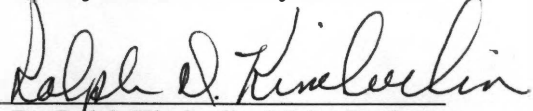
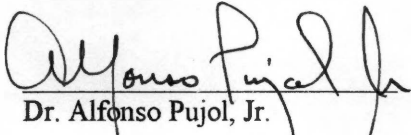


To the Graduate Council:

I am submitting herewith a thesis written by James A. Winship entitled "Target Location Using Azimuth Only Techniques." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

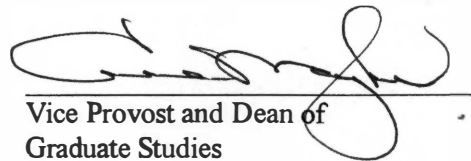

Dr. Ralph Kimberlin, Major Professor

We have read this thesis and
Recommend its acceptance:


Dr. Alfonso Pujol, Jr.


Mr. Richard Ranaudo

Acceptance for the Council:


Vice Provost and Dean of
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Thesis
2003
.W56

TARGET LOCATION USING AZIMUTH ONLY TECHNIQUES

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

James A Winship
May 2003

DEDICATION

This thesis is dedicated to:

Susan

John and Judy

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I wish to thank all those who helped me in completing this course of study. Dr. Bob Richards and the staff at UTSI Patuxent River deserve special thanks for their support of this program that has allowed many active duty personnel to receive their advanced degrees. I have always enjoyed working with the UTSI staff. All of these people have always been helpful, cheerful and competent. Thank you. I thank my Mom and Dad who gave me the background to continue, although difficulties arise. Finally, I thank my wife without whose encouragement and support this would have never been completed.

ABSTRACT

Procedures for determining the target location capability using azimuth only techniques are presented. These procedures were developed specifically to determine the target location capability of the EA-6B using its azimuth only receiver system. The target location capability of the aircraft system was compared to the requirements of the High Speed Anti-radiation Missile (HARM). The weapon system was studied to determine the sources for error and the precise method used to locate. Due to the man-in-the-loop system and needing a statement of target location capability relevant to the HARM, a simulation was developed with the relevant features and limitations of the aircraft system and HARM. Data were collected from two operators locating targets over various ranges using the accuracy for each of the aircraft's receivers and HARM accuracy requirements. The results of the simulation were used to determine if target location was possible and under what conditions. Rules of thumb were developed that could be used to verify the simulation using flight testing and then in actual conditions. Due to classification limitations, the weapon system accuracy for the EA-6B receiver system and the accuracy requirement for the HARM have been changed to demonstrate the procedures and techniques used and not the actual data generated had these classified capabilities been used.

PREFACE

This project started out with a simple question, “What is the EA-6B’s capability with regard to employing the HARM reactively?” This question was posed to our Squadron during our 1999 Operation Northern Watch (ONW) deployment. Although the EA-6B routinely employs HARM, it is targeted using known threat locations or along the line of bearing of the threat radar. No knowledge within the Squadron existed regarding how to employ it by using the EA-6B to locate the threat first. Research revealed that this knowledge did not exist in the community either.

The EA-6B is primarily a radar jamming aircraft and has a receiver system designed to support that mission. The HARM was developed and employed significantly later than the EA-6B. Surprisingly, little was known within the EA-6B community regarding the capability of the EA-6B to locate a radar and then shoot HARM at it. This gap in knowledge was caused partially by the difference in time between the introduction of the EA-6B and HARM, but was also caused by several other factors. The receiver system was designed to support the jamming system, to make sure that the transmitters were steered in the right direction, no geographic location required! A great degree of accuracy was not required to accomplish this task. Additionally, the HARM was introduced into a community that considered jamming the primary mission and HARM employment a secondary mission. Geographic target location was difficult, required airborne time to accomplish and was counter to the primary mission. Yet, we were being asked to investigate this exact area.

Any system that shows the direction of a received signal has a basic capability to locate that signal via a process called triangulation. Triangulation requires that the received signal’s direction is plotted from the aircraft location at the time of reception on something that shows the location of

the aircraft in a geographic format. A paper map works fine as well as scaled electronic displays. As the aircraft flies along, lines of bearing (LOB) of the received signal are drawn from the aircraft position. The emitter is located where these LOB cross. A certain amount of location uncertainty is associated with performing this operation, a central area of exploration in this project. Receiver direction of arrival (DOA) accuracy is a key factor in determining the location uncertainty of the target. The original performance specification for the EA-6B receiver system was available, so “closed form” mathematical solutions were considered. Closed form solutions were not appropriate in this case, because they didn’t model the system. The EA-6B location system involved multiple steps and a “man in the loop” making mathematical solutions inappropriate. The approach taken was to develop a simulation of the system, which would allow data to be generated for analysis. The purpose of the simulation was two fold, given the limitations of the location system, was it possible to locate the target to such accuracy as HARM could be employed and, if target location was possible, could a “rule of thumb” be developed allowing a simple target location tactic to be developed which could be employed in flight?

The simulation was developed, statistically significant number of simulations were run for each of the receiver frequency ranges (each having different DOA accuracy) resulting in a rule of thumb that made employing the target location tactic easy. This rule of thumb was verified by flight testing using it to locate radars and execute simulated HARM shots on these located threats. Post flight analysis of this test flight showed that the rule of thumb was valid. This tactic, as well as all the wealth of information about how to employ the aircraft that was discovered in the process was developed into a Squadron tactic and was used on our 2000 ONW deployment.

A thesis detailing the original project summarized above could not be written due the classification of specific details of the project. This thesis rigorously details how the problem was

solved using unclassified data. It will detail how problems of this type, using airborne systems that are capable of only manual triangulation to locate a target within specific accuracy requirements, can be solved using contrived parameters, to avoid classification issues. Additionally, verification of the rule of thumb determined in this thesis is not possible, as it was in the original effort, because the system modeled does not represent a specific system, resulting in a rule of thumb that cannot be flight tested. Additionally, funding and assets for flight testing were not available. Procedures to verify the rule of thumb will be discussed.

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Plate 1. Simulation Program In Pocket

LIST OF SYMBOLS AND ABBREVIATIONS

σ	standard deviation
α	aircraft to pseudo target angle
β	aircraft to true target angle
ADF	automatic direction finder
DOA	direction of arrival
HARM	high speed anti-radiation missile
LOB	line(s) of bearing
nmi	nautical miles
ONW	Operation Northern Watch
R	aircraft to pseudo target range
r	aircraft to true target range

Chapter 1

BACKGROUND

TRIANGULATION PROCEDURE

Triangulation is a procedure used to determine the location of an emitter by drawing LOB from an aircraft using the DOA of the signal as detected by a system on the aircraft. Many aircraft systems in use today, have systems that display the DOA of a received signal. An automatic direction finder (ADF) is one such system, common to many aircraft. Many military aircraft have some portion of the weapon system that indicates the direction of a received signal. Radar warning receivers are one example as well as dedicated electronic intelligence collection systems. If the actual location of that signal is important, most newer weapon systems have the technology in place to display not only the direction that the signal is coming from but also the location. Older generation aircraft often do not incorporate the technology required to automatically display the location of the signal. Although the LOB of the received signal, may be an enemy radar signal or communication signal, is used to make tactical decisions, it is not commonly used to attempt to locate the transmitter geographically. Even when using a system with special capability that can be used to locate the transmitter geographically via manual triangulation, very few of the operators understand the limitation of the location they determined manually with regard to the accuracy of that plotted location. An inherent capability of any system that will display the bearing of a received signal is the ability to locate that signal to some degree of accuracy.

Triangulation is the plotting of the direction of arrival of a series of received signals as the aircraft moves along. Figure 1 shows this in simplified form. All figures and tables are located in the Appendix. At position A, the system on the aircraft displays the direction of arrival of a signal from the transmitter. The pilot plots this in some manner so that the location of the aircraft when the signal was detected is shown to scale, normally a map or one of the aircraft's scaled displays is used for this. A little later, after the aircraft has moved to position B, the signal is again detected and the direction of arrival of the signal is again plotted. At this point, where the two lines of bearing cross, position 1, would be a best guess of the location from which the signal is coming. A better guess at where the transmitter could really be located would be found after a third line of bearing is plotted at some later time. This is shown as the line of bearing plotted from aircraft position C. This results in a common situation. The three lines of bearing do not cross at a single point, but instead, enclose a triangle which, with no better information, the pilot should assume the transmitter is contained within, therefore making our best guess move to position 2. In this example the actual location of the transmitter could be as shown by the solid black triangle at position 3. The reason why the best guess location is at 2 while the actual location is at position 3 will be discussed in the following paragraphs. But, in short, it is due to inaccuracies in the method. Using triangulation any system that can display the DOA of a signal can be used to locate, to a certain degree of accuracy, that signal. This is a very basic capability in most aircraft that although used upon occasion (the specific limitations of it; how close to the real target is your best guess using this method) is commonly not fully understood.

ANALYSIS OF ERROR IN TRIANGULATION

It is of critical importance when locating a transmitter using manual triangulation that the limitations of the method are understood. This is because, unlike an automatic system that can show a location area of uncertainty, the operator conducting the triangulation must understand all the location inaccuracies. The first series of inaccuracies creep into the line of bearing due to uncertainty as to the actual location of the origin of the line of bearing. The inaccuracies can be thought of as a circle around the origin of the LOB. The origin of the actual LOB, the theoretical one that could be plotted with no error, would lie somewhere within this circle. This uncertainty is caused by not knowing exactly where the aircraft is at the time of receipt of the signal, called navigation error. There is always some time delay in the time from which the signal was received to when the aircraft's position is fixed upon the media being used to plot aircraft location causing another error. The transcription of the aircraft position to the media being used for plotting the line of bearing causes errors. Estimates for the magnitude of each of these errors must be made for the system being analyzed. Further errors occur when determining and plotting the angle of the line of bearing. The largest error will most likely be the accuracy with which the aircraft system can determine the direction of the received signal. The accuracy with which the operator can read the display should be considered and finally, the accuracy the operator can draw the angle of the line of bearing on the media must be considered. All of these errors combine to make the situation shown in Figure 2. The uncertainty of the origin of the line of bearing is shown as a circle. For the figure to be completely accurate, if all of the probable LOB where to be shown, LOB should be shown from each point on this circle of uncertainty. The errors that occur drawing the angle of the LOB are shown by adding and subtracting these errors from the actual angle plotted. For a single LOB the uncertainty is shown as a triangle which would contain the actual line of bearing if all

uncertainties where considered. The effect on the location of the target versus the true location of the target can be seen when looking at all three LOB including their respective uncertainties. If all the errors where considered in the analysis and plotted, then the true target location must be within the geographic area which is mutual to all three lines of bearing plus uncertainties. This area is highlighted in a heavy dark line. It is now easy to see how the true target location could actually be where the black triangle is, location 3, versus either position 1 or 2. One final element must be pointed out when triangulation errors are being analyzed. That is the statistics involved.

Consistency in the statistics used must be maintained throughout the analysis for the final area of uncertainty of the actual target to be valid. In other words if the target area of uncertainty is desired to be known to a 90% confidence, then all the errors leading up to the final result should be estimated using a 90% confidence. In our example, the navigation accuracy of the aircraft should be determined to 90% confidence as well as the accuracy that the origin of the line of bearing could be plotted as well as the direction of arrival of the signal, all of these should be determined to a confidence of 90% for the final area of uncertainty to contain the actual transmitter to an accuracy of 90%.

TARGETING ACCURACY REQUIREMENTS

We have discussed in the previous paragraphs the relevant issues for determining the accuracy with which the receiver system can locate a target, but one of the key issues for this project is exactly what is the accuracy with which the target must be located. Depending upon what the target being located is, the accuracy required could change dramatically. An analysis of the required accuracy for each application is required. For example, if a survival beacon was being located, and the requirement was to bring the airborne platform within visual site of the victim, then

the analysis may result in a requirement that the beacon should be located to within one-mile in open terrain, one-half mile in partially wooded terrain and one-quarter mile in heavily wooded terrain. If the requirement was to locate the target such that with 50% probability the location could be passed off to a visual sensor, maybe a FLIR, so that the target was within the field of view, then the analysis would be heavily dependent upon the specifications of the sensor itself. Although the analysis of the target location accuracy requirements is simpler than the error analysis of the aircraft weapon system, it must be understood to successfully determine if, and under what conditions, the aircraft is able to locate within this accuracy requirement.

Chapter 2

RELATED SYSTEMS

THE AIRCRAFT SYSTEM

The EA-6B weapon system is designed to perform the mission of electronic attack. This means that the primary component of the system being supported is the high power radar jamming transmitters carried on the wing stations. The transmitters must be steered along the LOB of the victim receiver to be effective. The job of the EA-6Bs receiver system is to provide the information to the crew to ensure that this occurs. Because the receiver system was designed to support the transmitter, which has a fairly broad transmitted energy beam width, direction of arrival precision was not a primary design criteria. When a signal was received, it was displayed on a frequency versus azimuth (FREQ-AZ) display. This display showed the operator the azimuth horizontally across the top of the display and frequency vertically down the left side of the display from high frequency (top) to low frequency (bottom). Figure 3 shows the basic layout of the EA-6B displays. On the geographic display, called GEO, the operator was presented with the current tactical situation presented in an overhead geographic view. The aircraft's location relative to friendly units, enemy threats and country boundaries and land/water borders could be displayed. The GEO display also allowed the operator to draw LOB (called strobes) from the aircraft's position. Up to six strobes could be drawn with the ability to position an icon where the operator believed the target to be located. Figure 3 shows the basic features of the EA-6B display. The procedure used to locate a transmitter via triangulation was the following:

1. Observe the emitter on the FREQ-AZ display indicated by a symbol along the intersection of a specific frequency and azimuth. Use the cursor to pick off the azimuth of the received signal.
2. Switch to the GEO display and draw a strobe using the azimuth picked off of the FREQ-AZ display. In order to get the system to draw a strobe from the aircraft's position the operator entered X bbb, where X indicated the strobe number and bbb indicated the strobe angle. With this entry, the system would draw a strobe from the aircraft's location, bearing bbb.
3. Switch to the FREQ-AZ display and observe the received signal for a bearing shift. When, in the operator's opinion, a significant bearing shift occurred another azimuth could be picked off for the signal.
4. Switch to GEO and draw a second strobe. An icon could be moved to the intersection of the two strobes depicting where the operator thought the target was located.
5. The procedure of moving back and forth between FREQ-AZ and GEO could be repeated drawing up to six strobes and repositioning the icon to update the target's location.

SOURCES OF ERROR IN THE AIRCRAFT SYSTEM

Determining the accuracy with which a target can be located requires a detailed analysis of how the information is presented to the operator of the weapon system and the accuracy with which it is presented in each step. For the EA-6B, a symbol is presented in the FREQ-AZ display showing the radar's bearing and frequency. The accuracy with which the bearing is displayed was determined by specification and varies by the frequency being detected. To avoid classification, we will use three contrived accuracies for these values of 20 degrees, 12 degrees and 5 degrees for one

standard deviation. The bearing of the symbol is shown to the nearest degree on the FREQ-AZ display with a digital readout that is available. As the system displays the emitters, multiple emitters commonly appear due to bearing shift making the operator estimate the current bearing of the emitter. The operator's cursor displays bearing to 1 degree of bearing. Assuming he could position the cursor incorrectly by one degree and the cursor itself is only showing to the nearest degree, then the operator's estimate of the bearing to the emitter could be ± 1 degree of the actual displayed emitter bearing. Once the operator determines the bearing he must switch displays to the GEO display and type in 5 characters on the edit line (X bbb) and press the strobe button to display the strobe (X) at the desired bearing (bbb). This operation requires approximately 5 seconds to accomplish. At an average speed of 420 KGS this time delay would cause a 0.5 mile error in the direction that the aircraft is heading in the origin of the strobe. The strobe origin is taken directly from the current position of the aircraft, so no additional error is introduced at this step. The strobe bearing is digitally entered based upon the value determined from FREQ-AZ therefore there is no additional error introduced. Finally, when the strobes intersect showing the possible location of the emitter, a symbol is placed. The symbol's coordinates are used to target HARM. The symbol can be placed to an accuracy of one-tenth of a mile in both latitude and longitude (about one-tenth of a degree in latitude). The position of the target is handed off digitally to HARM resulting in no additional errors.

HARM

The requirement for location accuracy came directly from the HARM weapon itself. The accuracy required for the HARM was specified as a specific number of degrees in azimuth and a specific percent of range from the aircraft to the target. We will use contrived accuracy values for

the HARM of $\pm 20\%$ in range and $\pm 20^\circ$ in angle. Figure 4 shows this graphically. This type of specification results in a required location area that appears to be a truncated pie. The actual target position must be within the truncated pie shape area centered on the location that is being targeted for HARM to hit the actual target. In this figure, the actual target is within the range (R) and bearing (α) requirements.

Chapter 3

OPTIONS FOR ANALYSIS

Several options existed that could have been used to analyze the accuracy of this system. The first considered was solving the geolocation accuracy of the receiver system using a mathematical approach resulting in a “closed form” solution. After some effort in this area, it was realized that although possible, this approach was not the correct one to take. The primary reason that this was not the best approach to solve the problem was the operator in the loop. Performing a mathematical analysis of the effect of the operator in the loop would have been very difficult and would have most likely have resulted in an answer that did not really fully address the accuracy question as it would have provided a single answer when in fact a range of accuracy was most likely caused by various operators. After consideration of the operator in the loop, a simulation was considered. The simulation was conceived as having several key features. The basic features of the simulation would be a **FREQ-AZ** and **GEO** display similar to that presented in the aircraft. The **FREQ-AZ** display would show the operator a symbol representing a signal with the same statistical accuracy as the aircraft. The operator would select the **DOA** that he wished to use and would have a **GEO** display upon which Strokes could be drawn. Up to six strokes could be used. When the operator believed the target had been located, a symbol would be placed by the operator where the target was believed to be. Once the target had been placed the simulation would evaluate if the target was located accurately enough for **HARM** to hit it. If it had been placed within the accuracy requirements of **HARM**, the simulation would stop and specific data would be captured for later analysis. Although the simulation would not produce a specific result as to the geolocation

accuracy of the weapon system, a great advantage of this approach would be the result of the simulation would produce the inter-relationship between the geolocation accuracy of the receiver system with the geolocation accuracy requirements of the HARM, with the operator in the loop.

Chapter 4

SIMULATON REQUIREMENTS

DATA APPROACH

The requirements for the simulation are summarized in Table 2. The simulation was designed to generate data that could be used to determine the required distance flown to target HARM given the accuracy of each receiver and the target location accuracy required by HARM. The data needed to start the simulation was the statistical accuracy of the receiver system and the accuracy requirements of HARM. The original project allowed five different accuracy values to be entered corresponding to the five different receivers in the aircraft. As discussed above we used a representative set of three, representing receivers of high, medium and low accuracy. Values of 5, 12 and 20 degrees one standard deviation were used. The second set of input data is the geolocation accuracy of the targeting system, in this case HARM. We specified that the targeting system require an accuracy of 20° in azimuth and 20% of the aircraft to target range value in range. Given these values, the simulation would run until the target had been located within the required accuracy values of HARM. Once the target had been located, the simulation would stop and capture the data required to perform analysis at a later time. At the time of the simulation design, the specific data needed for analysis was not known. This resulted in some extra data being collected that was not used. The data captured at the end of each run to support the analysis were; aircraft final position, true target location, pseudo target location, HARM location accuracy required in angle and range,

actual range and angle difference of true target to pseudo target, aircraft total angle traversed the band for the run and the operator's name. How this data were used for analysis is discussed below.

USER INTERFACE

The user interface was designed to simulate the aircraft interface as closely as possible. The basic simulation layout is shown in Figure 5. In the lower portion of the display, the **FREQ-AZ** information is provided. The band of the signal being simulated is shown on the left hand side and the bearing of the received signal is shown across the top of the display. The current DOA of the signal is shown highlighted and the 10 previous DOAs are shown subdued. The signal is shown as coming from approximately 090° at the start of this simulation. The upper part of the display simulates the **GEO** display in the aircraft. This display is an overhead situational awareness display. Various objects are shown on the display to give a sense of scale. Figure 6 shows how the simulation would appear a few minutes later. The aircraft has progressed down its track, heading 090°, and the operator has drawn the first strobe. The **FREQ-AZ** display is showing the received DOA as coming from approximately 060°. Figure 7, shows the appearance of the simulation a couple of minutes later. The aircraft has again proceeded down track some more causing the signal to shift to a 030° relative bearing. The operator has drawn a second strobe along that line of bearing. In Figure 8 the operator has placed a target at the location of the strobe's intersection, currently the best guess for the target's location. Figure 9 shows the display after a couple of minutes have passed allowing the operator to place a third strobe. In Figure 10 the target is again updated. This time the target is placed within the accuracy requirements for the **HARM** and the simulation stops. This would complete one simulation run.

SIMULATION CALCULATIONS

At the start of each simulation run several parameters were initialized. The aircraft was positioned at the origin heading East. Various objects were positioned on the GEO display to give some sense of scale and a new true target position was calculated. A new band was selected at the start of each run, cycling sequentially through the 5 DOA accuracy values entered in the initialization screen between runs. As the simulation progressed the emitter was shown to the operator just as the aircraft would with a standard deviation of the band being simulated centered on the actual true target location. The aircraft proceeded East at about twice the normal tactical airspeed of 420 KGS to increase data collection efficiency causing the relative position of the true target to change. The operator could draw up to 6 strobes and position an icon at the location of his current best guess as to target location. This icon was used as the pseudo target location for comparison to the true target location. When the operator positioned the pseudo target within the range and bearing accuracy values entered in the initialization screen, the simulation stopped showed the true target location and wrote relevant data to file. The operator then proceeded to the next run. The following paragraphs explain the calculations performed during the simulation.

SCREEN SCALING

The accurate scaling of the display was of particular concern during simulation development. The FREQ-AZ display would have to show the operator the received DOA of the signal accurately so that the angle of the strobe would be accurate drawn on the GEO display. The accuracy of the strobes was critical to the positioning of the icon representing the pseudo target from which the most important calculations of the simulation were derived. In order to accomplish this, the GEO was divided into an 300 by 300 pixel matrix, representing an 80 by 80 mile

geographic situation. All the graphical elements displayed; ownship, strobes and pseudo target, were shown using this matrix. Accuracy in calculation and realism in aircraft positioning was attained by scaling. The FREQ-AZ displayed converted the 180 degrees of bearing shown into 360 pixels, allowing accurate display of DOA to the operator.

TRUE TARGET LOCATION

At the start of each simulation run, the location of the target had to be generated. This target, the true target location, was calculated but not shown to the operator. The target position was randomized so that each run was different. The target location was bound in both angle and range to provide realistic values. The target was located between 030° and 060° relative to the aircraft position at ranges from 11 nmi to 120 nmi. The true target's location angle was calculated as:

$$B = 30^\circ \leq \text{random number} \leq 60^\circ$$

where;

$$\beta = \text{true target angle}$$

The true target's location was calculated as:

$$\text{Target Y location} = 10 \leq Y \leq 60$$

$$\text{Target X location} = \frac{Y}{\tan(\beta)}$$

Once the true targets location was calculated, the DOA relative to the aircraft position could be calculated centered on this position. The Box-Muller transformation was used to calculate a DOA, randomized around the true target DOA with a standard deviation provided from the initialization screen. The true DOA to the target was calculated as:

$$\text{True DOA} = \text{ARCCOS} \left(\frac{(\text{true}X - \text{aircraft}X)}{\sqrt{(\text{true}X - \text{aircraft}X)^2 + (\text{true}Y)^2}} \right)$$

where;

trueX = true target X location

trueY = true target Y location

aircraftX = aircraft's X location

The received DOA was calculated as:

$$\text{Received DOA} = \sigma \sqrt{-2 \ln(\text{rnd}\#)} \cos(2 \Pi (\text{rnd}\#)) + \text{true DOA} \quad (\text{USNTPS,1994})$$

Where:

σ = standard deviation entered from initialization screen

rnd# = random number between 0 and 1

true DOA = the actual DOA calculated from true target to aircraft location

PSEUDO TARGET AND ACTUAL TARGET CALCULATIONS

Once the operator had placed the pseudo target on the geo display, calculations were made to determine the position of that target relative to the true target location. The first calculation that was made was to determine if it was within the angle requirement of HARM. Figure 11 shows the geometry of the angle calculation. Figure 12 shows the geometry of the range calculation. The angle calculation was:

$$\alpha = \text{ARCTAN} \left(\frac{\text{pseudo}Y}{\text{pseudo}X - \text{aircraft}X} \right)$$

$$\beta = \text{ARCTAN} \left(\frac{\text{true}Y}{\text{true}X - \text{aircraft}X} \right)$$

$$\text{Pseudo/Actual Target Angle difference} = |\alpha - \beta|$$

Where

$pseudoY$ = pseudo target Y location

$pseudoX$ = pseudo target X location

$aircraftX$ = aircraft X location

α = aircraft to pseudo target angle

β = aircraft to true target angle

The range calculation was:

$$r = \sqrt{(trueY - aircraftY)^2 + (trueX - aircraftX)^2}$$

$$R = \sqrt{(pseudoY - aircraftY)^2 + (pseudoX - aircraftX)^2}$$

$$\text{Pseudo/Actual Target Range difference} = \frac{|R - r|}{R}$$

Where:

$trueY$ = true target Y position

$aircraftY$ = aircraft Y position

$trueX$ = true target X position

$aircraftX$ = aircraft X position

$pseudoY$ = pseudo target Y position

$pseudoX$ = pseudo target X position

R = aircraft to pseudo target range

r = aircraft to true target range

From the range and bearing calculations to the pseudo and true targets, comparisons were made to the required accuracy values entered by the operator in the initialization screen. If both the angle and range differences were less than the accuracy values entered by the operator, the simulation run was stopped. At the end of each run the true target location was displayed to the operator and all output values were written to file for later analysis. The values collected for each run were: aircraft x and y location at completion of run, true target x and y location, pseudo target x and y location, parameters entered for HARM required accuracy in range and azimuth, the calculated angle and range difference between the true and pseudo targets, the band and the operator's name.

Chapter 5

SIMULATION DESCRIPTION

My wife, and professional software engineer, turned the requirements into a simulation.

Her description of the program follows:

The harm target location simulation application was written in Object Pascal using the Borland Delphi 5 development environment. The program contains four forms and five Pascal code modules. The forms were designed using Delphi components and include the Input form, the Geographic Display form, the Frequency-Azimuth Display form, and the Simulation Control form with each form having an associated Pascal code module. The main portion of the code is contained within the Simulation Control module with an additional module for calculations. A timer that increments the aircraft position on the Geographic Display and a timer that updates the emitter symbols on the Frequency-Azimuth Display drive the simulation.

The program is very compact requiring only one executable file which runs on Windows 95/98 operating system named "HarmTest.exe". The program is included as plate 1. It creates an output file named "HarmOut.csv" in which the data was collected for later analysis. To start the program, double-click on "HarmTest.exe". The initialization screen, the first screen to be displayed, is shown in Figure 13. The operator enters his name, the DOA accuracy in standard deviation for up to five bands and the targetting accuracy requirements in angle and range. All angles are entered in degrees and delta range is entered as a fraction. In other words, the 0.2 entered is the same as an accuracy requirement of $\pm 20\%$. After the initialization screen is completed, pressing the "start simulation" button starts the simulation. Figure 14 shows the simulation at the completion of a run. The operator enters a strobe number (1 to 6) and a strobe bearing based upon

the emitter DOA shown in the FreqAzForm. This strobe is displayed on the GEOform. After every strobe an estimate of the target's location can be made by placing the cursor over the desired location and left clicking. The simulation calculates if the operator's estimate is within the accuracy requirements from the actual target, which is not displayed. If the accuracy requirements are not met, the simulation continues until the target is located. If the operator's estimate at the target location meets the accuracy requirements, the simulation is stopped and the program shows the actual target location. To begin a new simulation run the "New Run" button is pressed. The simulation increments to the next band and begins a new run. Data was sent to the file indicated by the "Simulation Output" portion of the screen.

Chapter 6

DATA ANALYSIS

Two operators with a minimum of 16 simulations per band generated data. Band 4, 6 and 7 were used using 20, 12 and 5 degrees of standard deviation respectively for the receiver accuracy. The location accuracy used was 20 degrees in azimuth and ± 0.2 in range. Once the data runs had been accomplished, the data from operator 1 and 2 were combined. The data were examined for trends resulting in grouping, or binning, the data by band and then into three categories. The three categories chosen were based upon the initial range to the target of less than 40 nmi, between 40 and 60 nmi and greater than 60 nmi. This division was necessary because in addition to different distances traveled in different bands, the data indicated that greater ranges were necessary to locate targets that were further away. The data were grouped into these particular bands because the bins were small enough not to have too great a variation in range required to locate in each band, but large enough to contain a statistically significant number of data points. All the data collected are shown in Table 3 This table lists the following parameters:

1. Aircraft X – the aircraft location at the end of the run. Because the aircraft started at 0, and the data were based upon a nautical mile scale, the final position is the same as the distance required to locate the target on each run.
2. Aircraft Y – extraneous parameter because the aircraft held a constant value of 0 during the simulation.
3. True Target X – the X coordinate of the actual target location
4. True Target Y – the Y coordinate of the actual target location

5. Pseudo Target X – the X coordinate of the target positioned by the operator. The position recorded is the final position, the one that matched the target location accuracy requirements.
6. Pseudo Target Y – the Y coordinate of the target positioned by the operator. Corresponds to the X position in 5 above.
7. Harm Delta Angle – the target location accuracy requirement in angle.
8. Harm Delta Range – the target location accuracy requirement in range.
9. Delta Angle – the measured difference in angle between the pseudo target and the true target location.
10. Delta Range – the measured difference in range between the pseudo target and the true target location.
11. Total Angle – the angle of the target relative to the aircraft position when the simulation run was finished.
12. Band – the band being simulated. Corresponds to the band standard deviation entered in the initialization window.
13. ECMO – Electronic Counter Measures Officer (ECMO). Technical term for an operator in the EA-6B.

Figure 15 thru Figure 17 show the simulation data by band for both operators. These graphs show the aircraft distance traveled to locate the target versus the initial distance to the target. From these figures some general data trends can be noted. Generally, with longer initial range to the target, the aircraft will travel longer distances to locate the target. By comparing these three graphs it can be seen that band 4, the least accurate DOA, requires the aircraft to travel the longest distances to locate the target, band 7 the shortest distance and band 6 requires a distance somewhere

in between. Finally, it can be seen that generally the data collected from operator 1 and operator 2 is consistent, showing no significant performance difference between these two operators, which allows combining the operator data in the next analysis steps. Table 4 thru Table 12 show the data after it has been categorized or binned by initial distance to target and band groups. The binned data were used to plot the distance required to locate the target for each run versus the initial range to target in Figure 18 to Figure 26. The graphs, in general, do show a trend that targets that were at greater distances initially, required the aircraft to travel greater distances to locate, as expected, but binning breaks this trend up into smaller data groups allowing the calculation of mean and standard deviation for each of these groups.

Chapter 7

RESULTS

After the data were grouped, the mean and standard deviations were calculated. Data are shown in Table 13. The distance required to locate the target in each group was calculated by adding the standard deviation of each group of data to the mean. This calculation shows if this distance were traveled the target would have been located for 68% of the simulation runs. These data are graphed in Figure 27. Figure 27 makes the trends in the data very clear. As expected, receivers with less accuracy require greater distances to locate a target. Also, targets that are located at greater distances from the aircraft require the aircraft to travel greater distances to locate them. The graph also shows that for receivers of less accuracy, the distance the aircraft is required to travel increases by greater amounts as the range to the target increases. Most importantly, this analysis allows not only trends to be established, but the actual distance the aircraft must travel to locate a target in each band based upon the range to the target is presented. This analysis allows the formation of rules of thumb that can be used to verify the simulation and then use in real world situations. The rules of thumb, rounded up to the next whole number, supported by this analysis are shown in Table 1.

Table 1. Rules of Thumb for Aircraft Distance Traveled to Locate Target (nmi).

Initial Distance to Target (nmi)	Band		
	4	6	7
<40	22	20	19
$40 \leq X \leq 60$	33	28	24
$X > 60$	51	41	30

Chapter 8

VERIFICATION

The rules of thumb developed out of the simulation should be verified and potentially adjusted using flight tests. The flight test would be conducted using emitters of known location in an area in which the aircraft is free to maneuver to locate these emitters. The aircrew would not know the actual location of the emitters but would use the rules of thumb. When the rule of thumb requirement had been met the emitter would be targeted. The aircrew would record the aircraft position at the time that the weapon had been launched as well as the targeted location of the weapon. The data collected during the flight could be plotted on a chart to verify if the rule of thumb had been successful. The aircraft location and the targeted emitter location could be plotted and compared to the actual location of the target. The required accuracy requirement for the weapon could be overlaid on the plotted information to evaluate if the weapon employment had been successful. Based upon the results of the post flight analysis, the rules of thumb could be adjusted. Although the resources to conduct flight tests are not available for this project, the first project was verified using flight tests. The detailed results of those flight tests cannot be presented here due to classification, but they can be summarized. Approximately 12 targeting runs were conducted in a military operating area against a variety of emitters. Of the 12 runs, 10 resulted in the successful location of the target, one was evaluated as a near miss as the target was located just outside the criteria and one missed due to aircraft equipment malfunction, one of the aircraft's receivers was malfunctioning. Although more tests would have been desirable, the result of the first

tests were quite promising, indicating that useful rules of thumb had been developed using this technique.

Chapter 9

CONCLUSION

Rules of thumb that may be used to locate items of interest can be effectively developed for aircraft systems that have no automated location capability. The aircraft system's essential elements may be used to develop a simulation in which the system and the desired location accuracy requirements are modeled. The simulation can be used to generate enough data to characterize the requirements to locate the target using the aircraft systems. Operator experience should be considered when selecting personnel to conduct the simulations. Analysis of the data produced by the simulation can be used to produce rules of thumb, which will result in the reliable location of targets. Once the rules of thumb are developed, they should be verified and refined using flight test when possible.

Bibliography

(1) Data Analysis Techniques, U.S. Naval Test Pilot School, Flight Test Engineering Group, NAWC-AD Patuxent River MD, Revised February 1994

(2) Weapon System Operator's Manual Navy Model EA-6B Aircraft Improved Capability Version Two (ICAP-2), Naval Air Systems Command (NAVAIR), December 2002.

Appendices

APPENDIX A - FIGURES.

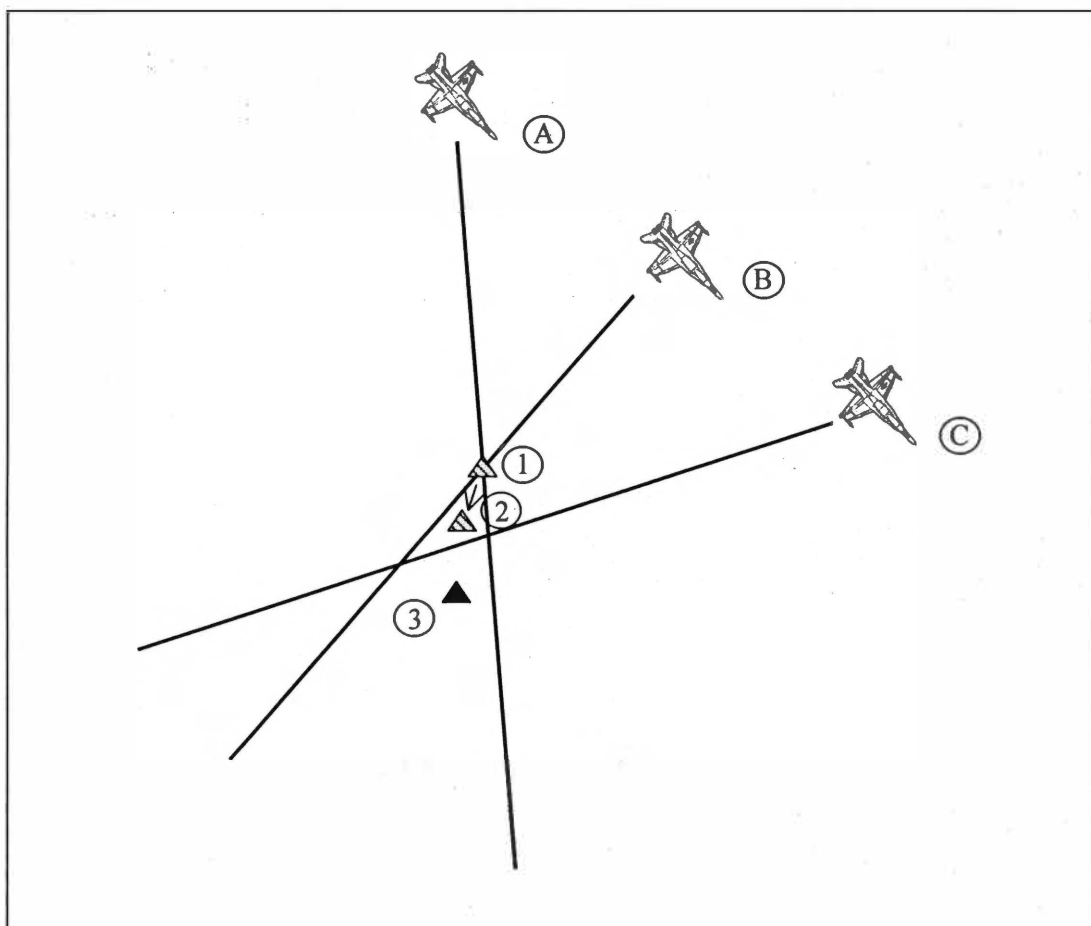


Figure 1. Triangulation Procedure.

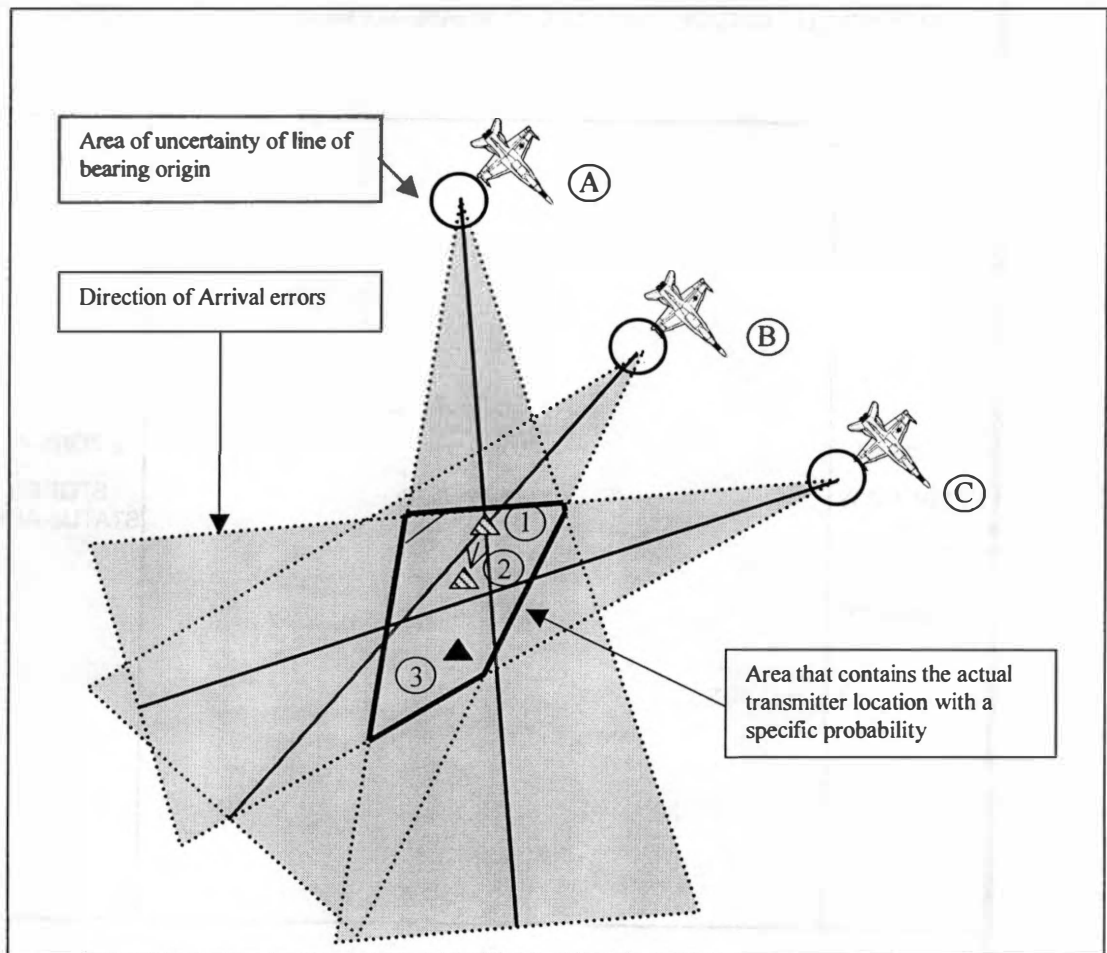


Figure 2. Airborne Triangulation with Bearing Errors.

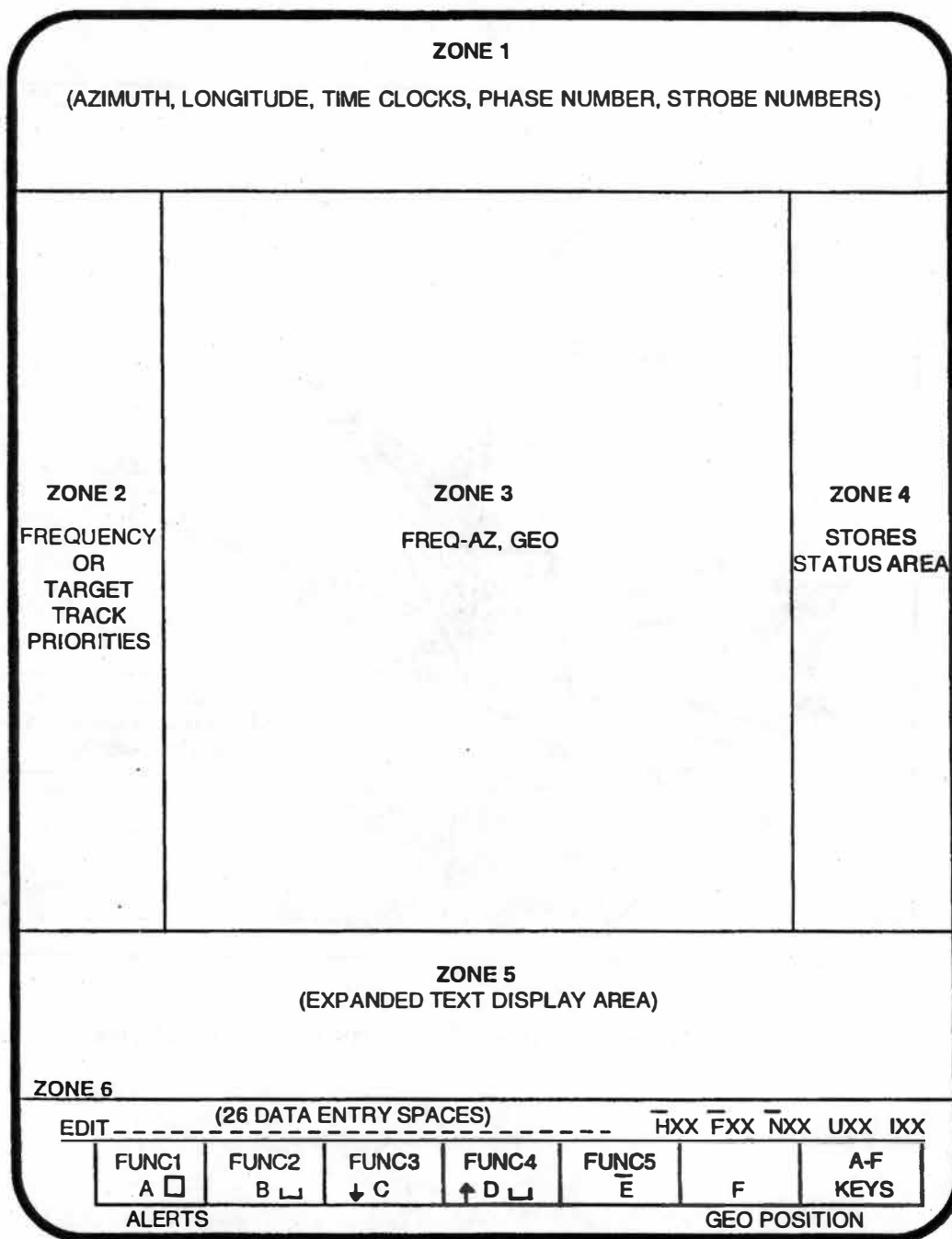


Figure 3. The EA-6B Display (NAVAIR, 2002).

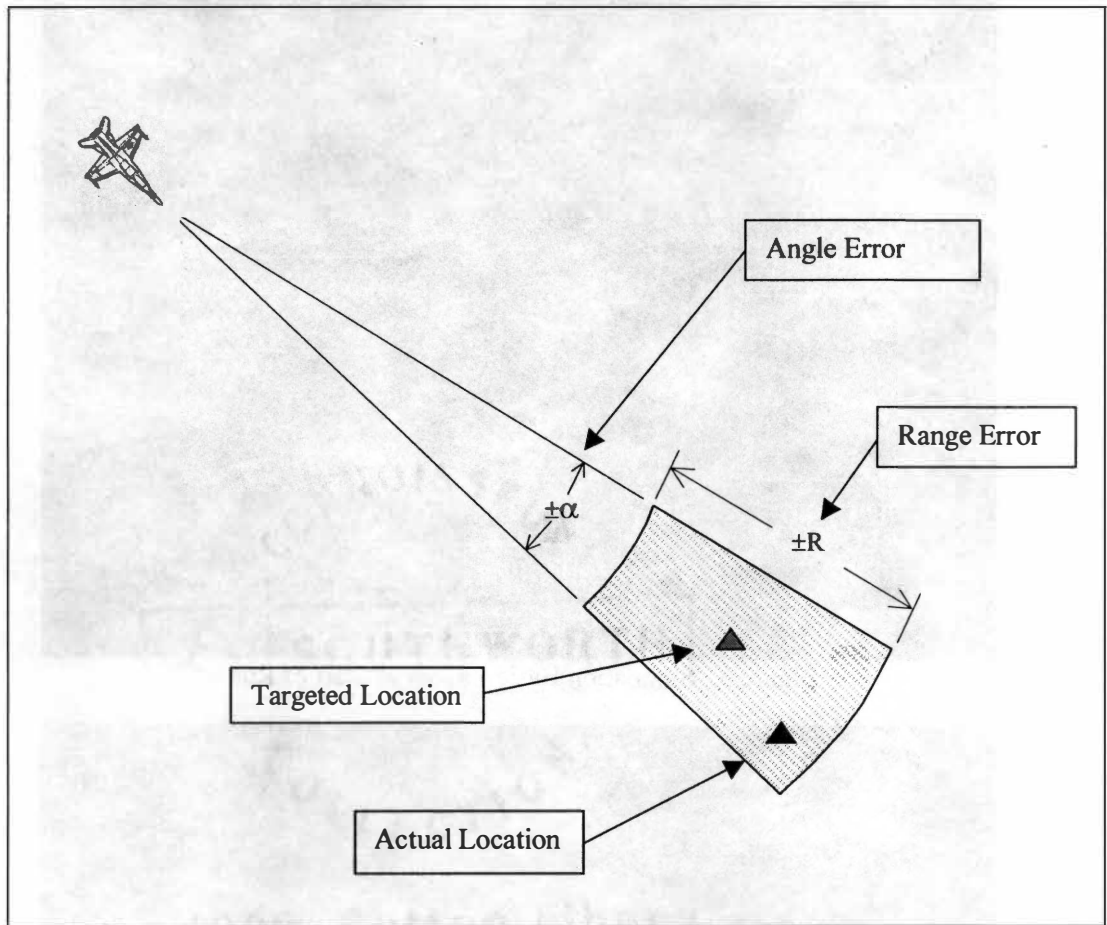


Figure 4. Targeting Accuracy Requirements.

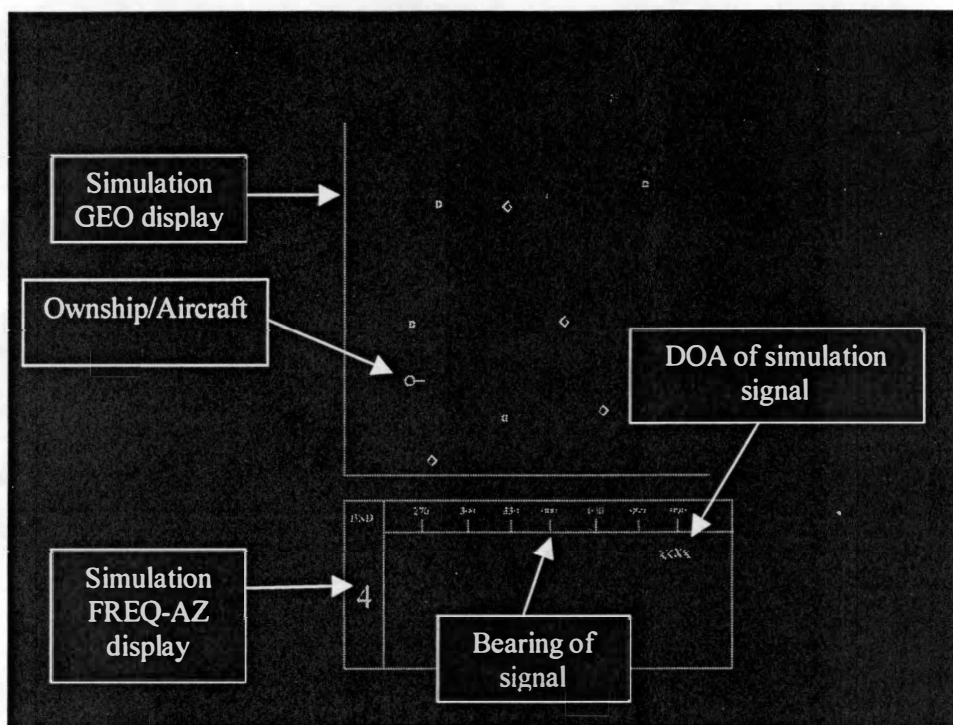


Figure 5. Simulation Basic Layout at Start of Run.

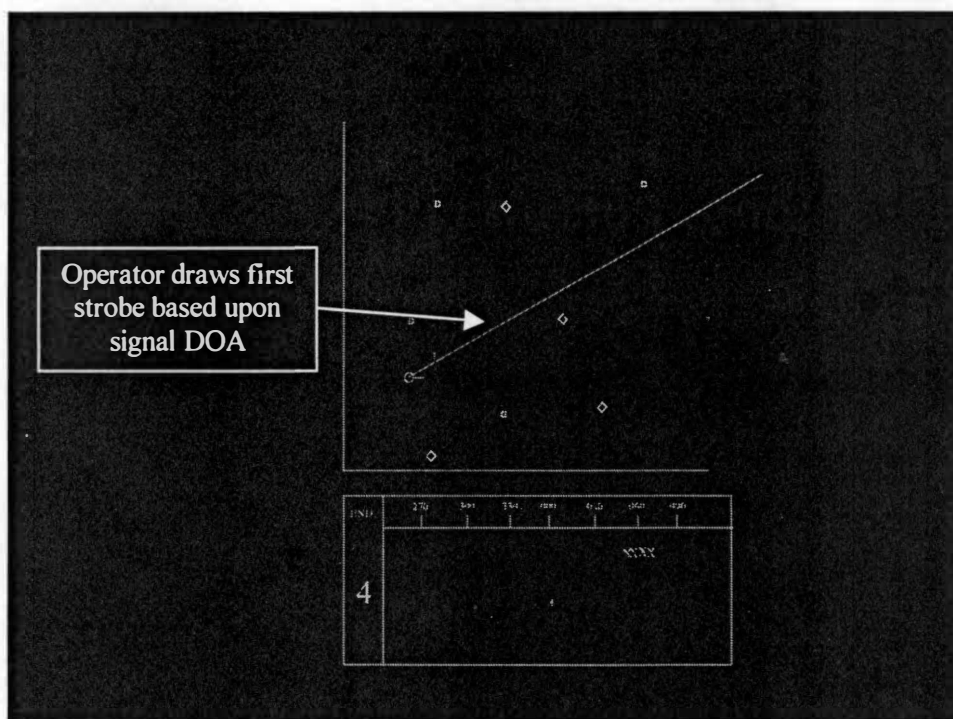


Figure 6. Simulation Layout After First Strobe is Drawn.

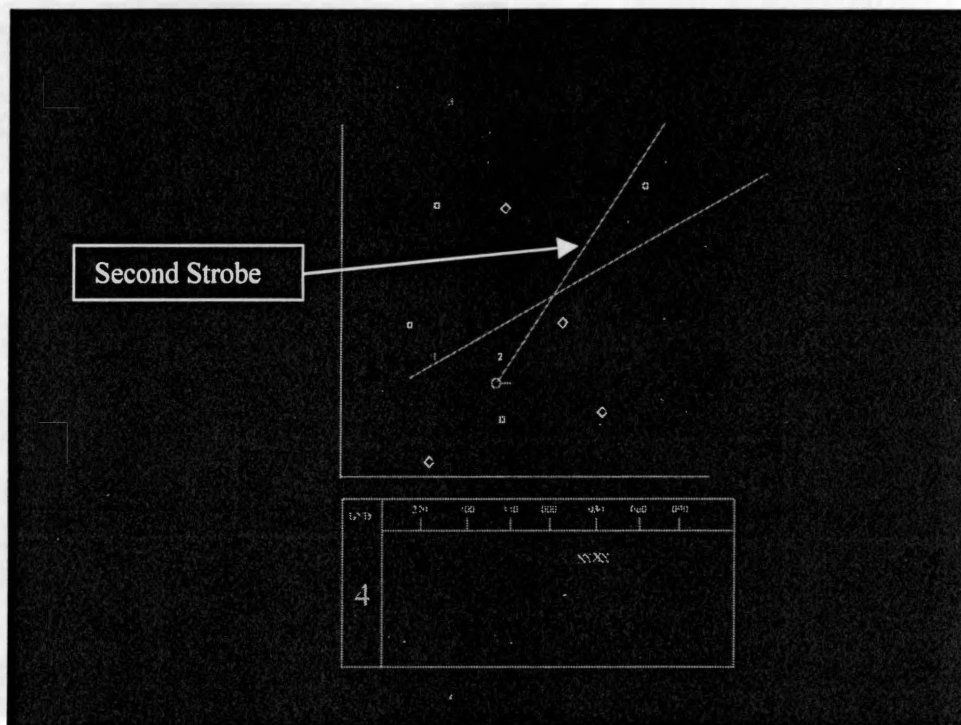


Figure 7. Simulation After Second Strobe is Drawn.

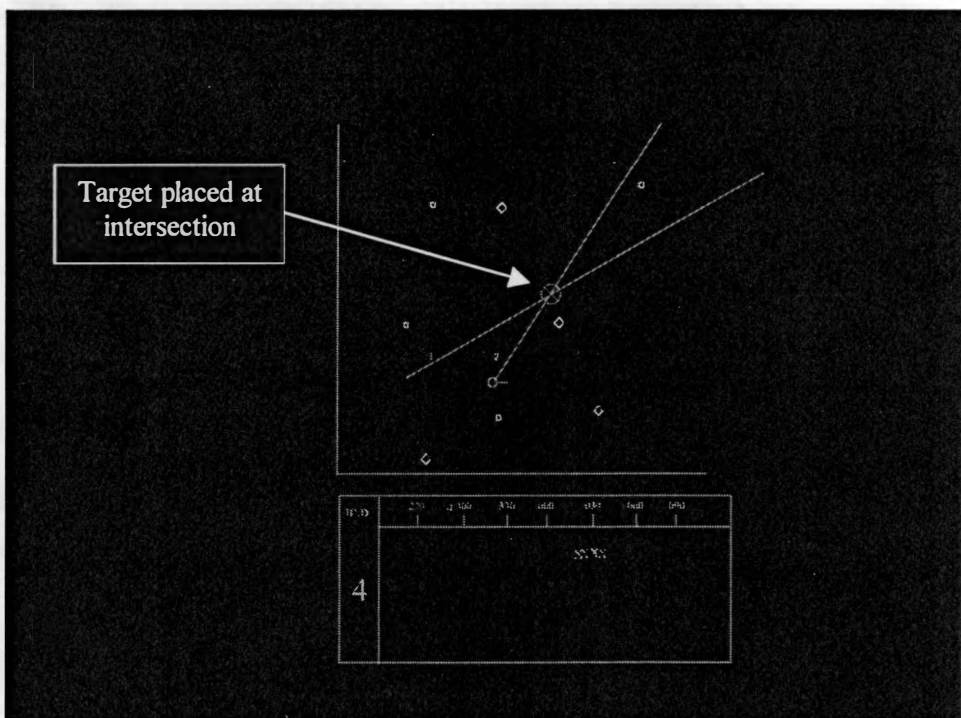


Figure 8. Simulation Appearance After Target is Placed at Intersection.

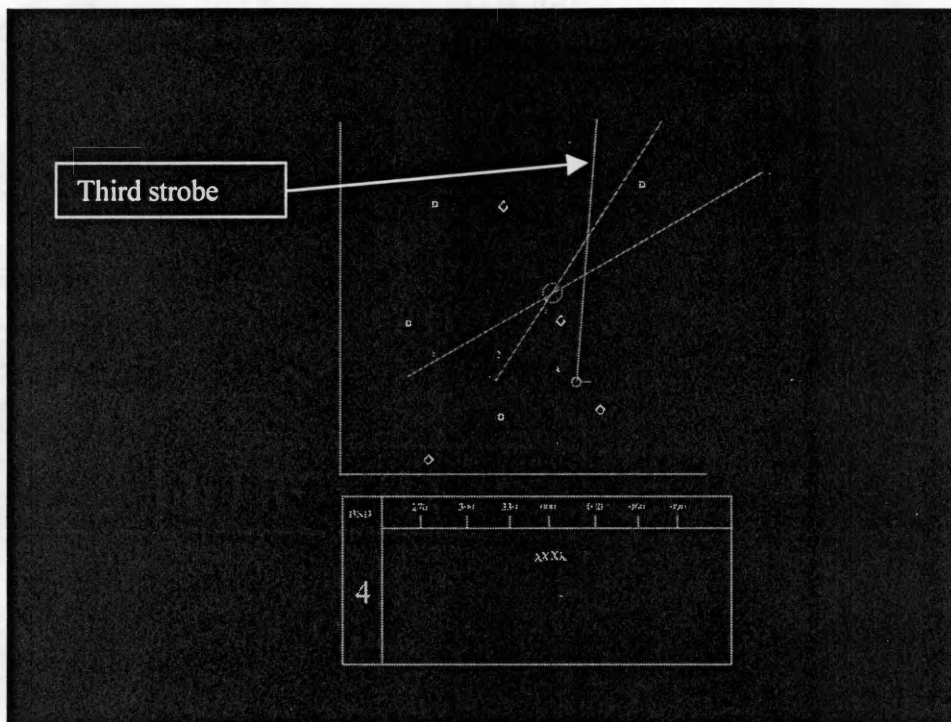


Figure 9. Simulation Appearance After Third Strobe is Drawn

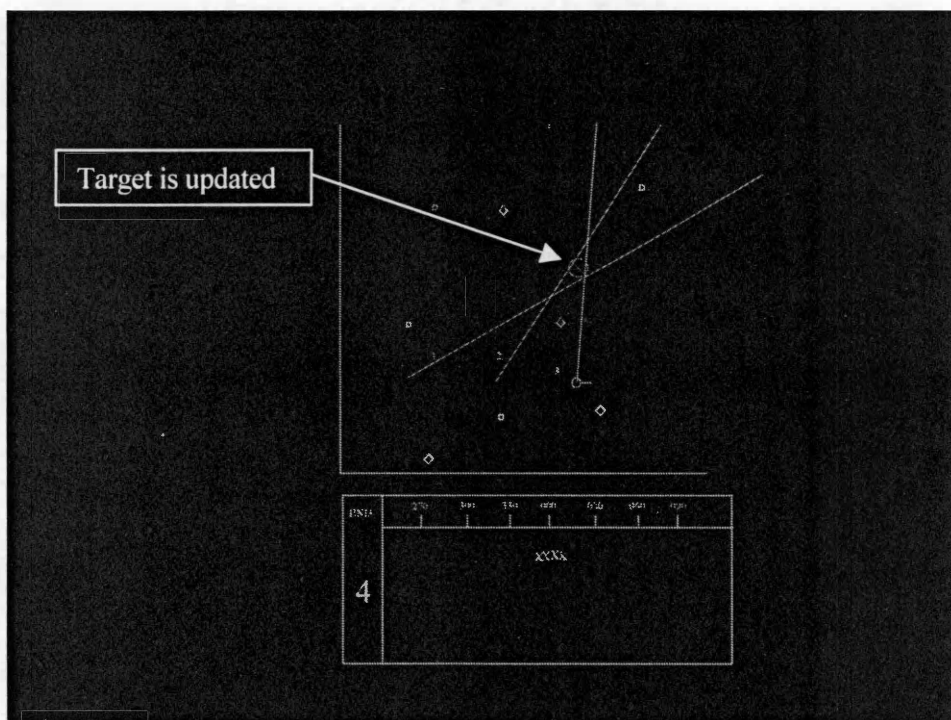


Figure 10. Appearance of Simulation After Target is Updated.

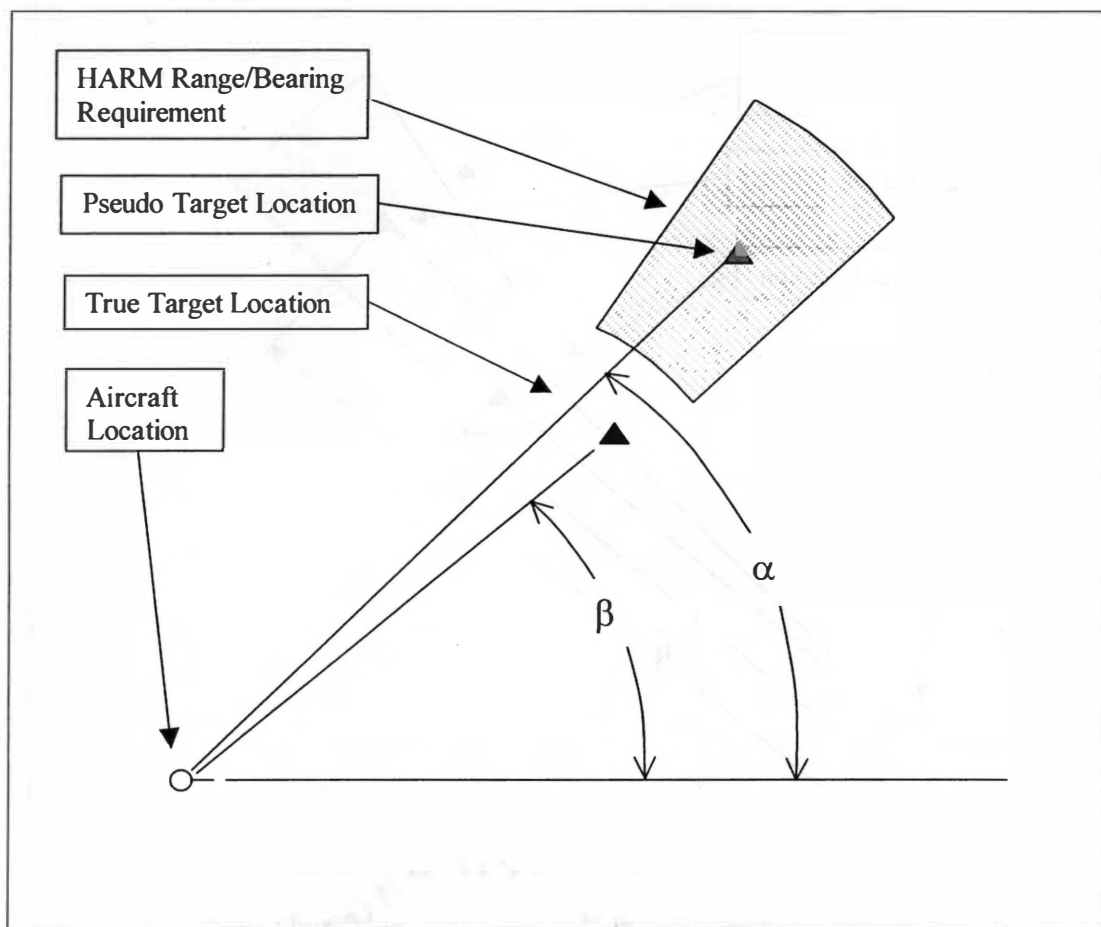


Figure 11. Angle Calculation to True and Pseudo Targets.

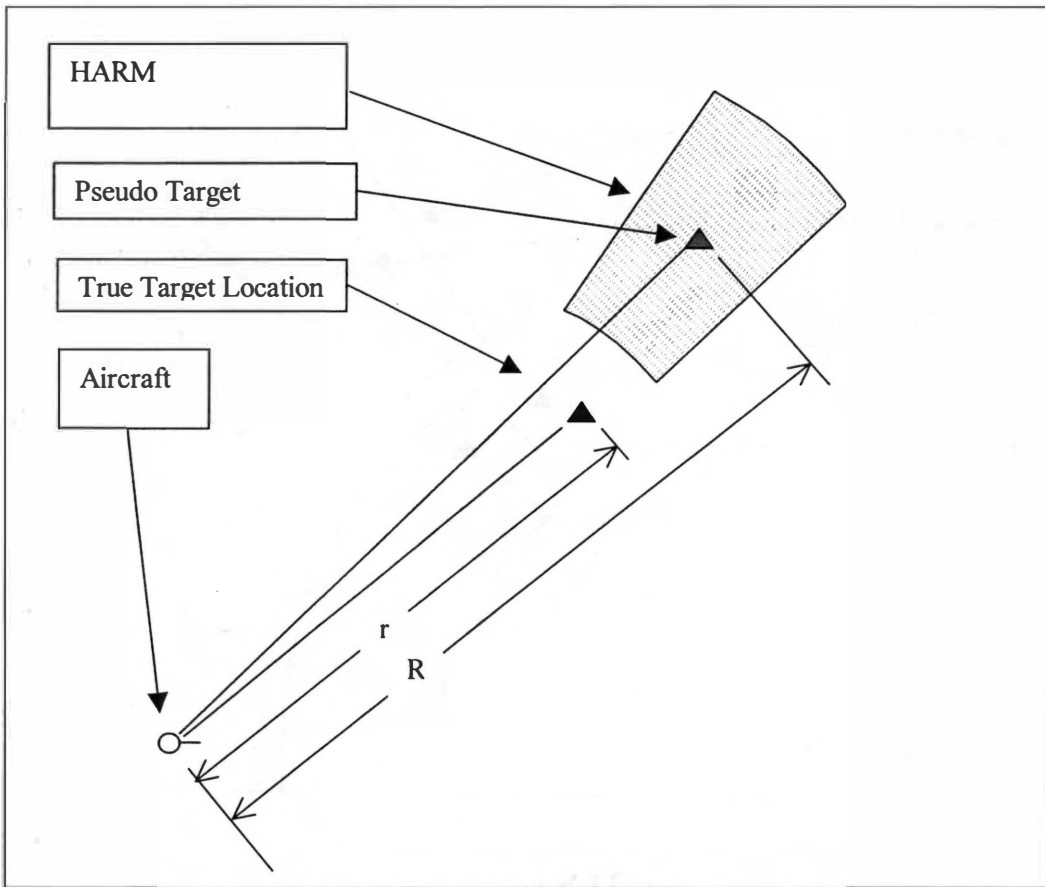


Figure 12. Range Calculation to the True and Pseudo Targets.

InputForm

HARM Simulation

Name
operator1

DOA Accuracy/standard deviation

BAND4	20
BAND6	12
BAND7	5
BAND8	0
BAND9	0

HARM Mode

Delta Angle 20

Delta Range .2

Start Simulation

Figure 13. Simulation Initialization Screen.

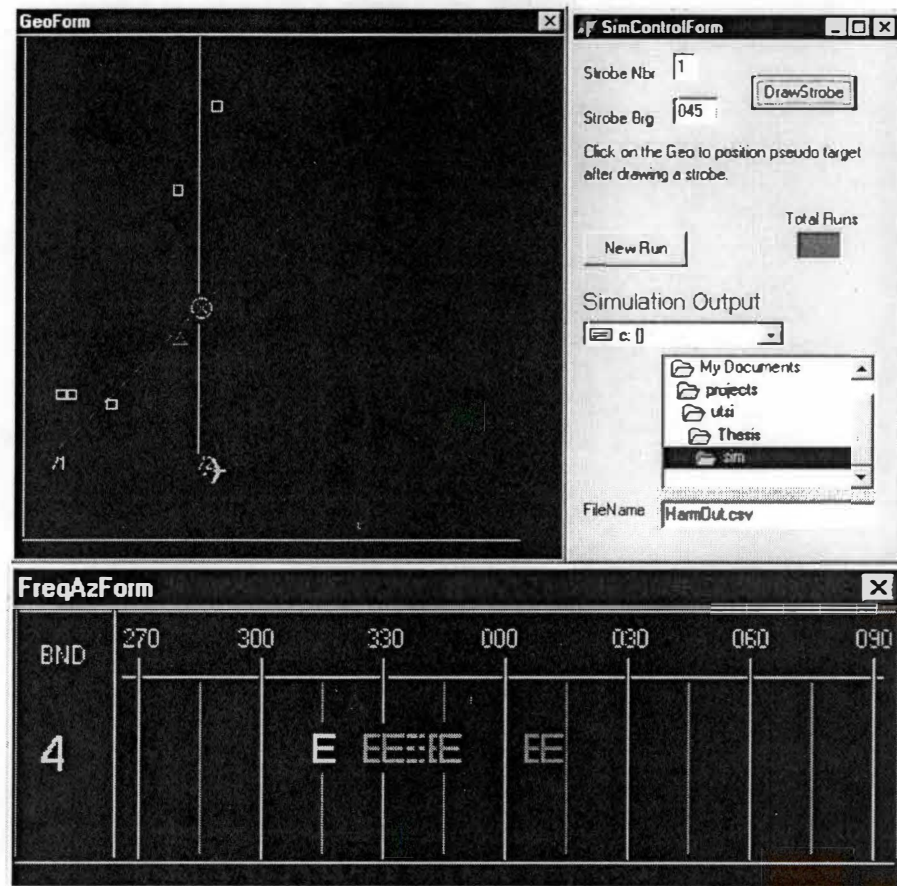


Figure 14. Simulation Displays.

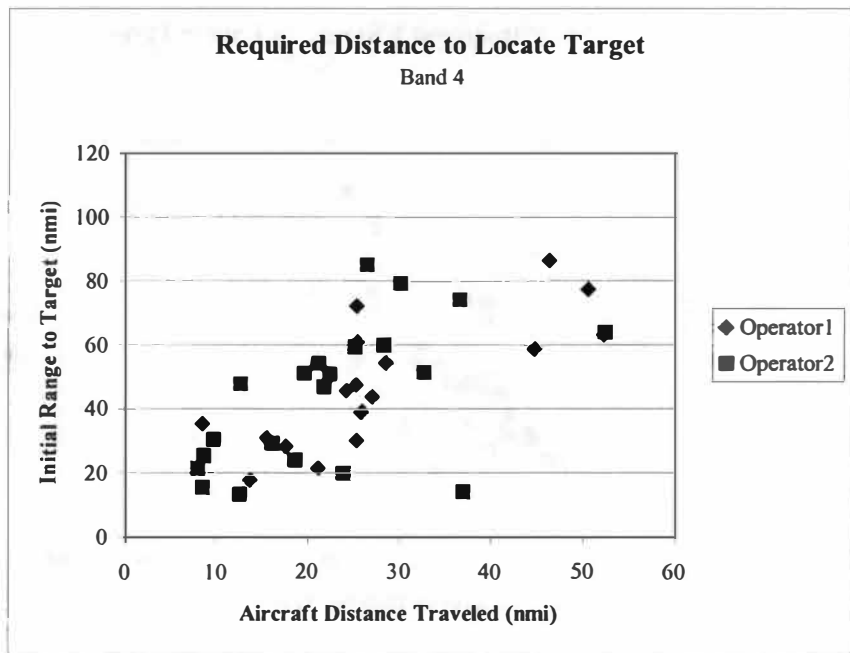


Figure 15. Required Distance to Locate for Band 4.

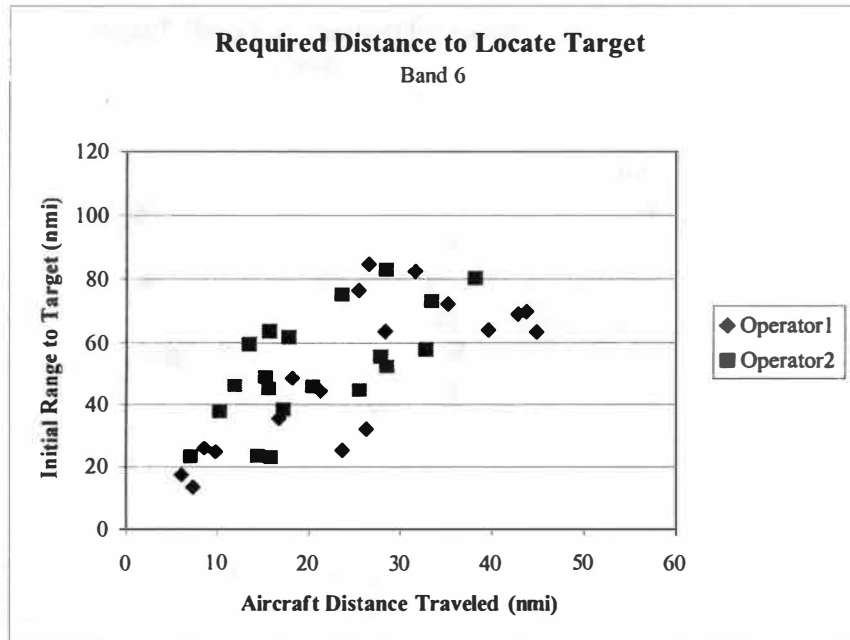


Figure 16. Required Distance to Locate for Band 6.

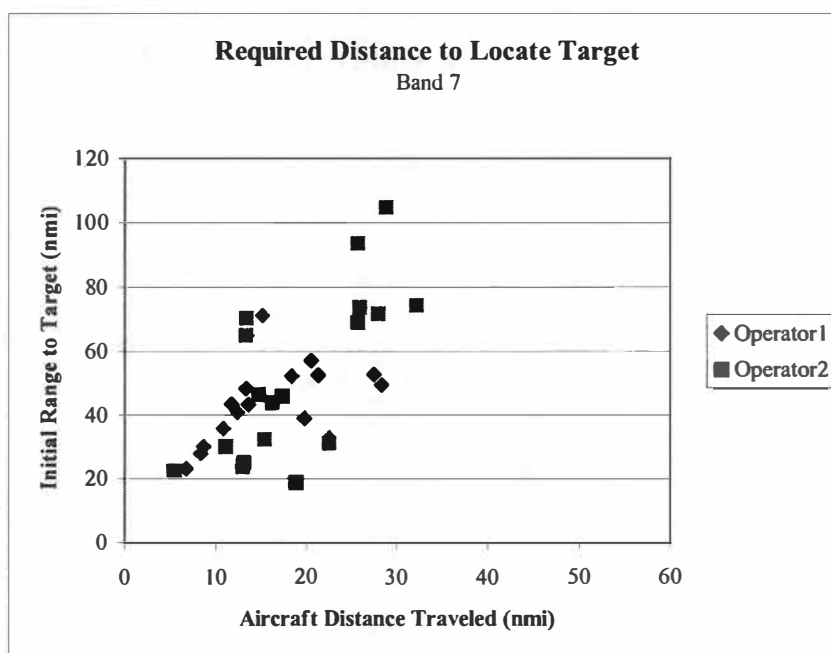


Figure 17. Required Distance to Locate for Band 7.

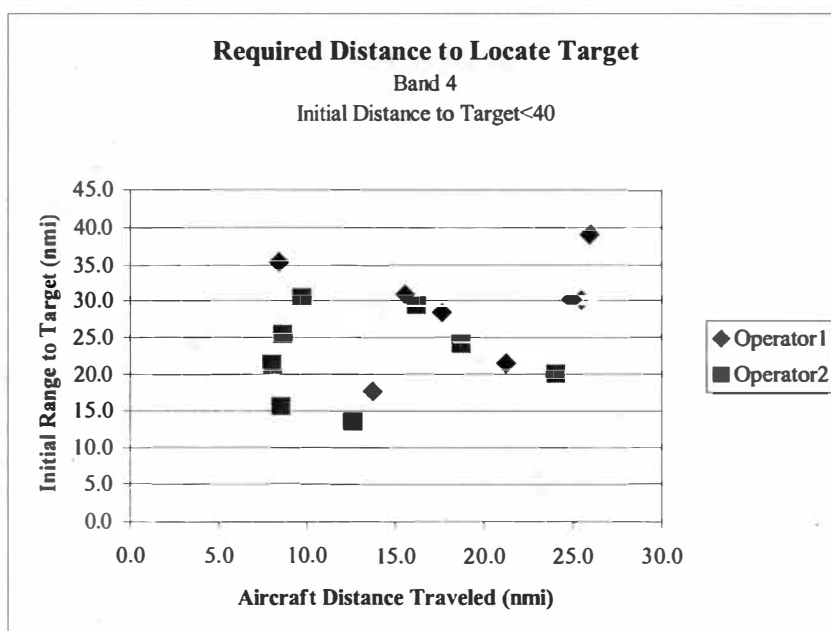


Figure 18. Required Distance to Locate Target for Band 4 and Range to Target < 40 nmi.

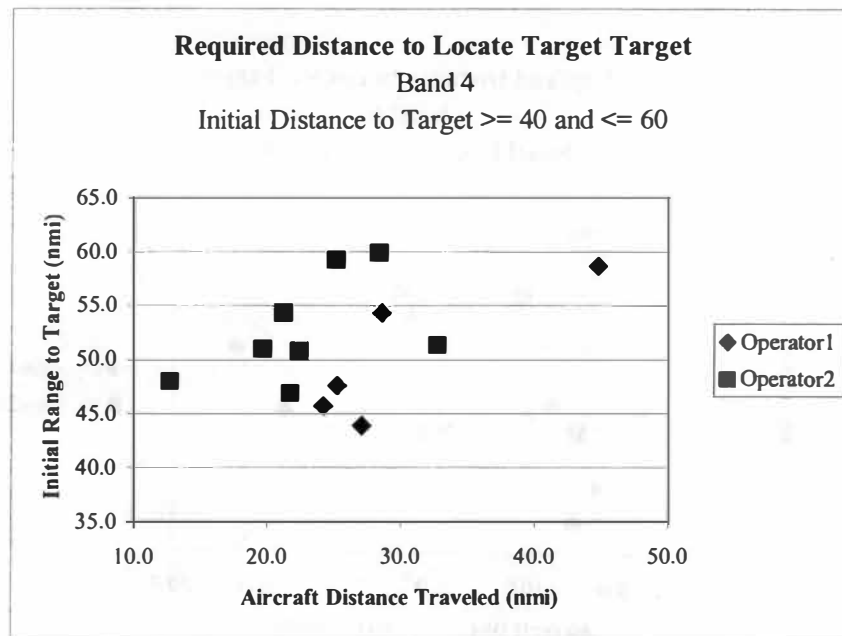


Figure 19. Required Distance to Locate Target for Band 4 and Range to Target ≥ 40 nmi and ≤ 60 nmi.

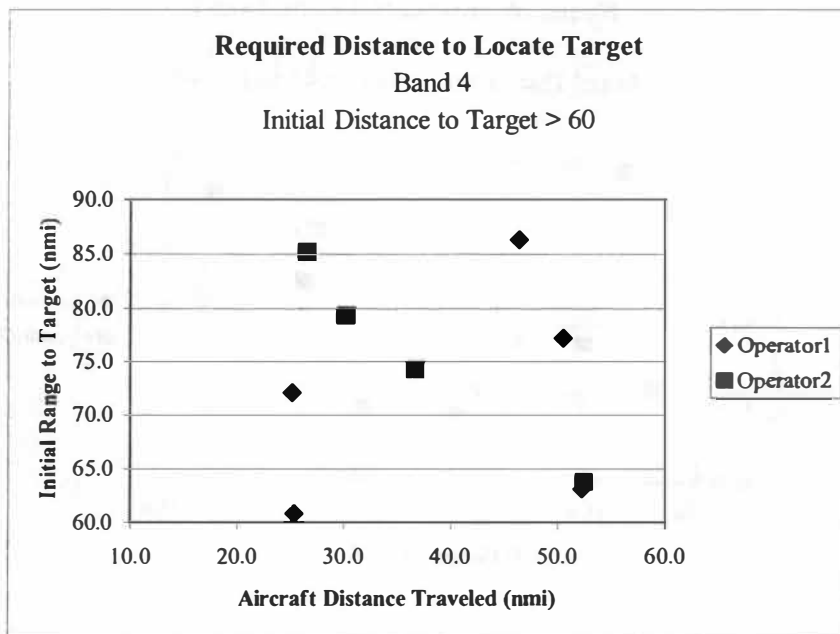


Figure 20. Required Distance to Locate Target for Band 4 and Range to Target > 60 nmi.

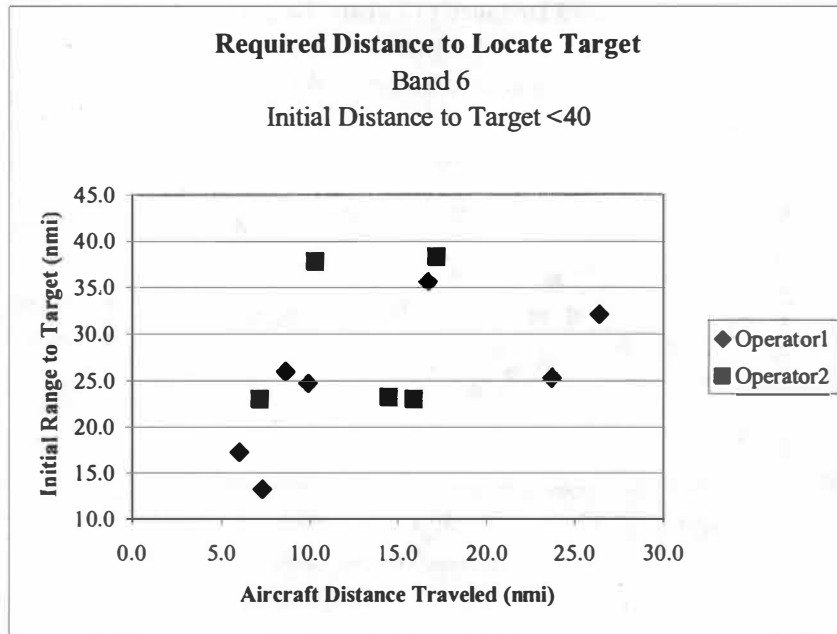


Figure 21. Required Distance to Locate Target for Band 6 and Range to Target < 40 nmi.

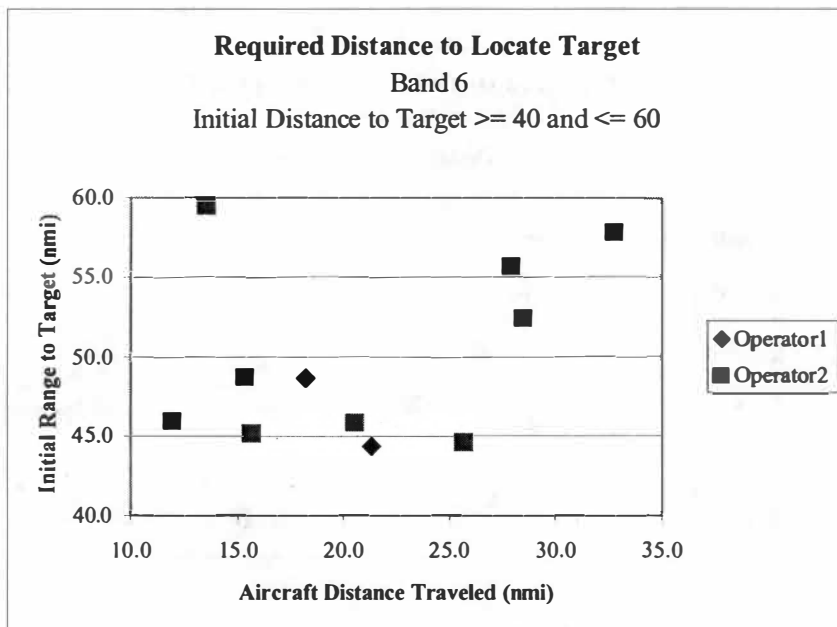


Figure 22. Required Distance to Locate Target for Band 6 and Range to Target ≥ 40 nmi and ≤ 60 nmi

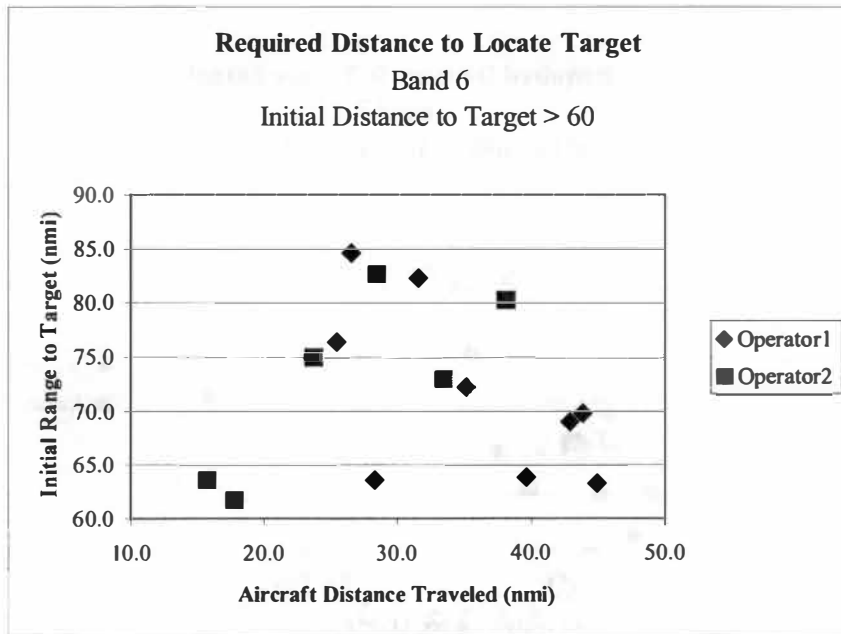


Figure 23. Required Distance to Locate Target for Band 6 and Range to Target > 60 nmi

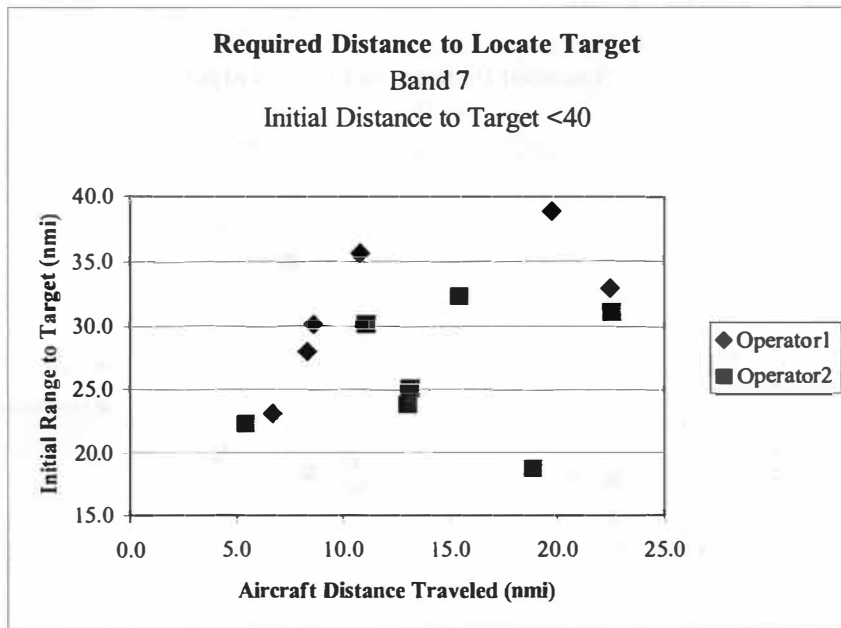


Figure 24. Required Distance to Locate Target for Band 7 and Range to Target < 40 nmi.

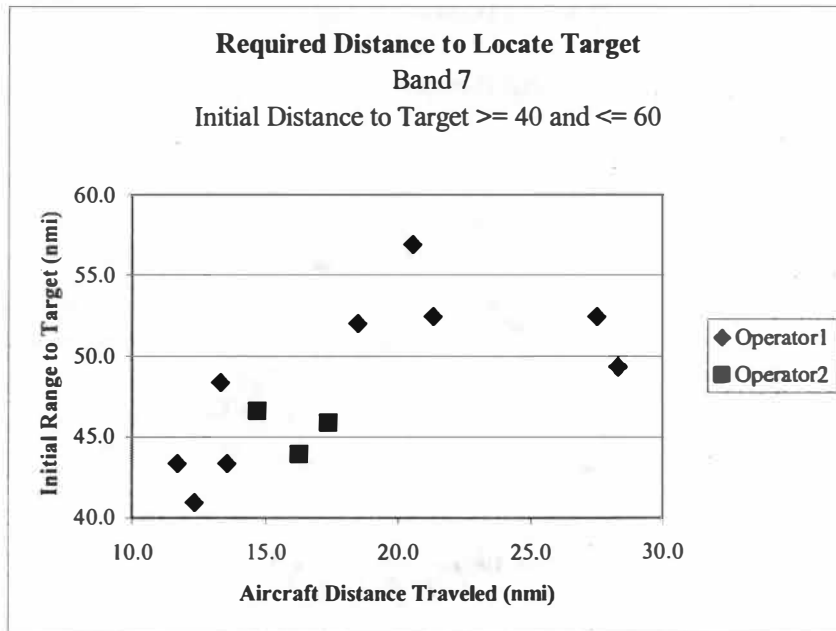


Figure 25. Required Distance to Locate Target for Band 7 and Range to Target ≥ 40 nmi and ≤ 60 nmi.

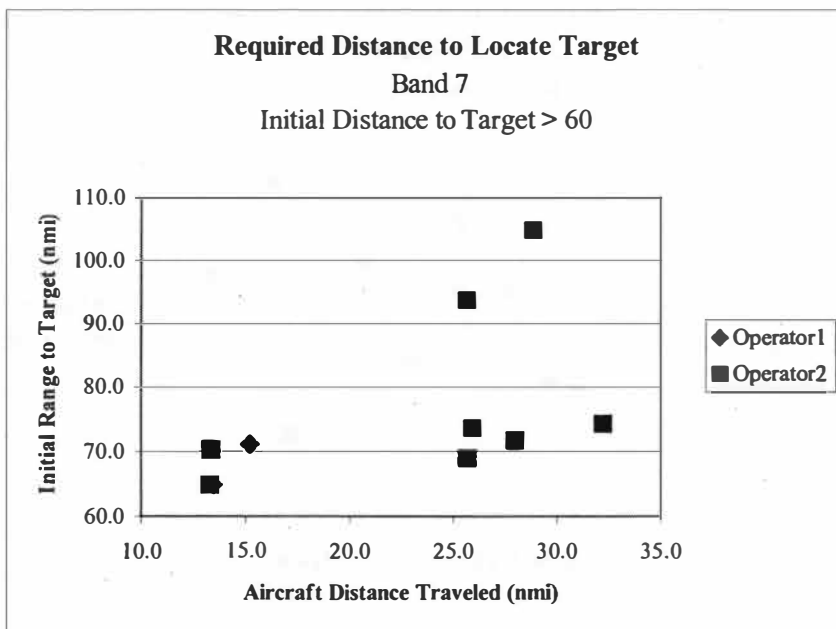


Figure 26. Required Distance to Locate Target for Band 7 and Range to Target > 60 nmi.

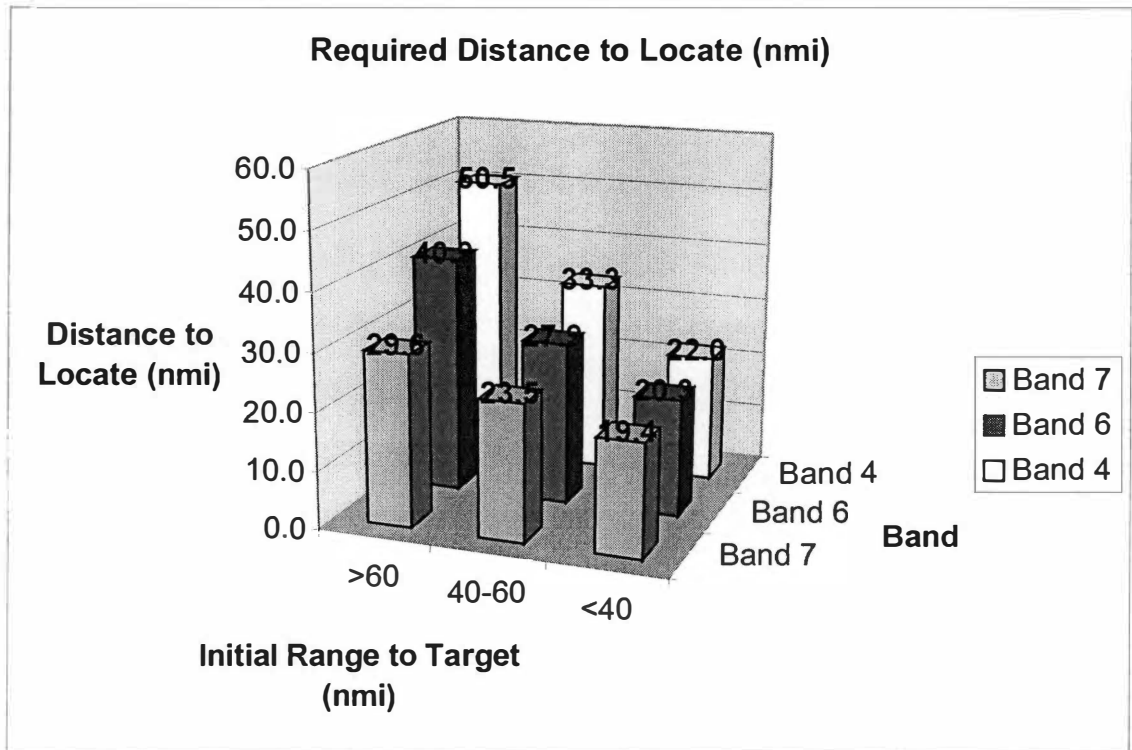


Figure 27. Required Distance to Locate.

APPENDIX B – TABLES.

Table 2. Simulation Requirements

Requirement	Description
Initialization Screen	The initialization screen shall allow the operator to initialize the following parameters: operator name, band accuracy for 5 bands labeled 4, 6, 7, 8, 9 and accuracy requirements in range (fraction) and angle (degrees) for HARM
Simulation Display	The simulation display shall be scaled so as to present an accurate (to scale) view to the operator appropriate to the ranges and angles being presented.
GEO Display	The simulation shall have a GEO display, upon which various randomly placed symbols will be placed at the start of each run. The GEO display will also display the current location of the aircraft starting initially at the origin and then proceeding East at approximately 840 nmi. The display will allow the operator to draw up to six strobes at bearings from 270 to 090 degrees. At the completion of drawing a strobe the display will allow the operator to place the cursor on the current pseudo target location and left click. The cursor left click will reposition the pseudo target to the cursor current location. At the completion of a run (as determined in calculations below) the GEO display will display the true target location.

Table 2. Continued.

Requirement	Description
FREQ-AZ Display	The simulation shall have a FREQ-AZ display, upon which the current band being simulated and the received DOA of the signal will be presented. Between each run the band will increment. The DOA will be presented to the operator with the most recent highlighted and the previous 9 shown but subdued. The DOA presented will be calculated and presented to scale using the DOA from the true target location plus an error such that the sum of the DOAs presented to the operator will fall within the specification requirements for each band.
Control	The simulation shall have a control screen from which the operator will select the strobe number and strobe bearing and can initiate the strobe to be drawn. It shall count the run number and provide provisions to start a new run. It shall allow the operator to select a file name and location for the data to be output.
Simulation Run initialization	At the start of each simulation run the aircraft shall be positioned at the origin with a heading of 090°. The band being simulated will be incremented and a new true target location will be calculated. Symbols will be randomly placed on the GEO form to provide a sense of scale.

Table 2. Continued.

Requirement	Description
True Target Location Calculation	At the start of each run a new true target location will be calculated. The true target location will be bounded in angle from 30° to 60° left of aircraft heading and from Y values of 10 to 60 nmi.
DOA calculation	The DOA shall be presented to the operator using the following formula: $\text{Received DOA} = \sigma \sqrt{-2\ln(\text{rnd\#})} \cos(2\Pi(\text{rnd\#})) + \text{true DOA}$ Where: σ = standard deviation entered from initialization screen true DOA = the actual DOA calculated from the true target location to the aircraft
True target to pseudo target calculation	When the operator selects a new position for the pseudo target the simulation shall calculate if the pseudo target lies within the range and bearing accuracy requirements of HARM. If the pseudo target lies within the accuracy requirements, the simulation stops and the actual target position is shown to the operator. If the pseudo target lies outside the accuracy requirements, the simulation continues.

Table 2. Continued.

Requirement	Description
Pseudo/Actual Target Angle Calculation	Pseudo/Actual Target Angle difference = $\alpha - \beta$ Where α = aircraft to pseudo target angle β = aircraft to true target angle
Pseudo/Actual Target Range Calculation	Pseudo/Actual Target Range difference = $\frac{ R - r }{R}$ Where: R = aircraft to pseudo target range r = aircraft to true target range
Output	Aircraft X – the aircraft X location at the end of the run Aircraft Y – the aircraft Y location at the end of the run True Target X – the X coordinate of the actual target location True Target Y – the Y coordinate of the actual target location Pseudo Target X – the X coordinate of the target positioned by the operator. The position recorded is the final position, the one that matched the target location accuracy requirements. Pseudo Target Y – the Y coordinate of the target positioned by the operator. The position recorded is the final position, the one that matched the target location accuracy requirements. Harm Delta Angle – the target location accuracy requirement in angle.

Table 2. Continued.

Requirement	Description
Output	Harm Delta Range – the target location accuracy requirement in range. Delta Angle – the measured difference in angle between the pseudo target and the true target location. Delta Range – the measured difference in range between the pseudo target and the true target location. Total Angle – the angle of the target relative to the aircraft position when the simulation run was finished. Band – the band being simulated ECMO – Electronic Counter Measures Officer (ECMO).

Table 3. Simulation Data Ordered by Operator then Band.

Aircraft X	Aircraft Y	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	Harm Delta Angle	Harm Delta Range	Delta Angle	Delta Range	Total Angle	Band	ECMO
50.5	0.0	54.8	54.4	49.3	52.8	20	0.2	5.8	0.0	40.7	4	OP1
25.5	0.0	47.4	38.2	48.8	42.1	20	0.2	0.9	0.1	21.3	4	OP1
25.9	0.0	19.8	33.7	14.9	28.5	20	0.2	10.8	0.1	40.7	4	OP1
17.7	0.0	14.3	24.4	16.8	22.4	20	0.2	5.7	0.1	38.2	4	OP1
44.8	0.0	42.5	40.5	33.6	48.8	20	0.2	9.6	0.2	49.6	4	OP1
28.6	0.0	28.1	46.5	25.9	40.3	20	0.2	3.3	0.2	31.8	4	OP1
25.5	0.0	18.1	24.0	17.9	23.5	20	0.2	0.8	0.0	54.0	4	OP1
24.3	0.0	25.8	37.7	22.7	37.3	20	0.2	4.7	0.0	32.0	4	OP1
8.5	0.0	18.0	30.5	17.1	33.1	20	0.2	2.7	0.1	13.2	4	OP1
25.3	0.0	40.1	59.9	42.1	66.1	20	0.2	0.4	0.1	19.9	4	OP1
52.4	0.0	50.8	37.5	46.4	41.9	20	0.2	5.7	0.1	55.9	4	OP1
27.1	0.0	24.6	36.3	24.8	43.2	20	0.2	0.9	0.2	38.1	4	OP1
13.8	0.0	11.7	13.2	12.3	13.9	20	0.2	2.6	0.0	50.3	4	OP1
15.6	0.0	16.8	25.9	15.5	21.9	20	0.2	2.9	0.2	30.2	4	OP1
21.2	0.0	15.2	15.2	16.3	17.9	20	0.2	6.1	0.1	66.7	4	OP1
25.3	0.0	36.7	30.3	32.0	31.5	20	0.2	8.6	0.0	29.8	4	OP1
46.4	0.0	63.7	58.3	61.9	63.5	20	0.2	2.9	0.1	31.0	4	OP1
9.9	0.0	15.1	19.6	14.9	21.3	20	0.2	1.5	0.1	22.9	6	OP1
18.2	0.0	35.8	32.9	39.7	37.9	20	0.2	1.5	0.1	19.3	6	OP1
42.9	0.0	35.2	59.3	29.6	54.4	20	0.2	6.4	0.1	38.1	6	OP1
39.7	0.0	50.8	38.7	46.4	36.0	20	0.2	5.5	0.1	36.7	6	OP1
23.7	0.0	21.4	13.5	23.2	17.1	20	0.2	8.0	0.2	67.5	6	OP1
25.5	0.0	48.3	59.3	41.6	61.9	20	0.2	6.5	0.0	18.2	6	OP1
26.4	0.0	23.8	21.6	25.3	24.0	20	0.2	4.3	0.1	54.7	6	OP1
43.8	0.0	47.0	51.5	44.5	55.2	20	0.2	2.8	0.1	38.9	6	OP1
21.3	0.0	22.7	38.1	19.2	32.0	20	0.2	5.8	0.2	28.7	6	OP1
26.6	0.0	60.7	58.9	64.8	72.0	20	0.2	2.2	0.2	15.8	6	OP1
8.6	0.0	18.3	18.5	18.1	16.0	20	0.2	3.1	0.1	17.1	6	OP1
44.9	0.0	46.2	43.3	46.7	45.9	20	0.2	0.5	0.1	45.2	6	OP1
6.1	0.0	12.2	12.2	12.8	10.9	20	0.2	4.8	0.1	18.2	6	OP1
16.7	0.0	25.0	25.4	25.9	26.4	20	0.2	1.0	0.0	26.5	6	OP1
7.3	0.0	7.2	11.1	9.9	12.0	20	0.2	12.5	0.1	33.7	6	OP1
31.7	0.0	69.5	44.2	68.8	53.3	20	0.2	5.7	0.1	17.0	6	OP1
28.4	0.0	40.8	48.8	39.5	52.8	20	0.2	2.4	0.1	25.6	6	OP1
35.2	0.0	49.1	53.0	48.5	56.8	20	0.2	1.5	0.1	28.1	6	OP1
11.7	0.0	21.7	37.5	20.0	33.9	20	0.2	1.2	0.1	15.1	7	OP1
8.6	0.0	23.3	19.2	21.9	17.1	20	0.2	0.5	0.1	13.2	7	OP1

Table 3. Continued.

Aircraft X	Aircraft Y	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	Harm Delta Angle	Harm Delta Range	Delta Angle	Delta Range	Total Angle	Band	ECMO
6.7	0.0	15.8	16.8	14.9	14.4	20	0.2	1.3	0.2	14.8	7	OP1
22.5	0.0	20.6	25.7	23.5	31.2	20	0.2	5.9	0.2	43.0	7	OP1
15.2	0.0	39.9	58.8	37.3	55.5	20	0.2	1.0	0.1	11.4	7	OP1
10.8	0.0	18.8	30.3	17.6	28.0	20	0.2	1.0	0.1	17.0	7	OP1
13.6	0.0	22.4	37.1	21.9	35.7	20	0.2	0.3	0.0	17.8	7	OP1
18.5	0.0	44.6	26.9	40.3	23.7	20	0.2	1.6	0.2	14.8	7	OP1
20.6	0.0	32.5	46.6	34.7	50.4	20	0.2	1.2	0.1	20.5	7	OP1
13.4	0.0	26.9	40.2	27.7	36.8	20	0.2	2.6	0.1	15.2	7	OP1
28.3	0.0	41.9	26.0	44.3	29.6	20	0.2	0.8	0.1	30.7	7	OP1
8.3	0.0	21.5	18.0	22.1	18.7	20	0.2	0.3	0.0	13.9	7	OP1
19.8	0.0	22.3	31.8	22.9	33.1	20	0.2	0.8	0.0	30.5	7	OP1
12.4	0.0	21.4	34.9	20.3	35.5	20	0.2	1.9	0.0	17.0	7	OP1
21.3	0.0	27.3	44.7	28.3	48.5	20	0.2	0.5	0.1	23.8	7	OP1
27.5	0.0	40.2	33.6	41.3	36.5	20	0.2	0.0	0.1	29.4	7	OP1
13.5	0.0	37.6	52.8	34.4	53.1	20	0.2	3.0	0.0	10.9	7	OP1
8.6	0.0	11.1	11.1	14.7	12.0	20	0.2	14.2	0.2	32.2	4	OP2
25.2	0.0	33.5	48.9	30.9	49.1	20	0.2	3.0	0.0	24.8	4	OP2
32.8	0.0	32.8	39.6	30.9	35.2	20	0.2	3.0	0.1	39.7	4	OP2
30.2	0.0	61.9	49.7	52.5	50.1	20	0.2	8.6	0.1	18.7	4	OP2
8.7	0.0	17.5	18.4	19.5	19.2	20	0.2	3.7	0.1	18.0	4	OP2
52.5	0.0	50.8	38.7	52.3	45.9	20	0.2	2.2	0.2	55.2	4	OP2
21.3	0.0	38.3	38.7	37.3	43.5	20	0.2	3.4	0.1	21.0	4	OP2
12.7	0.0	7.8	11.0	10.7	10.1	20	0.2	12.8	0.2	59.1	4	OP2
36.7	0.0	45.4	58.7	53.9	66.9	20	0.2	5.9	0.1	29.3	4	OP2
18.7	0.0	15.9	18.2	18.7	20.0	20	0.2	8.7	0.1	50.0	4	OP2
22.4	0.0	37.3	34.5	38.9	43.2	20	0.2	2.5	0.2	23.9	4	OP2
8.1	0.0	13.7	16.4	17.1	16.5	20	0.2	9.6	0.1	21.0	4	OP2
9.7	0.0	25.2	17.2	26.7	17.3	20	0.2	2.2	0.0	13.7	4	OP2
19.7	0.0	38.7	33.3	36.8	29.9	20	0.2	0.0	0.1	19.6	4	OP2
37.0	0.0	9.5	10.5	13.9	13.1	20	0.2	8.6	0.1	111.4	4	OP2
24.0	0.0	15.7	12.4	18.4	16.5	20	0.2	14.9	0.1	85.3	4	OP2
26.6	0.0	69.9	48.7	58.7	44.3	20	0.2	5.7	0.2	13.5	4	OP2
12.8	0.0	30.9	36.7	35.2	39.2	20	0.2	3.5	0.1	13.8	4	OP2
28.4	0.0	46.8	37.6	42.1	33.1	20	0.2	3.5	0.2	25.2	4	OP2
16.2	0.0	16.3	24.4	20.3	22.4	20	0.2	10.1	0.1	33.6	4	OP2
21.8	0.0	26.0	39.1	28.3	41.3	20	0.2	2.8	0.1	27.5	4	OP2
15.8	0.0	43.7	46.2	33.9	46.1	20	0.2	9.8	0.1	12.3	6	OP2
15.9	0.0	19.5	12.3	20.8	13.1	20	0.2	4.3	0.1	41.6	6	OP2

Table 3. Continued.

Aircraft X	Aircraft Y	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	Harm Delta Angle	Harm Delta Range	Delta Angle	Delta Range	Total Angle	Band	ECMO
13.5	0.0	41.9	42.3	39.7	47.2	20	0.2	4.8	0.1	10.9	6	OP2
15.7	0.0	32.9	30.9	34.1	34.9	20	0.2	1.3	0.1	17.6	6	OP2
17.2	0.0	28.6	25.5	27.2	27.7	20	0.2	4.3	0.1	24.2	6	OP2
32.8	0.0	45.2	36.2	46.9	37.6	20	0.2	1.7	0.0	32.4	6	OP2
38.1	0.0	66.1	45.5	62.7	43.5	20	0.2	2.2	0.1	23.9	6	OP2
17.8	0.0	42.4	44.9	43.5	45.6	20	0.2	0.7	0.0	14.7	6	OP2
15.3	0.0	36.6	32.2	33.6	31.7	20	0.2	3.4	0.1	15.2	6	OP2
12.0	0.0	37.9	25.9	36.8	24.8	20	0.2	0.0	0.0	10.7	6	OP2
33.5	0.0	43.3	58.8	42.7	60.8	20	0.2	0.9	0.0	26.9	6	OP2
10.3	0.0	26.6	26.9	29.1	33.9	20	0.2	2.2	0.2	13.4	6	OP2
7.2	0.0	19.2	12.7	16.8	11.2	20	0.2	2.8	0.2	13.0	6	OP2
27.9	0.0	31.3	46.1	28.3	49.6	20	0.2	3.8	0.1	30.0	6	OP2
28.6	0.0	62.4	54.4	61.6	58.4	20	0.2	2.4	0.0	17.0	6	OP2
20.5	0.0	30.6	34.2	36.8	40.3	20	0.2	5.6	0.2	25.4	6	OP2
25.7	0.0	24.8	37.1	24.8	33.9	20	0.2	0.2	0.1	35.1	6	OP2
28.5	0.0	40.2	33.8	42.1	38.4	20	0.2	0.5	0.1	30.9	6	OP2
23.7	0.0	62.7	41.2	55.7	42.9	20	0.2	6.7	0.1	13.3	6	OP2
14.5	0.0	18.5	14.0	20.0	13.6	20	0.2	6.0	0.0	36.9	6	OP2
22.6	0.0	25.6	17.8	25.9	16.0	20	0.2	1.9	0.1	45.5	7	OP2
25.7	0.0	76.1	54.7	62.9	49.9	20	0.2	5.9	0.2	11.7	7	OP2
32.2	0.0	56.4	48.4	57.3	57.9	20	0.2	3.1	0.1	22.8	7	OP2
25.9	0.0	54.0	50.2	54.7	54.1	20	0.2	1.2	0.1	17.9	7	OP2
13.3	0.0	37.6	52.8	37.1	58.7	20	0.2	2.7	0.1	10.7	7	OP2
28.9	0.0	89.4	54.7	80.3	52.5	20	0.2	3.5	0.1	10.6	7	OP2
15.4	0.0	18.1	26.8	19.2	29.9	20	0.2	1.5	0.1	28.4	7	OP2
17.4	0.0	30.6	34.2	33.6	41.9	20	0.2	0.0	0.2	20.7	7	OP2
5.4	0.0	16.7	14.8	15.5	12.8	20	0.2	0.7	0.1	11.1	7	OP2
25.7	0.0	57.0	38.9	56.8	40.8	20	0.2	1.5	0.0	16.9	7	OP2
14.7	0.0	32.9	33.0	35.2	36.8	20	0.2	0.3	0.1	16.0	7	OP2
13.4	0.0	46.9	52.3	43.5	50.9	20	0.2	2.1	0.1	9.2	7	OP2
16.3	0.0	33.4	28.5	33.9	30.4	20	0.2	1.0	0.1	18.5	7	OP2
28.0	0.0	50.5	50.8	50.7	53.1	20	0.2	0.8	0.0	20.9	7	OP2
18.9	0.0	14.2	12.3	15.7	13.6	20	0.2	7.9	0.1	70.1	7	OP2
13.0	0.0	17.3	16.4	19.2	17.6	20	0.2	4.8	0.1	31.9	7	OP2
11.1	0.0	21.7	21.0	25.3	25.6	20	0.2	2.2	0.2	19.1	7	OP2
13.1	0.0	13.7	21.0	15.5	22.4	20	0.2	4.3	0.1	31.5	7	OP2

Table 4. Binned Data for Band 4, Initial Range to Target <40 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
13.8	11.7	13.2	12.3	13.9	OP1	17.7
21.2	15.2	15.2	16.3	17.9	OP1	21.5
17.7	14.3	24.4	16.8	22.4	OP1	28.3
25.5	18.1	24.0	17.9	23.5	OP1	30.1
15.6	16.8	25.9	15.5	21.9	OP1	30.9
8.5	18.0	30.5	17.1	33.1	OP1	35.4
25.9	19.8	33.7	14.9	28.5	OP1	39.1
12.7	7.8	11.0	10.7	10.1	OP2	13.5
8.6	11.1	11.1	14.7	12.0	OP2	15.7
24.0	15.7	12.4	18.4	16.5	OP2	20.1
8.1	13.7	16.4	17.1	16.5	OP2	21.4
18.7	15.9	18.2	18.7	20.0	OP2	24.2
8.7	17.5	18.4	19.5	19.2	OP2	25.4
16.2	16.3	24.4	20.3	22.4	OP2	29.3
9.7	25.2	17.2	26.7	17.3	OP2	30.5

Table 5. Binned Data for Band 4, Initial Range to Target ≥ 40 but ≤ 60 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
27.1	24.6	36.3	24.8	43.2	OP1	43.8
24.3	25.8	37.7	22.7	37.3	OP1	45.7
25.3	36.7	30.3	32.0	31.5	OP1	47.6
28.6	28.1	46.5	25.9	40.3	OP1	54.4
44.8	42.5	40.5	33.6	48.8	OP1	58.7
21.8	26.0	39.1	28.3	41.3	OP2	46.9
12.8	30.9	36.7	35.2	39.2	OP2	48.0
22.4	37.3	34.5	38.9	43.2	OP2	50.8
19.7	38.7	33.3	36.8	29.9	OP2	51.1
32.8	32.8	39.6	30.9	35.2	OP2	51.4
21.3	38.3	38.7	37.3	43.5	OP2	54.4
25.2	33.5	48.9	30.9	49.1	OP2	59.3
28.4	46.8	37.6	42.1	33.1	OP2	60.0

Table 6. Binned Data for Band 4, Initial Range to Target >60 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
25.5	47.4	38.2	48.8	42.1	OP1	60.8
52.4	50.8	37.5	46.4	41.9	OP1	63.1
25.3	40.1	59.9	42.1	66.1	OP1	72.1
50.5	54.8	54.4	49.3	52.8	OP1	77.2
46.4	63.7	58.3	61.9	63.5	OP1	86.4
52.5	50.8	38.7	52.3	45.9	OP2	63.8
36.7	45.4	58.7	53.9	66.9	OP2	74.3
30.2	61.9	49.7	52.5	50.1	OP2	79.4
26.6	69.9	48.7	58.7	44.3	OP2	85.2

Table 7. Binned Data for Band 6, Initial Range to Target <40 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
7.3	7.2	11.1	9.9	12.0	OP1	13.2
6.1	12.2	12.2	12.8	10.9	OP1	17.3
9.9	15.1	19.6	14.9	21.3	OP1	24.7
23.7	21.4	13.5	23.2	17.1	OP1	25.3
8.6	18.3	18.5	18.1	16.0	OP1	26.0
26.4	23.8	21.6	25.3	24.0	OP1	32.1
16.7	25.0	25.4	25.9	26.4	OP1	35.7
15.9	19.5	12.3	20.8	13.1	OP2	23.0
7.2	19.2	12.7	16.8	11.2	OP2	23.0
14.5	18.5	14.0	20.0	13.6	OP2	23.3
10.3	26.6	26.9	29.1	33.9	OP2	37.8
17.2	28.6	25.5	27.2	27.7	OP2	38.3

Table 8. Binned Data for Band 6, Initial Range to Target ≥ 40 but ≤ 60 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
21.3	22.7	38.1	19.2	32.0	OP1	44.4
18.2	35.8	32.9	39.7	37.9	OP1	48.7
25.7	24.8	37.1	24.8	33.9	OP2	44.6
15.7	32.9	30.9	34.1	34.9	OP2	45.2
20.5	30.6	34.2	36.8	40.3	OP2	45.8
12.0	37.9	25.9	36.8	24.8	OP2	45.9
15.3	36.6	32.2	33.6	31.7	OP2	48.8
28.5	40.2	33.8	42.1	38.4	OP2	52.5
27.9	31.3	46.1	28.3	49.6	OP2	55.7
32.8	45.2	36.2	46.9	37.6	OP2	57.9
13.5	41.9	42.3	39.7	47.2	OP2	59.5

Table 9. Binned Data for Band 6, Initial Range to Target > 60 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
44.9	46.2	43.3	46.7	45.9	OP1	63.4
28.4	40.8	48.8	39.5	52.8	OP1	63.6
39.7	50.8	38.7	46.4	36.0	OP1	63.8
42.9	35.2	59.3	29.6	54.4	OP1	69.0
43.8	47.0	51.5	44.5	55.2	OP1	69.7
35.2	49.1	53.0	48.5	56.8	OP1	72.2
25.5	48.3	59.3	41.6	61.9	OP1	76.5
31.7	69.5	44.2	68.8	53.3	OP1	82.4
26.6	60.7	58.9	64.8	72.0	OP1	84.6
17.8	42.4	44.9	43.5	45.6	OP2	61.7
15.8	43.7	46.2	33.9	46.1	OP2	63.6
33.5	43.3	58.8	42.7	60.8	OP2	73.0
23.7	62.7	41.2	55.7	42.9	OP2	75.0
38.1	66.1	45.5	62.7	43.5	OP2	80.3
28.6	62.4	54.4	61.6	58.4	OP2	82.8

Table 10. Binned Data for Band 7, Initial Range to Target <40 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
6.7	15.8	16.8	14.9	14.4	OP1	23.1
8.3	21.5	18.0	22.1	18.7	OP1	28.0
8.6	23.3	19.2	21.9	17.1	OP1	30.1
22.5	20.6	25.7	23.5	31.2	OP1	32.9
10.8	18.8	30.3	17.6	28.0	OP1	35.7
19.8	22.3	31.8	22.9	33.1	OP1	38.9
18.9	14.2	12.3	15.7	13.6	OP2	18.8
5.4	16.7	14.8	15.5	12.8	OP2	22.3
13.0	17.3	16.4	19.2	17.6	OP2	23.8
13.1	13.7	21.0	15.5	22.4	OP2	25.1
11.1	21.7	21.0	25.3	25.6	OP2	30.2
22.6	25.6	17.8	25.9	16.0	OP2	31.2
15.4	18.1	26.8	19.2	29.9	OP2	32.4

Table 11. Binned Data for Band 7, Initial Range to Target ≥ 40 but ≤ 60 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
12.4	21.4	34.9	20.3	35.5	OP1	40.9
13.6	22.4	37.1	21.9	35.7	OP1	43.3
11.7	21.7	37.5	20.0	33.9	OP1	43.4
13.4	26.9	40.2	27.7	36.8	OP1	48.4
28.3	41.9	26.0	44.3	29.6	OP1	49.3
18.5	44.6	26.9	40.3	23.7	OP1	52.0
21.3	27.3	44.7	28.3	48.5	OP1	52.4
27.5	40.2	33.6	41.3	36.5	OP1	52.4
20.6	32.5	46.6	34.7	50.4	OP1	56.9
16.3	33.4	28.5	33.9	30.4	OP2	43.9
17.4	30.6	34.2	33.6	41.9	OP2	45.8
14.7	32.9	33.0	35.2	36.8	OP2	46.6

Table 12. Binned Data for Band 7, Initial Range to Target >60 nmi.

Aircraft X	True Target X	True Target Y	Pseudo Target X	Pseudo Target Y	ECMO	Initial Range to Target
13.5	37.6	52.8	34.4	53.1	OP1	64.9
15.2	39.9	58.8	37.3	55.5	OP1	71.1
13.3	37.6	52.8	37.1	58.7	OP2	64.9
25.7	57.0	38.9	56.8	40.8	OP2	69.0
13.4	46.9	52.3	43.5	50.9	OP2	70.3
28.0	50.5	50.8	50.7	53.1	OP2	71.6
25.9	54.0	50.2	54.7	54.1	OP2	73.7
32.2	56.4	48.4	57.3	57.9	OP2	74.3
25.7	76.1	54.7	62.9	49.9	OP2	93.7
28.9	89.4	54.7	80.3	52.5	OP2	104.9

Table 13. Distance Required to Locate Targets by Band and Initial Distance to Target.

Initial Distance to Target	Band 7			Band 6			Band 4		
	Mean	Standard Deviation	Distance Required to Locate	Mean	Standard Deviation	Distance Required to Locate	Mean	Standard Deviation	Distance Required to Locate
>60	22.2	7.5	29.6	31.8	9.1	40.9	38.5	12.0	50.5
40-60	18.0	5.6	23.5	21.0	6.9	27.9	25.7	7.5	33.3
<40	13.6	5.9	19.4	13.7	6.6	20.3	15.7	6.4	22.0

V i t a

James Winship was born in Abilene, Texas on December 18, 1964. He attended school in the Austin County, Texas School District and graduated from Bellville High School in 1983. He attended college at Texas A&M University earning a degree in Mechanical Engineering in 1988. He joined the United States Navy following college, with assignments to VAQ-138 aboard USS Nimitz as an Electronic Counter Measures Officer (ECMO) in the EA-6B and as an Operational Test Director at VX-9 prior to being selected for the United States Naval Test Pilot School. He had a follow-on developmental testing tour at the Naval Strike Aircraft Test Squadron before returning to VAQ-128, an operational EA-6B squadron. He is currently attached to VX-9 as the EW Branch Head and is pursuing a Master's Degree in the Aviation Systems Program at the University of Tennessee Space Institute.

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