test data. Conversely, the INS position keeping altitudes are significantly greater than the flight test data.

Table 5-4 clearly indicates the ARBS to be the most accurate for designating targets. The HUD would be the second choice provided the ARBS or radar could be used to produce target elevation. Given the resolution of the MRSAR map (30'x 30'), the resultant large TLE is no surprise. While not within the TLE desired for JDAM (7.2 m), the MRSAR map could still prove useful validating target location for resolvable targets. The HUD could then be used to update the horizontal position during the diving attack.

Finally, as the primary objective is to define which sensor should be used for directing the BOC weapon, an understanding of the sensitivity of the aircraft TLE to a vertical error is required. Assuming perfect weapon guidance, the sensitivity of the CEP portion of the TLE to the LEP is dependent on the magnitude of the LEP and the weapon impact angle (See Figure 5-2). To conduct this analysis, an assumption of weapon impact angle programmed to 45^{o} was made.

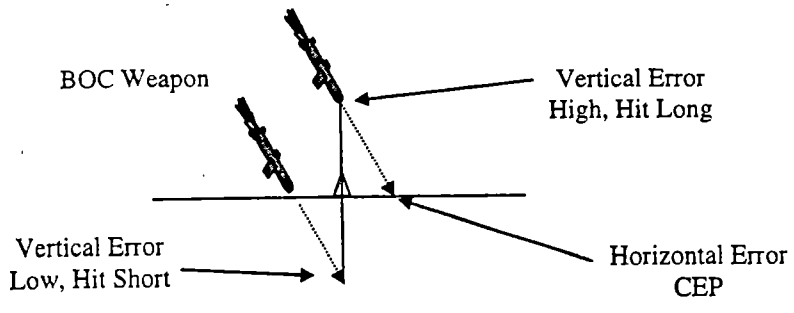


Figure 5-2
Horizontal Error Sensitivity to Vertical Error

The greater the LEP, the greater the probable effect on the horizontal TLE. Given the weapon impact angle equal to 45° and the LEP less than or equal to 50% of the CEP, the total TLE may not be increased. Table 5-5 details the possible outcomes of a vertical error given a constant weapon impact angle of, 45°.

Table 5-5
Horizontal Error Sensitivity to Vertical Error

LEP	LEP ≤ CEP			LEP > CEP		
CEP / LEP	Short	On Target	Long	Short	On Target	Long
High	No Increase	No Increase	Increase	Increase	Increase	Increase
On Target	No Increase	No Increase	No Increase	No Increase	No Increase	No Increase
Low	Increase	No Increase	No Increase	Increase	Increase	Increase

A review of Table 5-4 indicates that for flight test, LEP was less than or nearly equal to CEP. The left side of Table 5-5 therefore applies. Generally speaking, the effect of LEP on the horizontal CEP could be surmised to be minimal.

5.3 TARGET LOCATION ERROR ANALYSIS

Given the results in Tables 5-1 through 5-5, the following sensor decision trees (Figures 5-3 and 5-4) were formulated for use by the pilot during mission planning and in flight. The decision trees were applied against EO or radar significant targets to identify the sensor that should be used. The recommendations that can be drawn from the decision trees are: **The ARBS should be used as the primary designation source for BOC weapons (AV-8B II+). The HUD should be used as the secondary designation source for BOC weapons (AV-8B II+ and AV-8B II) provided AGR or ARBS are used for HAT. The MRSAR map should be used for target validation and updated with the HUD as a designation source for BOC weapons (AV-8B II+).**

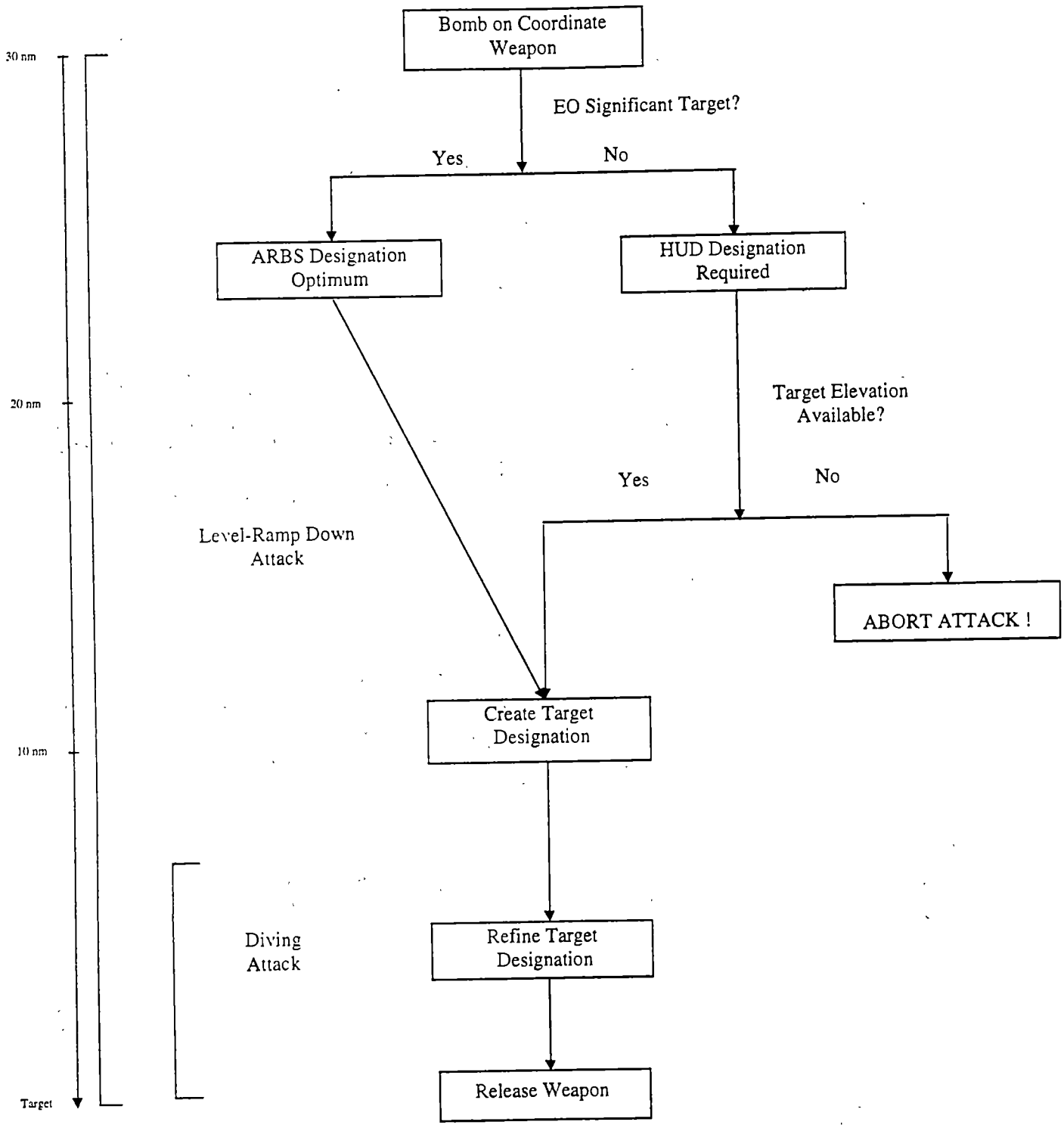


Figure 5-3
AV-8B II Sensor Decision Tree

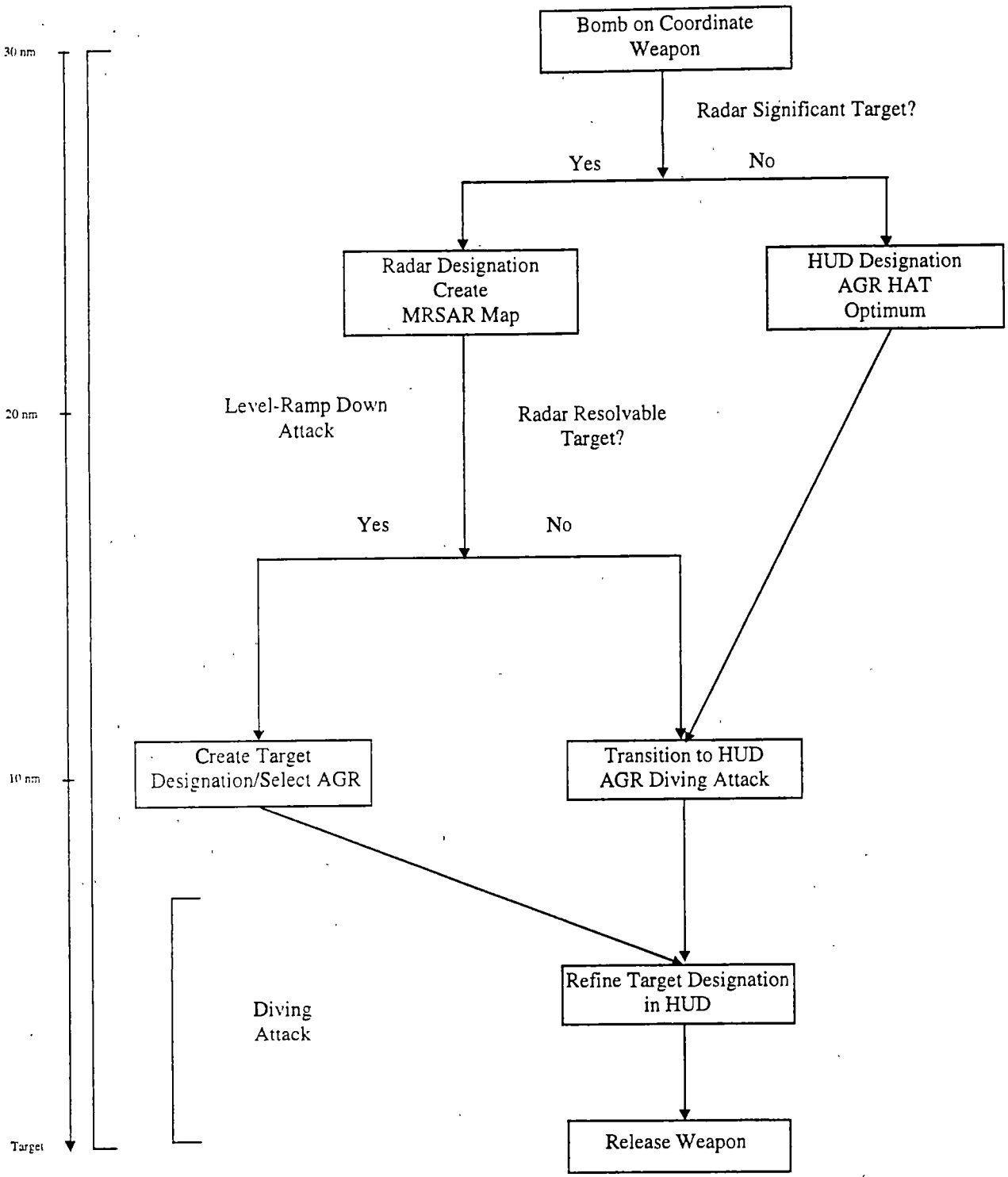


Figure 5-4
AV-8B II+ Sensor Decision Tree

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This ground and limited flight testing analysis has provided the pilot an understanding of which sensor will minimize TLE, based on a given attack profile. More importantly, this analysis has improved planning for and execution of an attack mission. The following statements about employment of BOC weapons from the AV-8B have been validated:

(1) The MRSAR MAP designations do not provide for minimization of TLE and should not be used to direct a single BOC weapon against a single target designation. However, upon further testing, the designations may be found to be accurate enough to direct multiple weapons against a single target designation (AV-8B II+).

(2) The Angle-Rate Bombing System designations provide for the minimum TLE and should be used as the primary source for direction of BOC weapons such as JDAM (AV-8B II).

(3) Head-Up Display sensor designations provide for a minimization of TLE and should be used as the secondary source for direction of BOC weapons such as JDAM provided the ARBS or AN/APG-65 radar are used to determine target elevation (AV-8B II and AV-8B II+).

(4) When integrated onto the AV-8B, BOC standoff weapons such as the JDAM, JSOW and JASM will result in increased survivability for the platform. An increase in survivability will be realized by the capability to reactively target these

weapons on a changing battlefield without degrading the effectiveness of the weapon (AV-8B II+ and AV-8B).

6.2 RECOMMENDATIONS

The following recommendations apply to employment of the aircraft and BOC weapon as they exist today. Software corrections associated with the integration of BOC weapons such as JDAM, have been recommended to improve the aircraft autonomous target designation capability, prior to fleet release of the new war-fighting capability. Recommendations have been delineated by aircraft type where appropriate.

Aircraft Error

(1) GPS position keeping should be selected for creation of a target coordinate from an on-board sensor provided PPS capabilities are enabled (AV-8B II+ and AV-8B II).

Operator Error

(2) The pilot should finalize, i.e. sweeten the HUD or ARBS designation when the flight path angle has increased to 30° - 45° and slant range has decreased to the minimum possible prior to release (AV-8B II+ and AV-8B II).

(3) The operator should optimize the MRSAR map by increasing squint angle while minimizing addition to TLE by accurately placing the designation symbol in range (AV-8B II+).

Sensor Error

(4) The operator should attempt to maximize line of sight angle or minimize slant range to the target during the attack profile, to minimize TLE induced by ARBS pointing errors (AV-8B II).

(5) The operator should optimize the MRSAR map by increasing squint angle and forward velocity, thus reducing the effect on TLE (AV-8B II+).

(6) Prior to use for BOC weapon designations, the sensors should be analyzed for pointing accuracy to minimize the effects of TLE (AV-8B II+ and AV-8B II).

(7) The ARBS should be used as the primary designation source for BOC weapons (AV-8B II+).

(8) The HUD should be used as the secondary designation source for BOC weapons (AV-8B II+ and AV-8B II) provided AGR or ARBS are used for HAT.

(9) The MRSAR map should be used for target validation and updated with the HUD as a designation source for BOC weapons (AV-8B II+). Further testing should be conducted to validate effectiveness of multiple weapons against an MRSAR designated target.

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APPENDIX A

STATISTICAL THEORY, FORMULA AND DERIVATIONS

This section describes the theory behind the statistical analysis and provides some insight into the terms and quantities used in the thesis. The formulas and principles are DoD standard and can be applied to weapon system accuracy evaluations provided that the assumption of a normal distribution of independent random variables is consistent with actual error data.

STATISTICS, ERROR ASSUMPTIONS AND FORMULA.

1. All error distributions are considered to be normal (i.e. Gaussian).
2. The mean and standard deviations for the flight test data were calculated using the Microsoft Excel spreadsheet functions for Average and Standard Deviation.
3. Conceptual error analysis tables are valid for the moment of designation only, and are included to indicate error trends with respect to aircraft, operator and sensor error. They do not represent statistically significant values.
4. Small angle approximations are made with respect to mils vs. milliradians. At small angles, the two quantities are treated as equivalent.
5. The linear errors (σ) are used because two and three dimensional error distributions are more easily analyzed statistically by individual treatment of the linear components.
6. Circular errors are computed from the linear components to analyze the horizontal error distribution. 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 and is determined from the 1-sigma values of two orthogonal linear distribution [15]. The

units of CEP will be the same as the units of the 1-sigma values. The formula for CEP is dependent on the ratio of the 1-sigma values. The formula is as follows:

Given the ratio of $\sigma_{min} / \sigma_{max}$:

If Ratio ≥ 0.3 $\quad CEP_{xy} = 0.5887 * (\sigma_x + \sigma_y)$

If $0.3 \geq$ Ratio ≥ 0.2 $\quad CEP_{xy} = 0.6196 * \sigma_{max} + 0.4263 * \sigma_{min}$

If $0.2 \geq$ Ratio ≥ 0.1 $\quad CEP_{xy} = 0.6621 * \sigma_{max} + 0.2141 * \sigma_{min}$

If $0.1 \geq$ Ratio $\quad CEP_{xy} = 0.6745 * \sigma_{max} + 0.0900 * \sigma_{min}$

σ_x – 1 – sigma x-axis error $\quad$ σ_y – 1 – sigma y-axis error

σ_{max} – Maximum of either σ_x or σ_y $\quad$ σ_{min} – Minimum of either σ_x or σ_y

7. 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 a possible error in range, depending on the sensitivity of the horizontal CEP to that error. LEP is computed by the following:

LEP = $.6745 * \sigma_z$, where σ_z = 1 – sigma z-axis error.

DERIVATIONS.

CHAPTER 1 - INTRODUCTION

The statistical measure of standard deviation calculated to an accuracy of 68% (1-σ) is used during the analysis to compute aircraft generated TLE. In this study, total TLE is defined in terms of:

$\sigma_{a/c}$ - Aircraft position error
σ_{op} - Operator induced designation error
σ_{sens} - Sensor induced pointing error

The root sum square of each error provides an accurate measure of aircraft TLE.

Therefore, TLE is defined by the following expression:

$$\sigma_{TLE} = \sqrt{(\sigma_{a/c})^2 + (\sigma_{op})^2 + (\sigma_{sens})^2} \quad \text{(Section 1.4).}$$

CHAPTER 2 - AIRCRAFT POSITION ERROR

Aircraft position error ($\sigma_{a/c}$) is defined by the following terms, as depicted in Figure 2-1, Chapter 2:

$\sigma_{x\ a/c}$ – Longitudinal axis aircraft position error
$\sigma_{y\ a/c}$ – Lateral axis aircraft position error
$\sigma_{z\ a/c}$ – Vertical axis aircraft position error

The root sum square of each error provides an accurate measure of aircraft position error.

Therefore aircraft position error is defined by the following expression:

$$\sigma_{a/c} = \sqrt{(\sigma_{x\ a/c})^2 + (\sigma_{y\ a/c})^2 + (\sigma_{z\ a/c})^2} \quad \text{(Section 2.2).}$$

Aircraft position error contributes to TLE as depicted in Figures 2-2 through 2-4 using the following terms:

$\sigma_{x\ tgt}$ – Down-track contribution to target location error
$\sigma_{y\ tgt}$ – Cross-track contribution to target location error
$\sigma_{z\ tgt}$ – Vertical contribution to target location error

The root sum square of each error provides an accurate measure of aircraft position error contribution to target location error. Therefore the following expression applies:

$$\sigma_{tgt\ a/c} = \sqrt{(\sigma_{x\ tgt})^2 + (\sigma_{y\ tgt})^2 + (\sigma_{z\ tgt})^2} \quad \text{(Section 2.2).}$$

CHAPTER 3 - OPERATOR ERROR

Operator error (σ_{op}) is defined by the following terms, as discussed in Chapter 3:

$\sigma_{x\ op}$ – Operator induced pointing error in display down-range
$\sigma_{y\ op}$ – Operator induced pointing error in display cross-range

Total operator pointing error can be expressed by the following root sum of squares relationship:

$$\sigma_{op} = \sqrt{(\sigma_{x\ op})^2 + (\sigma_{y\ op})^2} \quad \text{(Section 3.2).}$$

Operator error contributes to TLE as depicted in Figures 3-5 through 3-11 using the following terms:

$\sigma_{x\ tgt}$ – Down-track contribution to target location error
$\sigma_{y\ tgt}$ – Cross-track contribution to target location error

The effects of operator error on the generated target coordinate, σ_{tgt} can be derived using the relationship of: 1 mil = .3048 meters at 304.8 meters of slant range. The greater the slant range, the greater the effect of an operator designation error. Given this, a known display index/mil ratio and the flight path or LOS angle the down-range effects of an operator designation error are:

$$\sigma_{x\ tgt} = \frac{\sigma_{op}(SR/304.8\ m)(.3048\ m)\cos(\text{flight path angle } (\theta) \text{ or LOS angle}(\phi))}{\text{(display index/mil)}}$$

$$\sigma_{y\ tgt} = \frac{\sigma_{op}(SR/304.8\ m)(.3048\ m)}{\text{(display index/mil)}}$$

The equations for each sensor – operator error therefore are:

HUD:

$$\sigma_{x\,tgt} = \sigma_{x\,op}(SR/304.8\ m)(.3048\ m)\cos(\theta)/(2.65\ DI/mil)\ meters$$
$$\sigma_{y\,tgt} = \sigma_{y\,op}(SR/304.8\ m)(.3048\ m)/(2.65\ DI/mil)\ meters$$

MPCD:

MRSAR Map:

$$\sigma_{x\,tgt} = (\sigma_{x\,op}\cos(\gamma) + \sigma_{y\,op}\sin(\gamma))(8.68\ m/DI)\ meters$$
$$\sigma_{y\,tgt} = (\sigma_{x\,op}\sin(\gamma) + \sigma_{y\,op}\cos(\gamma))(8.68\ m/DI)\ meters$$

ARBS:

$$\sigma_{x\,tgt} = 6*\sigma_{x\,op}(SR/304.8\ m)(.3048\ m)\cos(\phi)/(16\ DI/mil)\ meters$$
$$\sigma_{y\,tgt} = 6*\sigma_{y\,op}(SR/304.8\ m)(.3048\ m)/(14\ DI/mil)\ meters$$

CHAPTER 4 - SENSOR ERROR

Sensor error (σ_{sens}) is defined by the following terms, as discussed in Chapter 4:

$\sigma_{APG\text{-}65}$ - AN/APG-65 sensor error
σ_{ARBS} - ARBS sensor error
σ_{HUD} - HUD sensor error

$\sigma_{x\,sens}$ - Equals the standard deviation in down-range error
$\sigma_{y\,sens}$ - Equals the standard deviation in cross-range error

Sensor pointing error can be expressed by the following relationship:

$$\sigma_{sens} = \sqrt{(\sigma_{x\,sens})^2 + (\sigma_{y\,sens})^2} \quad \text{(Section 4.2)}$$

Sensor error contributes to TLE as depicted in Figures 4-4 through 4-6 using the following terms:

$\sigma_{x\,tgt}$ – Down-range target location error
$\sigma_{y\,tgt}$ – Cross-range target location error
$\sigma_{z\,tgt}$ – Vertical axis target location error

The effects of sensor error on the generated target coordinate, σ_{tgt} can be derived using the relationship described for operator error: 1 mil = .3048 meters at 304.8 meters of slant range. The greater the slant range, the greater the effect of a sensor pointing

error. Given this, the flight path or LOS angle, the velocity error and the down-range effects of a sensor pointing error are:

$$\sigma_{x\ tgt} = \sigma_{sens}(SR/304.8\ m)(.3048\ m)\cos(\text{flight path angle } (\theta) \text{ or LOS angle}(\phi))$$
$$\sigma_{y\ tgt} = \sigma_{sens}(SR/304.8\ m)(.3048\ m)$$

The effects of sensor error on the generated target coordinate location error, σ_{tgt} are:

HUD:

$$\sigma_{x\ tgt} = \sigma_{x\ HUD}(SR/304.8\ m)(.3048\ m)\cos(\theta)\ meters$$
$$\sigma_{y\ tgt} = \sigma_{y\ HUD}(SR/304.8\ m)(.3048\ m)\ meters$$

MPCD:

ARBS:

$$\sigma_{x\ tgt} = \sigma_{x\ ARBS}(SR/304.8\ m)(.3048\ m)\cos(\phi)\ meters$$
$$\sigma_{y\ tgt} = \sigma_{y\ ARBS}(SR/304.8\ m)(.3048\ m)\ meters$$

MRSAR Map:

$$\sigma_{x\ rdr} = \sigma_{vel}\cos(\gamma)(time)$$
$$\sigma_{y\ rdr} = \sigma_{vel}\sin(\gamma)(time)$$

$$\sigma_{x\ tgt} = \sigma_{x\ rdr}\cos(\gamma) + \sigma_{y\ rdr}\sin(\gamma)\ meters$$
$$\sigma_{y\ tgt} = \sigma_{x\ rdr}\sin(\gamma) + \sigma_{y\ rdr}\cos(\gamma)\ meters$$

CHAPTER 5 - FLIGHT TEST

The total TLE was defined in terms of aircraft position error ($\sigma_{a/c}$), operator error (σ_{op}), and sensor error ($\sigma_{sens} = \sigma_{APG\text{-}65}, \sigma_{ARBS}, \sigma_{HUD}$) using the following expression:

$$\sigma_{TLE} = \sqrt{(\sigma_{a/c})^2 + (\sigma_{op})^2 + (\sigma_{sens})^2} \quad \text{(Section 5.2)}$$

From the information in Table 5-3, the CEP and LEP by sensor are calculated using the following expressions:

$$\sigma_{x,y,z\ tgt} = \sqrt{(\sigma_{tgt\ a/c})^2 + (\sigma_{tgt\ op})^2 + (\sigma_{tgt\ sens})^2} \quad \text{by axis respectively,}$$

$$CEP = 0.5887 * (\sigma_x + \sigma_y),$$

$$LEP = 0.6745 * \sigma_z.$$

APPENDIX B

DATA TABLES

Table B-1
TLE Due to Head-Up Display/Angle-Rate Bombing System and
Medium Resolution Synthetic Aperture Radar Map Operator Error

HUD Operator Error							
Err_xy	Dive Del	Slant Range					
σ_{xHUD} (mils)	FPA (°)	1524 m $\sigma_{x\ tgt}$	3048 m $\sigma_{x\ tgt}$	4572 m $\sigma_{x\ tgt}$	6096 m $\sigma_{x\ tgt}$	7620 m $\sigma_{x\ tgt}$	9144 m $\sigma_{x\ tgt}$
1.15	10	0.65	1.30	1.95	2.60	3.25	3.90
1.15	30	0.57	1.14	1.71	2.28	2.85	3.43
1.15	45	0.47	0.93	1.40	1.86	2.33	2.80
1.15	60	0.33	0.66	0.99	1.32	1.65	1.98
$\sigma_{y\ HUD}$ (mils)	FPA (°)	1524 m $\sigma_{y\ tgt}$	3048 m $\sigma_{y\ tgt}$	4572 m $\sigma_{y\ tgt}$	6096 m $\sigma_{y\ tgt}$	7620 m $\sigma_{y\ tgt}$	9144 m $\sigma_{y\ tgt}$
1.36	10	0.78	1.57	2.35	3.14	3.92	4.71
1.36	30	0.78	1.57	2.35	3.14	3.92	4.71
1.36	45	0.78	1.57	2.35	3.14	3.92	4.71
1.36	60	0.78	1.57	2.35	3.14	3.92	4.71
CEP_{xy} (m)	FPA (°)	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
CEP_{xy} (m)	10	0.84	1.69	2.53	3.38	4.22	5.07
CEP_{xy} (m)	30	0.80	1.60	2.39	3.19	3.99	4.79
CEP_{xy} (m)	45	0.74	1.47	2.21	2.95	3.68	4.42
CEP_{xy} (m)	60	0.66	1.31	1.97	2.62	3.28	3.94
ARBS Operator Error							
Err_xy	Dive Del	Slant Range					
$\sigma_{x\ ARBS}$ (mils)	LOS (°)	1524 m $\sigma_{x\ tgt}$	3048 m $\sigma_{x\ tgt}$	4572 m $\sigma_{x\ tgt}$	6096 m $\sigma_{x\ tgt}$	7620 m $\sigma_{x\ tgt}$	9144 m $\sigma_{x\ tgt}$
0.75	10	0.42	0.85	1.27	1.70	2.12	2.54
0.75	30	0.37	0.75	1.12	1.49	1.86	2.24
0.75	45	0.30	0.61	0.91	1.22	1.52	1.83
0.75	60	0.22	0.43	0.65	0.86	1.08	1.29
$\sigma_{y\ ARBS}$ (mils)	LOS (°)	1524 m $\sigma_{y\ tgt}$	3048 m $\sigma_{y\ tgt}$	4572 m $\sigma_{y\ tgt}$	6096 m $\sigma_{y\ tgt}$	7620 m $\sigma_{y\ tgt}$	9144 m $\sigma_{y\ tgt}$
0.84	10	0.55	1.10	1.66	2.21	2.76	3.31
0.84	30	0.55	1.10	1.66	2.21	2.76	3.31
0.84	45	0.55	1.10	1.66	2.21	2.76	3.31
0.84	60	0.55	1.10	1.66	2.21	2.76	3.31
CEP_{xy} (m)	LOS (°)	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
CEP_{xy} (m)	10	0.57	1.15	1.72	2.30	2.87	3.45
CEP_{xy} (m)	30	0.54	1.09	1.63	2.18	2.72	3.27
CEP_{xy} (m)	45	0.50	1.01	1.51	2.02	2.52	3.02
CEP_{xy} (m)	60	0.45	0.90	1.35	1.81	2.26	2.71

MRSAR Operator Error					
$\sigma_{x\ op}$ (mils)	$\sigma_{y\ op}$ (mils)	Squint (°)	$\sigma_{x\ tgt}$ (mils)	$\sigma_{y\ tgt}$ (mils)	CEP (m)
0.75	0.84	10	7.58	8.49	9.46
0.75	0.84	20	8.38	9.40	10.47
0.75	0.84	30	8.94	10.02	11.16
0.75	0.84	40	9.22	10.33	11.51
0.75	0.84	50	9.22	10.33	11.51
0.75	0.84	60	8.94	10.02	11.16

Table B-2

TLE Due to Head-Up Display/Angle-Rate Bombing System and Medium Resolution Synthetic Aperture Radar Map Sensor Error

HUD Boresight Error							
Err_xy	Dive Del	Slant Range					
σ_x (mils)	FPA (°)	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
3.54	10	5.31	10.63	15.94	21.25	26.57	31.88
3.54	30	4.67	9.34	14.02	18.69	23.36	28.03
3.54	45	3.82	7.63	11.45	15.26	19.08	22.89
3.54	60	2.70	5.40	8.09	10.79	13.49	16.19
σ_y (mils)	FPA (°)	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
2.02	10	3.08	6.16	9.24	12.31	15.39	18.47
2.02	30	3.08	6.16	9.24	12.31	15.39	18.47
2.02	45	3.08	6.16	9.24	12.31	15.39	18.47
2.02	60	3.08	6.16	9.24	12.31	15.39	18.47
CEP_{xy} (m)	FPA (°)	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
CEP_{xy} (m)	10	4.94	9.88	14.82	19.76	24.70	29.64
CEP_{xy} (m)	30	4.56	9.13	13.69	18.25	22.81	27.38
CEP_{xy} (m)	45	4.06	8.12	12.17	16.23	20.29	24.35
CEP_{xy} (m)	60	3.40	6.80	10.20	13.60	17.00	20.40
ARBS Pointing Angle Error							
Err_xy	Dive Del	Slant Range					
σ_x (mils)	LOS (°)	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
1.54	10	2.31	4.62	6.93	9.25	11.56	13.87
1.54	30	2.03	4.07	6.10	8.13	10.16	12.20
1.54	45	1.66	3.32	4.98	6.64	8.30	9.96
1.54	60	1.17	2.35	3.52	4.69	5.87	7.04
σ_y (mils)	LOS (°)	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
1.05	10	1.60	3.20	4.80	6.40	8.00	9.60
1.05	30	1.60	3.20	4.80	6.40	8.00	9.60
1.05	45	1.60	3.20	4.80	6.40	8.00	9.60
1.05	60	1.60	3.20	4.80	6.40	8.00	9.60
CEP_{xy} (m)	LOS (°)	1524 m	3048 m	4572 m	6096 m	7620 m	9144 m
CEP_{xy} (m)	10	2.30	4.61	6.91	9.21	11.51	13.82
CEP_{xy} (m)	30	2.14	4.28	6.42	8.55	10.69	12.83
CEP_{xy} (m)	45	1.92	3.84	5.76	7.68	9.60	11.51
CEP_{xy} (m)	60	1.63	3.27	4.90	6.53	8.16	9.80

MRSAR Mapping Error					
Vel (m/s)	Time (s)	Squint (°)	σ_x (mils)	σ_y (mils)	CEP (m)
0.93	5	10	4.63	1.58	3.66
0.93	5	20	4.63	2.98	4.48
0.93	5	30	4.63	4.01	5.09
0.93	5	40	4.63	4.56	5.41
0.93	5	50	4.63	4.56	5.41
0.93	5	60	4.63	4.01	5.09

Table B-3
Flight Test Medium Resolution Synthetic Aperture Radar and
Angle-Rate Bombing System Target Location Error

MRSAR – Designation/AGR Altitude Calculation				ARBS – Designation/ARBS Altitude Calculation			
Sample	σ_x	σ_y	σ_z	Sample	σ_x	σ_y	σ_z
1	22.72	18.73	3.09	1	2.79	4.44	0.32
2	15.00	23.55	3.82	2	1.48	1.30	3.38
3	2.26	27.21	0.45	3	4.22	4.43	8.47
4	1.96	18.05	6.26	4	1.57	3.00	9.91
5	3.25	6.74	4.07	5	1.47	3.76	9.35
6	18.13	3.35	1.13	6	0.54	4.11	5.03
7	21.99	27.27	4.61	7	0.75	0.85	1.68
8	25.48	1.67	6.57	8	0.10	3.19	6.61
9	9.24	12.49	9.69	9	1.19	0.12	7.31
10	13.82	12.55	1.01	10	1.95	0.87	3.88
11	0.61	19.65	1.35	11	0.53	3.42	6.38
12	14.81	22.50	2.13	12	3.41	1.84	7.23
13	0.51	15.29	5.32	13	3.22	2.20	8.74
14	7.64	2.54	6.51	14	3.81	1.85	9.62
15	21.70	16.17	9.55	15	1.08	0.31	3.88
16	22.23	22.36	8.43	16	0.12	4.02	9.48
17	4.84	4.16	6.61	17	1.44	3.69	2.94
18	0.72	6.06	4.72	18	4.12	3.29	9.98
19	7.70	11.36	6.65	19	2.20	3.35	2.89
20	20.49	29.03	9.34	20	2.06	2.07	3.80
21	10.85	28.70	2.20	21	4.78	1.55	7.08
22	19.18	22.21	3.50	22	3.54	4.53	1.20
23	26.61	2.01	0.53	23	4.66	3.54	8.71
24	26.25	10.46	7.01	24	1.65	0.50	4.40
25	21.61	1.90	5.12	25	2.79	1.18	9.92
26	4.01	17.81	4.42	26	4.14	1.50	2.86
27	2.82	3.97	1.55	27	0.74	0.70	8.53
28	14.74	18.22	9.39	28	4.09	1.69	8.40
29	1.87	26.47	9.56	29	2.39	2.34	2.76
30	29.94	2.46	1.49	30	3.99	2.85	0.91
31	9.04	23.56	9.08	31	2.09	4.16	0.71
32	0.92	18.93	3.80	32	3.27	4.07	6.10
33	9.86	3.09	2.74	33	3.84	2.87	8.24
34	27.27	1.72	8.05	34	2.76	4.08	7.33
35	6.18	17.95	9.95	35	3.83	0.84	2.57
36	7.69	10.18	4.33	36	2.30	4.52	2.37
37	4.12	28.88	7.79	37	0.96	1.45	3.03
38	13.27	21.92	3.77	38	4.25	4.39	4.37
39	25.23	8.98	0.78	39	3.94	1.86	2.96
40	27.98	17.24	4.88	40	0.07	4.05	2.67
41	23.44	25.36	5.68	41	2.91	4.98	6.00
42	2.05	3.30	6.41	42	3.81	0.50	8.97
43	18.05	10.73	6.40	43	3.95	1.30	1.50
44	22.10	16.37	8.70	44	3.61	1.10	0.17
45	6.49	21.78	3.89	45	2.56	0.23	7.32
46	10.68	20.15	2.26	46	4.61	0.21	6.76
47	4.37	1.67	8.08	47	0.08	1.91	9.61
48	4.81	23.52	2.25	48	3.53	0.73	4.56
49	10.57	15.70	1.76	49	2.98	1.43	2.78
50	7.80	10.52	7.25	50	0.42	2.81	2.24
Mean	12.70	14.73	5.08	**Mean**	2.53	2.40	5.32
Std Dev	9.09	8.85	2.88	**Std Dev**	1.43	1.46	3.06
CEP/LEP	10.56		1.94	**CEP/LEP**	1.70		2.06

1. Pseudo Data

Table B-4

Flight Test Head-Up Display Target Location Error

HUD – Designation/ARBS Altitude Calculation				HUD – Designation/AGR Altitude Calculation			
Sample	σ_x	σ_y	σ_z	Sample	σ_x	σ_y	σ_z
1	0.86	7.55	10.43	1	11.75	12.63	4.83
2	2.26	1.31	5.27	2	5.63	9.94	4.96
3	14.90	10.19	9.09	3	9.05	14.75	6.83
4	1.52	9.11	0.66	4	12.33	9.06	3.12
5	2.67	11.15	4.03	5	1.48	12.43	5.62
6	8.06	0.63	14.03	6	11.80	6.22	1.13
7	8.43	9.20	10.74	7	3.48	6.35	0.60
8	3.29	8.32	16.05	8	8.98	12.49	4.48
9	0.97	4.10	13.01	9	6.58	7.80	3.58
10	14.13	13.24	17.30	10	8.44	12.93	6.03
11	4.57	5.33	1.85	11	3.86	12.12	1.49
12	11.93	10.82	13.88	12	5.30	11.27	2.62
13	4.34	10.77	12.46	13	8.52	5.22	1.34
14	13.60	4.05	1.80	14	6.58	10.18	9.60
15	2.50	12.26	7.06	15	0.43	3.99	7.78
16	2.17	5.88	13.06	16	12.90	6.62	0.96
17	6.60	13.14	9.27	17	10.01	1.10	2.65
18	10.03	2.84	15.98	18	7.99	8.70	3.48
19	7.18	8.14	19.84	19	11.15	3.20	6.71
20	6.55	8.76	14.61	20	12.82	4.97	9.49
21	8.83	2.36	8.58	21	0.64	9.23	8.79
22	14.07	4.81	11.86	22	1.20	11.69	0.23
23	0.04	8.48	0.95	23	2.15	12.31	1.02
24	6.10	3.63	3.55	24	13.14	9.26	1.05
25	1.56	13.16	18.62	25	8.23	6.27	0.11
26	2.34	0.71	10.76	26	11.18	5.41	4.40
27	11.71	2.60	10.02	27	9.74	5.58	2.96
28	7.56	2.81	5.13	28	3.56	12.61	7.24
29	6.08	1.25	2.40	29	0.99	11.20	2.90
30	9.92	8.37	10.34	30	9.93	11.70	8.11
31	9.96	9.89	3.72	31	1.39	5.64	8.10
32	13.11	7.10	8.80	32	1.12	4.56	4.76
33	4.76	11.90	17.40	33	12.31	8.76	8.70
34	3.97	2.11	18.23	34	3.38	11.52	8.41
35	1.87	3.94	5.98	35	3.05	2.73	9.55
36	13.49	6.60	18.57	36	14.36	11.50	3.35
37	7.41	0.22	13.29	37	10.86	14.03	9.37
38	13.43	11.87	17.43	38	10.34	12.38	4.43
39	14.24	7.67	11.22	39	2.57	5.81	5.85
40	14.36	7.70	9.04	40	7.03	5.87	4.89
41	13.01	3.32	10.46	41	13.47	0.23	4.99
42	9.69	7.37	17.35	42	6.86	0.81	8.94
43	1.10	8.25	9.33	43	12.11	0.18	4.21
44	4.58	10.82	15.09	44	9.91	1.98	4.64
45	7.34	8.41	4.07	45	12.67	8.98	8.61
46	5.27	0.00	5.15	46	6.69	7.42	9.24
47	1.97	5.31	1.32	47	6.92	9.71	2.88
48	3.69	11.60	4.31	48	7.94	9.04	7.45
49	1.92	8.39	6.37	49	8.33	14.87	5.97
50	5.94	9.75	3.22	50	7.59	3.08	9.29
Mean	6.92	6.94	9.86	Mean	7.57	8.13	5.15
Std Dev	4.57	3.85	5.53	Std Dev	4.09	4.03	2.94
CEP/LEP	4.96		3.73	CEP/LEP	4.78		1.98

1. Pseudo Data

VITA

James Frederick Kromberg graduated from the Ohio State University in March of 1987 with a Bachelor of Science Degree in Aeronautical Engineering and was commissioned a Second Lieutenant of Marines. Jim's first assignment was to attend the 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. Jim was designated a Naval Aviator in February of 1990 and directed to VMAT-203, MCAS Cherry Point for AV-8B training. Since that initial Harrier training, he has served in 3 fleet AV-8B Squadrons, VMA-211 and VMA-513 at MCAS Yuma, Arizona and VMA-223, MCAS Cherry Pt., North Carolina. During his fleet tours, Jim has made overseas deployments to WestPac to include Iwakuni, Japan, Osan, Korea, the Philippines and aboard the LPH USS Belleau Wood with the 31st Marine Expeditionary Unit. In January of 1996 he was selected for test pilot training at the Air Force Test Pilot School, Edwards AFB, California. Jim attended Test Pilot School from July 1996 to June 1997 where he flew over 30 aircraft from the United States and other countries. Aircraft types were as simple as unpowered gliders to the USAF B-1 bomber. Following Test Pilot School, Jim was directed to his current position at the Operational Test Squadron, VX-9. Jim is married to the former Valerie Ann Wilkerson of Indianapolis, Indiana.