Electronic Countermeasure Effectiveness: Evaluation Methods and Tools

Introduction:

This paper addresses the application of engineering methods and tools to the evaluation of the effectiveness of electronic countermeasures (ECM) in anti-ship missile defence. The intent of the paper is to contribute to the development of structured methodologies for ECM effectiveness analysis, pre-trial planning, trials data reduction and operational ECM program determination.

The success or effectiveness offered by an electronic countermeasure used in anti-ship missile defence is generally recognized to be dependent on the specific characteristics of both the threat missile and the countermeasure. The interaction between the countermeasure and the missile is complex, involving a large number of ship, countermeasure, missile and engagement parameters. Furthermore, the interaction is dynamic, with the missile and ship positions changing with time, and the missile and countermeasure operating modes also potentially changing as the engagement unfolds. The dynamic complexity of the missile and countermeasure interaction represents a substantial analysis and evaluation challenge, particularly using intuitive approaches.

The primary means normally used to measure the effect of a specific countermeasure on a specific missile has been through the execution of hardware-in-the-loop (HIL) laboratory or field trials using countermeasure equipment and missile simulator systems. The conduct of such trials, involving substantial equipment and human resources, is expensive. Cost inevitably places a limitation on the number of test runs executable. This, in turn, limits the number of threat missile simulations, countermeasure options and engagement geometries testable.

In the face of these factors it seems reasonable that pre-trial planning should identify, using systematic engineering methodologies, the most critical missile, countermeasure and engagement parameter combinations in trials plans and procedures. It also follows that, for maximum trials benefit, systematic engineering analysis methodologies, supported by appropriate tools, should also be applied to the reduction and analysis of test data after the trials are complete.

To demonstrate the application of engineering methods and tools to the evaluation of countermeasure effectiveness a particular class of anti-ship missile and countermeasure is considered as a representative example.

The class of missile used in this example is a subsonic sea-skimming missile which uses a Lobe-On-Receive-Only (LORO) angle tracking mechanism. This angle tracking technique has been used on a variety of tracking radars, and was extensively discussed in the technical journals during the years when operational anti-ship missiles were being introduced into the world market. A common countermeasure to the LORO angle tracking technique is the Swept Audio jamming technique and is the technique selected for use in this effectiveness evaluation example. (Swept Audio is also variously called Swept Scan Rate Modulation, Swept Square Wave and Swept Scan Band)[1].

Outline Of ECM Effectiveness Evaluation Methodology

The primary Measure Of Effectiveness (MOE) used in this paper to describe anti-ship missile ECM performance is Missile Miss Distance. A secondary Measure Of Effectiveness which is also used is the Length Of Time (required for the countermeasure) To Generate a Large Angle Tracking Error in the missile's seeker. It should be noted that each of these MOEs requires the passage of time and therefore the consideration of the dynamic interaction between countermeasure and missile. The rationale for the selection of these MOEs is discussed later in the paper.

The evaluation methodology which is outlined in this paper includes the following basic elements:

- Threat missile description
- Electronic countermeasure description
- Static analysis: countermeasure and missile parameter static relationships
- Dynamic simulation: countermeasure, ship and missile fly-out engagement

Each of these ECM effectiveness evaluation elements is discussed briefly below.

Threat Missile Description

The threat missile chosen for use in this example is a subsonic, sea skimming missile which consists of the following major subsystems:

- Seeker
- Autopilot
- Airframe

The brief descriptions below of each of these threat missile subsystems focuses on those missile characteristics which have greatest impact on the two selected Measures of Effectiveness of:

- Missile Miss Distance; and,
- Length Of Time For The Generation Of A Large Tracking Angle Error.

Missile's Seeker

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[1] "Applied ECM", Vol 1, L. B. Van Brunt, EW Engineering Inc., 1978.

The missile seeker type used in this countermeasure effectiveness evaluation example employs a Lobe-On-Receive-Only angle tracking technique which involves the scanning or lobing of a single receive antenna beam between multiple beam positions as shown (in plan view with two positions). If the ship target platform is off the boresight of the composite antenna pattern, an amplitude modulated target echo, which is a result of the difference in beams' gains in the direction of the target, is received by the missile's radar seeker. The phase of the amplitude modulated echo return is compared to the phase of a lobing reference signal in the radar. The difference in phase between the envelope of the echo return and the lobing reference signal causes the antenna to be driven, under servo control, until the echo amplitude is equal in each of the receive beam positions, at which angle the antenna drive is neutral as shown in Figure 1.

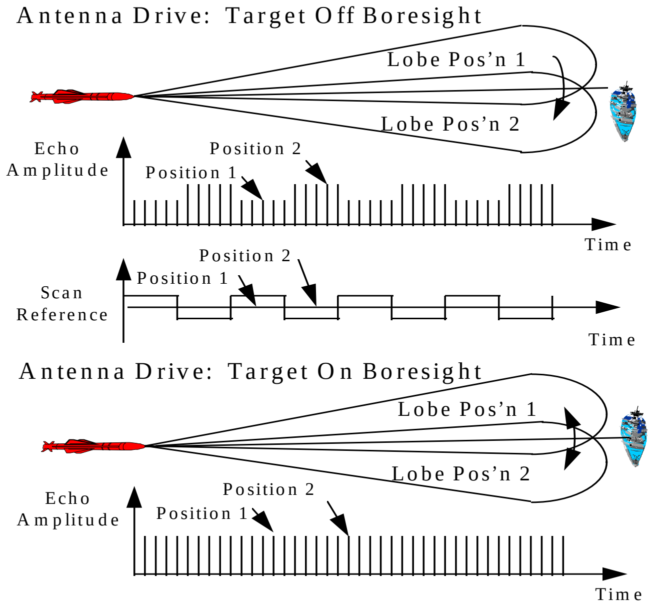

Figure 1. The LORO Tracking Mechanism

The primary measurement which the LORO angle tracker uses in determining the steering direction of the antenna is the relative phase between the amplitude envelope of the echo return and the seeker's lobing reference signal.

The primary parameters which characterize the seeker's LORO angle tracker for the determination of the selected MOEs are:

- Antenna Beamwidth
- LORO Scan Reference Frequency
- Angle Servo Bandwidth
- Angle Servo Type (ie. the number of integrators in the servo loop)

The rationale for the identification of the above angle tracker parameters is provided in the Static Analysis below. More description of the basic LORO angle tracking technique is provided in numerous texts, including those by Golden[2], Lothes, Symanski and Wiley[3] and Schleher[4].

Missile's Autopilot

The autopilot selected for this evaluation example uses Proportional Navigation (PN) guidance. In proportional navigation the rate of turn of the missile airframe axis is proportional to the rate of change of the seeker's angle tracking angle. The optimum value of PN constant for a missile designed for use against slow moving ship targets is approximately three. Garnell and East[5] show that with a PN constant of three the missile's rate of turn is greatest early in its tracking phase and reduces linearly to zero at end game. This implies no airframe lateral acceleration demand at end game against a non-maneuvering target and minimizes lateral acceleration demand against a maneuvering target.

Missile's Airframe

The primary physical parameters for the missile airframe which impact missile airframe maneuverability and hence Missile Miss Distance[5] are:

- Missile Velocity
- Cruise Altitude
- Mass
- Length
- Diameter
- Wing Span
- Wing Chord
- Wing Configuration (ie. planform or cruciform)

These parameters will be applied subsequently to the determination of the airframe's primary kinematic response parameters and to the assessment of an optimum value for the seeker's angle servo bandwidth.

Electronic Countermeasure Description

The Swept Audio (or Swept Scan Rate Modulation) electronic countermeasure signal consists of jamming pulses (synchronized in response to the received seeker pulses) which are amplitude modulated at a frequency which is swept repetitively through the seeker's reference lobing frequency.

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[2] "Radar Electronic Warfare", A. Golden Jr., AIAA Education Series, 1987

[3] "Radar Vulnerability To Jamming", R.N. Lothes, M.B. Symanski and R.G. Wiley, Artech House, 1990

[4] "Introduction To Electronic Warfare", D.C. Schleher, Artech House, 1986.

[5] "Guided Weapon Control Systems", P. Garnell and D.J. East, Pergamon Press, 1977.

The mechanism which Swept Audio (or Swept Scan Rate Modulation) ECM endeavors to exploit in providing angle deception to the LORO angle tracking radar is that of providing the radar with an ECM signal which is stronger than the target echo signal and which is amplitude modulated (normally with an on-off square wave) with a phase which is different from that of the target echo return. Since the radar uses the phase of the received signal to steer its antenna, the intent of the Swept Audio ECM signal is to introduce a composite target echo and ECM signal possessing a phase which drives the radar antenna away from the target platform as shown in Figure 2.

Since a Lobe-On-Receive-Only radar system transmits its signal using a steady (non-scanning) transmit antenna, the jamming platform may not be able to directly measure the frequency of the seeker's lobing reference signal to assist in amplitude modulating the jamming signal at the correct amplitude modulation rate. The jammer, in using Swept Audio ECM, endeavors to overcome this difficulty by sweeping the frequency of the amplitude modulation envelope of the jamming signal, usually using a triangular or saw-tooth frequency sweep, around the expected frequency of the radar's reference scan signal.

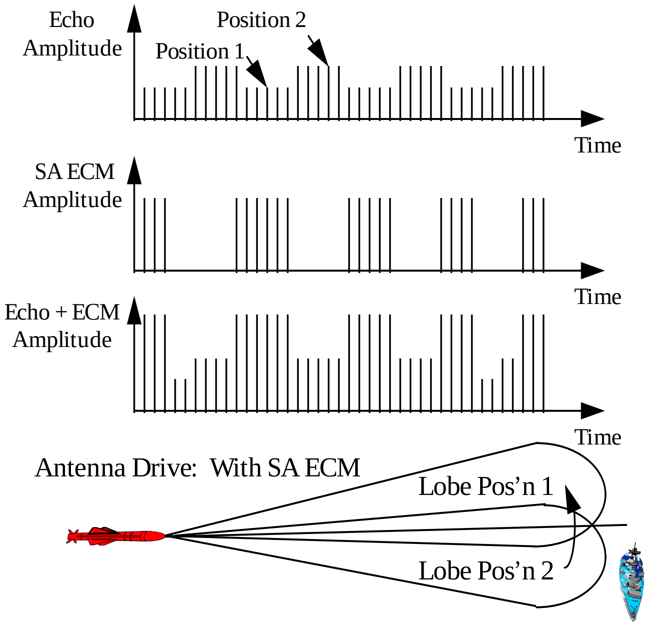

Figure 2. Impact of Swept Audio ECM on LORO Tracking

The primary parameters which characterize the Swept Audio ECM technique are:

- Sweep Rate
- Minimum Sweep Frequency
- Maximum Sweep Frequency

The success of Swept Audio jamming in generating a significant angle tracking error in the LORO seeker is related to the rate at which the amplitude modulation of the jamming waveform is swept and the upper and lower frequencies of this sweep relative to that of the seeker's lobing reference frequency. The discussion below demonstrates that Swept Audio successfulness is also related to other seeker parameters which characterize the angle response of the seeker, particularly angle servo bandwidth.

Static Analysis: Missile/Countermeasure Interaction

Since the seeker uses the relative phase between its internal lobing reference signal and the amplitude modulation envelope of the received (combined target echo and ECM) signal as its means for determining the direction in which to drive the antenna, the engineering static analysis of Swept Audio effectiveness requires quantifying the phase of the jamming signal's amplitude modulation envelope relative to that of the seeker's internal lobing reference.

A linear frequency sweep of the Swept Audio modulation relative to the seeker's LORO reference frequency is given by:

$$f_{SA} - f_{LORO} = R_{SA}t$$

where:

f_{SA} is the instantaneous frequency (Hz) of the amplitude modulation envelope of the Swept Audio ECM signal;

f_{LORO} is the frequency (Hz) of the seeker's internal lobing reference signal; and,

R_{SA} is the rate (Hz/sec) of sweep of the frequency of the Swept Audio modulation envelope.

From the above equation, the phase of the Swept Audio amplitude modulation envelope relative to the LORO reference frequency is therefore seen to change parabolically with time and is given by:

$$\phi_{SA} - \phi_{LORO} = \int R_{SA}t\,dt = R_{SA}t^2/2 - \phi_O$$

The antenna drive voltage (V_{Drive}) generated by the seeker's scan modulation phase detector is normally proportional to the cosine of the relative phase as given by[3] :

$$V_{Drive} = \cos(\phi_{SA} - \phi_{LORO})$$

A diagram showing the linear frequency sweep of the Swept Audio modulation relative to the seeker's LORO reference, the resulting relative phase (for $\phi_O = 90^o$) and the antenna drive voltage is provided in Figure 3. In this figure the relative phase offset at the instant the Swept Audio frequency equals the lobing reference frequency has been chosen for the condition that the antenna servo drive voltage has the same sign continuously (ie. either positive or negative, for continuous right or left drive of the antenna) for the longest allowable period of time ($\Delta\tau_{max}$ as shown).

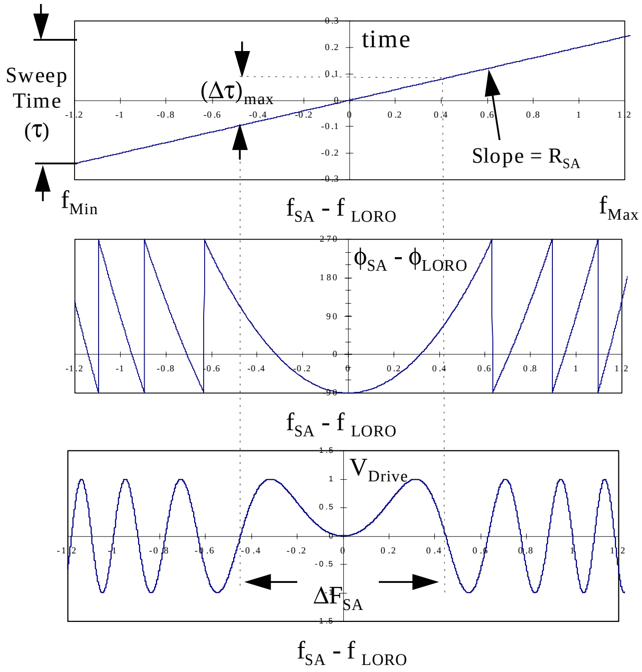

Figure 3. Swept Audio Frequency and Phase (Each Relative to the LORO Scan Reference) and the Antenna Drive Voltage

The maximum time duration for continuous antenna drive in one direction occurs when the Swept Audio phase relative to the LORO reference phase is restricted to lie within one-half cycle (ie. $|\phi_{SA} - \phi_{LORO}| < 90^o$) and is given from the previous equations by:

$$\Delta\tau_{max} = (2/R_{SA})^{0.5}$$

The condition that the Swept Audio jamming signal generates large angle error within this maximum single direction drive time implies that the antenna servo must generate a large antenna angle response within this time. The small signal response (rise) time for a linear servo control loop (ie. the time for the servo output to change from the 10% to the 90% point of the steady state output in response to a step input) is given by[6]:

$$(\tau_{Servo})_{ss} \sim 2/\,\omega_{Servo} = 1/\,\pi\, BW_{Servo}$$

where $(\tau_{Servo})_{ss}$ is the small signal rise time in seconds;

ω_{Servo} is the small signal 3 dB servo bandwidth in rad/sec; and,

BW_{Servo} is the small signal 3 dB servo bandwidth in Hertz.

The small signal (linear servo) response time as indicated above, however, can not be directly applied to the response of the angle servo to large signal Swept Audio ECM, because the angle servo loop contains a non-linear angle discriminator component. The over-all gain of this non-linear component saturates and ultimately goes negative with large input signals. Near its saturation point this non-linear discriminator characteristic results in small incremental loop gain which in turn causes a substantially slower servo angle response to large signals than to small signals. Assuming the time response of a non-linear angle discriminator $(\tau_{Servo})_{ls}$ under the condition of large signal drive input may be approximated by:

$$(\tau_{Servo})_{ls} \sim 1/\, K{*}BW_{Servo}$$

where π has been replaced in the previous equation by a generalized constant K which, to approximate the effect of the discriminator's non-linearity on the response time of the servo loop under large signal conditions, would normally be substantially less than the value of π which is appropriate for small signal conditions.

Equating the above large signal servo rise time $(\tau_{Servo})_{ls}$ to the maximum time duration of continuous Swept Audio drive voltage (Δt_{max}) results in the condition for the Swept Audio Sweep Rate (R_{SA}) for successful large angle error in a single Swept Audio frequency sweep of:

$$R_{SA} < 2(K{*}BW_{Servo})^2$$

This equation is applicable to the condition of a single Swept Audio sweep causing large angle error in the antenna pointing direction and is exactly the same as the equation quoted by Schleher (ref 4, p 152) if K is taken to be unity.

For the purposes of subsequent analysis the value of K is assumed to be one, giving rise to Schleher's equation:

$$\boxed{R_{SA} < 2(BW_{Servo})^2}$$

This equation is the first important engineering relationship between a Swept Audio ECM parameter (Sweep Rate, R_{SA}) and a threat seeker parameter (Small Signal Servo Bandwidth, BW_{Servo}) which arises from this static analysis.

There is another condition for the generation of large tracking angle errors. If the sweep rate of the Swept Audio's amplitude modulation envelope is large and its sweep width is

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[6] "Optimal Radar Tracking Systems", G. Biernson, Wiley-Interscience, 1990.

small, then the total phase excursion of the Swept Audio's amplitude envelope relative to the phase of the seeker's lobing reference is reduced, and may not exceed one-half cycle. This condition gives rise to mean continuous antenna drive in a single direction. Under this fast sweep rate/narrow sweep width condition the angle servo is not sufficiently responsive that large error is generated in a single sweep, but that angle error accumulates from sweep to sweep, ultimately resulting in large angular error. Equating the maximum time duration for continuous antenna drive ($\Delta\tau_{max}$) to the large signal servo rise time ($(\tau_{Servo})_{ls}$) results in the condition for fast sweep, large cumulative antenna angle error generation (assuming K = 1 as before) as follows:

$$\boxed{\Delta F_{SA} < (2R_{SA})^{0.5}}$$

where ΔF_{SA} is the total width of the Swept Audio frequency sweep in Hz (ie. $\Delta F_{SA} = F_{Max} - F_{Min}$).

The above static analysis was carried out assuming the upper and lower Swept Audio frequency limits were symmetrically placed about the seeker's lobing frequency and were without consideration for the phase between the amplitude envelope of the Swept Audio ECM signal and the lobing reference when their frequencies are equal. This relative phase at equal frequencies is determined from the initial conditions of the interaction.

If the upper and lower Swept Audio frequency limits are asymmetrically placed around the seeker's lobing frequency the mean relative phase may migrate slowly but continuously through complete 360 degree relative phase segments. To cause large angle errors during this migration, the mean Swept Audio phase must remain within each 180 degree continuous antenna drive phase region for a time which is greater than the angle servo loop large signal response time. This gives rise to another condition for large angle error generation, for the general case of asymmetric Swept Audio frequency sweep, as follows:

$$\boxed{\Delta F_{Offset} < BW_{Servo}/2}$$

where $\Delta F_{Offset} = F_{LORO} - (F_{Max} + F_{Min})/2$; and, F_{Max} and F_{Min} are the maximum and minimum Swept Audio amplitude modulation frequency sweep limits respectively.

A plot which shows the distinct regions associated with the generation of large angle errors for single slow sweep and multiple fast sweep Swept Audio ECM is provided in Figure 4 below. In this figure the small signal angle servo bandwidth is assumed to be 1 Hz, as discussed below, resulting in an upper Sweep Rate limit of 2 Hz/sec for a single slow sweep to cause large angle tracking error in the seeker.

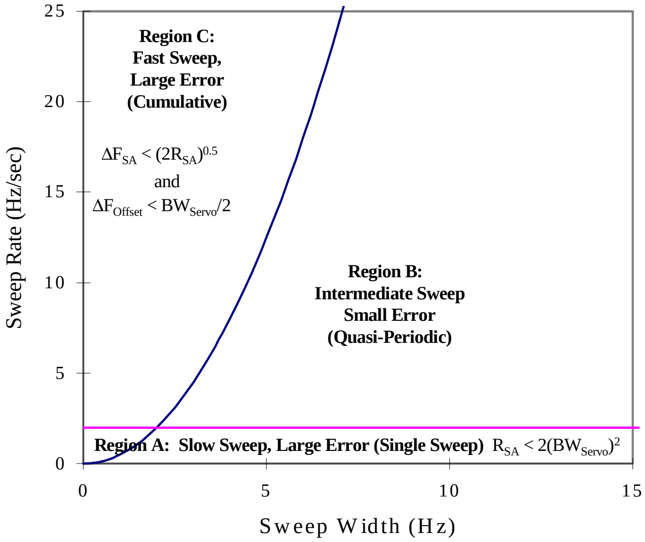

Figure 4. Regions of LORO Seeker Angle Tracking Error Generated By Swept Audio ECM

The use of a seeker angle tracking loop bandwidth of 1 Hz is consistent with the nominal value for angle servo bandwidth of 1 Hz discussed by Lothes[3] (p 99) and by Schleher[4] (p 152). It can also be verified as a reasonable value for a typical subsonic sea-skimming anti-ship missiles by applying Garnell and East's[5] principle of matching angle servo bandwidth and missile airframe natural resonance frequency. Airframe natural frequency can be calculated for a typical subsonic missile's airframe physical parameters (as identified previously) by applying Garnell and East's aerodynamic engineering equations.

Dynamic Analysis: Countermeasure, Ship and Missile Engagement

The above static analyses have resulted in equations which relate select Swept Audio ECM signal parameters (particularly sweep rate, and sweep limits) and missile seeker parameters (particularly the seeker's lobing frequency and its angle servo bandwidth) to produce large angle tracking errors. The above static analysis however, does not address two critical countermeasure effectiveness evaluation issues:

- The length of time required to generate large angle tracking error; and,
- The missile miss distance which results from the countermeasure's generation of angle tracking error.

The time required to produce significant angle errors may be important in the programming of ECM equipment which allows for switching among a number of countermeasure modes based on elapsed time in a particular mode. The ECM equipment's mode control program should enable the countermeasure mode for a sufficient length of time that the desired tracking error is generated in the seeker.

However, the missile's miss distance is almost certainly a more important measure of over-all countermeasure effectiveness than seeker tracking error since it is both more reliable and more operationally significant. It is more reliable because a large tracking error does not necessarily lead to the missile missing its ship target. To demonstrate this point, the countermeasure's introduction of a large seeker angle tracking error which is periodic and symmetric, with a mean value of zero, will normally lead to a small missile miss distance. Any negative steering errors generated in one portion of the periodic error will be canceled by positive steering errors generated in other portions as they are averaged over the flight time of the missile.

Also, if a countermeasure introduces a large but constant seeker angle tracking error in a proportional navigation missile the result is also likely to be a small missile miss distance. In a missile using proportional navigation the rate of turn of the missile airframe is proportional to the rate of change of the seeker's tracking angle. A large constant tracking error generated initially by a countermeasure would result in an initial missile airframe turn, but as the missile's flight progresses the autopilot, using the constant angle error generated by the countermeasure, would steer the missile toward a collision course to its ship target. Hence, the engagement outcome would normally be a small missile miss distance in spite of a large, but constant, missile seeker angle tracking error.

To address the critical issues of the time required to generate a large tracking error and the resulting missile miss distance, the countermeasure effectiveness evaluation methodologies and tools should provide for the dynamic interaction between the missile and the countermeasure. They inherently would draw on the following engineering disciplines:

- control system engineering for the evaluation of the seekers' servo tracking responses to countermeasures; and,
- aeronautical engineering for the evaluation of the autopilots' characteristics and the missile airframes' kinematic responses to error signals and control commands.

Each of the above are mature engineering disciplines readily adaptable to applying countermeasure effectiveness evaluation methods and tools.

In order to carry out the last of the proposed countermeasure effectiveness evaluation steps, that of simulating the dynamic engagement between the missile, ship and countermeasure, including the missile fly-out, calls up a requirement for an appropriate set of simulation tools. To incorporate the most important elements of the dynamic interaction between missile, ship and countermeasure and to provide the primary measures of effectiveness (Missile Miss Distance and Length Of Time To Generate Large Error) such simulation tools should include the following basic elements and characteristics:

- missile seeker which incorporates the antenna, transmitter, receiver and servo control functions, including the non-linearities associated with antenna patterns and tracking discriminators;
- missile autopilot which incorporates the appropriate guidance type and control compensation functions;
- missile airframe which incorporates rectilinear and rotational equations of motion, including aerodynamic lift, draft and moment coefficients and non-linearities;
- ship target which incorporates its equations of motion, maneuvers and the ship's radar cross section as a function of aspect angle;
- countermeasures which incorporate the following elements:
    - transmitter, antenna, countermeasure technique and parameter selection for on-board jammers; and,
    - deployment position, wind direction and speed and radar cross section as a function of time and aspect angle for chaff;
- signal propagation features which incorporate spreading loss and appropriate sea state, multi-path and sea clutter characteristics.

The simulation tool which was used to generate the subsequently described dynamic engagement simulation results was the Jamming Effectiveness Simulator For Sea Skimming Missiles (JESSS) which is one of the applications in TTI's Tactical Engagement Simulation Suite (TESS). TESS applications incorporate the elements and characteristics identified above. The parameters used for characterizing the threat radars and seekers in TESS are based on Electronic Warfare Integrated Reprogramming standard definitions.

To verify that the static analysis results discussed above and the dynamic simulation results produced by JESSS are consistent, sample missile engagements using Swept Audio jamming against a Lobe-On-Receive-Only seeker have been simulated. Typical simulation results for the three different Swept Audio regions of fast, moderate and slow sweep are shown in Figure 5. The three individual inlay plots in Figure 5 are superimposed on the Figure 4 plot (with Swept Audio Sweep Rate versus Sweep Width) and show the different angle error effects in the three Swept Audio regions.

Each of these three inlay plots include traces of the Swept Audio Frequency (in Hertz), Swept Audio Phase (in radians), both relative to the seeker's lobing reference, and most importantly, the Angle Tracking Error (in degrees).

In each of the inlay plots the Swept Audio sweep was from 3 Hz below the seeker's lobing frequency to 3 Hz above, a total sweep width of 6 Hz. The three sweep rates used were 1 Hz/sec (Point "A"), 8 Hz/sec (Point "B") and 24 Hz/sec (Point "C").

Point "A" in Figure 5, which is in the slow sweep, large error region identified in the static analysis, shows the generation of greater than 10 degrees of angle error with a single slow sweep of the Swept audio ECM signal. It also shows that the relative phase of the envelope of the Swept Audio ECM signal is parabolic in shape. Each of these features was predicted in the above static analysis. Finally, it is seen that the large angle tracking error is generated when the frequency of the envelope of the Swept Audio ECM signal equals that of the seeker's lobing reference (which also occurs at the minima and maxima of the phase parabola). This graph demonstrates that when the relative phase of the Swept Audio envelope changes relatively slowly (more slowly than the response time of the angle servo) it can generate large angle errors. This verifies the angle error generation process described in the static analysis above.

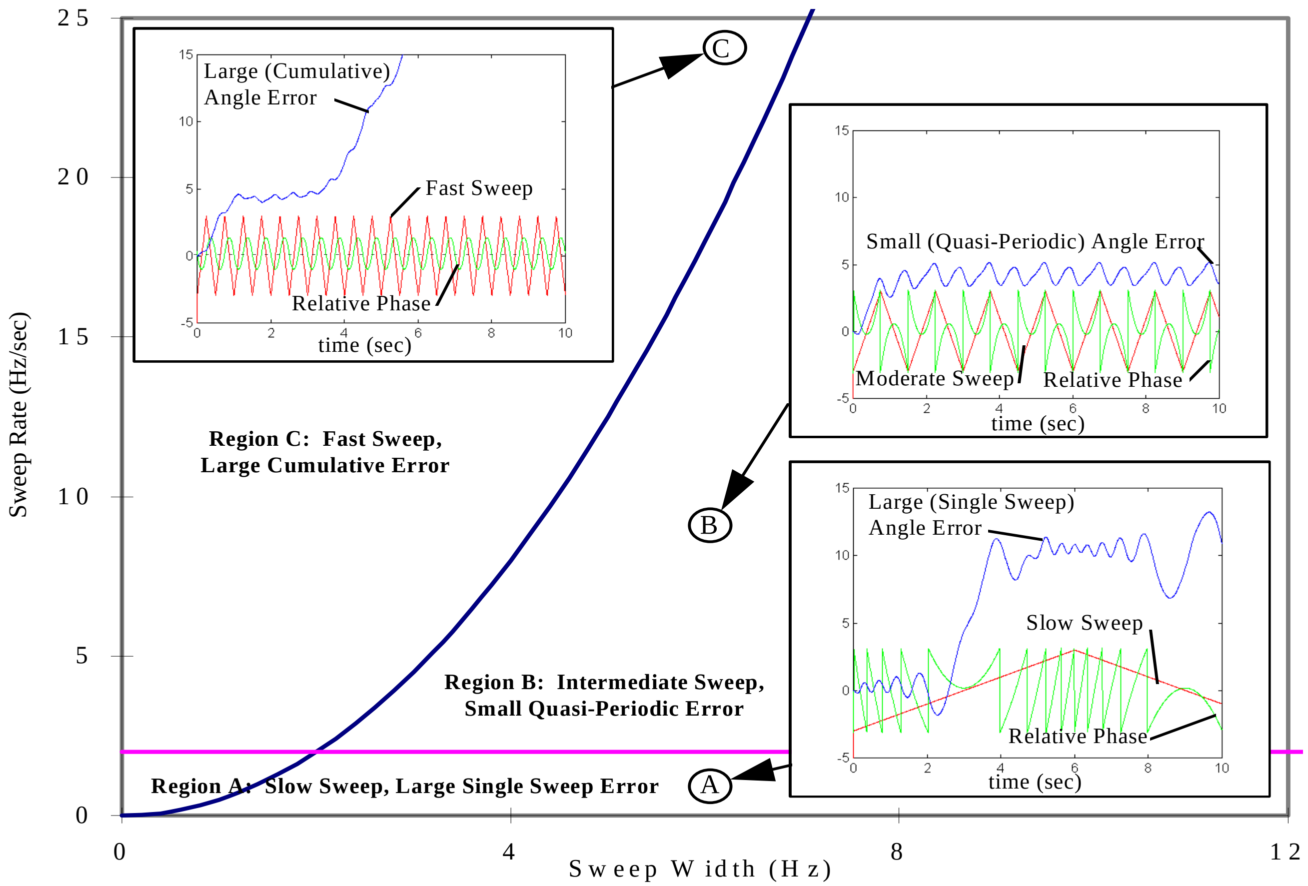

Figure 5. Three JESSS Generated Traces Of Seeker Angle Tracking Error, One In Each of the Slow Sweep, Moderate Sweep and Fast Sweep Regions (Also shown in each of the individual graphs are traces of Swept Audio frequency and phase relative to the seeker's lobing frequency and phase)

Point “B” in Figure 5, which is in the intermediate sweep, small quasi-periodic error region identified in the static analysis, shows the generation of less than 5 degrees of angle error as predicted in the static analysis.

Point “C” in Figure 5, which is in the fast sweep, large cumulative error region identified in the static analysis, shows the generation of greater than 15 degrees of angle error and that this error accumulates over a number of periods of the Swept Audio ECM’s sweep cycle.

Offset Fast Sweep, Large Cumulative Error

The previous simulation results were generated under the condition that the Swept Audio frequency sweep was symmetric above and below the LORO reference frequency (from -3.00 Hz to +3.00 Hz). For real operational equipment this condition is expected to be a rare occurrence. The case of an offset in the minimum and maximum Swept Audio frequency sweep about the radar’s reference frequency is a more likely occurrence. Typical simulation results for fast sweep Swept Audio (24 Hz/sec) using an offset sweep frequency relative to the LORO reference are shown in Figure 6 below (in the case shown the sweep range relative to the LORO frequency was from -2.80 Hz to +3.00 Hz).

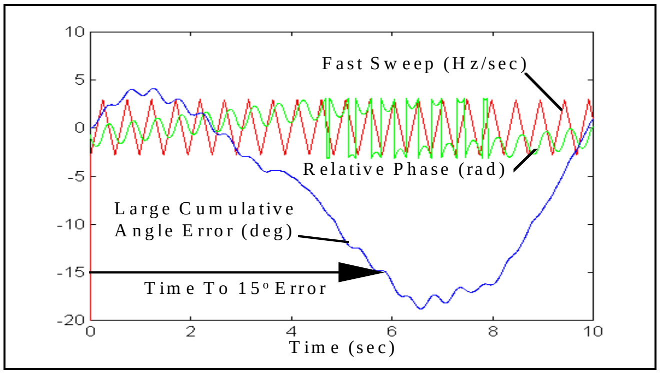

Figure 6. Large Cumulative Angle Error (Asymmetric Fast Sweep)

The asymmetric Fast Sweep trace in Figure 6 includes the sweep offset (-2.80 Hz to 3.00 Hz) which was used in setting the upper and lower limits of the Swept Audio frequency sweep. The Relative Phase trace shows that the mean phase of the Swept Audio modulation relative to the seeker’s lobing reference migrates linearly with time. The slope of this phase migration is equal to the mean frequency offset between the Swept Audio modulation and the seeker’s lobing reference. The Large Cumulative Angle Error trace in Figure 6 indicates that 15 degrees of angle tracking error was generated in less than 6 seconds.

Swept Audio ECM Effectiveness

The Swept Audio jamming effectiveness conditions and simulation results discussed above were derived on the assumption that the jamming signal was much larger than the ship target echo signal, a condition which holds when Swept Audio jamming modulation is applied subsequent to the successful application of Range Gate Pull-Off (often also called Range Gate Steal). There is, of course a time delay before angle error generation from Swept Audio which is associated with this RGPO phase of the engagement cycle.

It is also expected that, if slow sweep Swept Audio jamming is used with a large sweep width, it may take a relatively long period of time for the frequency of the ECM modulation to match the LORO reference frequency. This is probably undesirable for operational success. Hence, it is worthwhile to consider “Time To Generate Large Angle Errors” as one potentially significant measure of the effectiveness of the jamming technique and associated parameters.

Time to Generate Large Angle Errors

To demonstrate the impact of various combinations of Swept Audio sweep rates and sweep widths (imposed after successful Range Gate Pull-Off) on the time required to generate large angle errors, numerous simulation runs were carried out. In these runs the mean Swept Audio offset frequency relative to that of the scan reference was 0.1 Hz and the bandwidth of the angle servo was 1 Hz. The output parameter which was measured in these simulation runs was the time required for the antenna angle error to reach 15 degrees. The angle of 15 degrees was chosen since it represents the seeker antenna being driven off the ship target by several antenna beamwidths. This implies antenna tracking in the sidelobes, with its attendant attenuation of the signal as received by the seeker. It also implies substantial knowledge about the character of the seeker’s angle discriminator curve in the sidelobes. This is not a primary seeker design consideration and may vary substantially from equipment to equipment, even within a specific seeker type. A time limit of 20 seconds was taken to be representative of an operationally significant time. With the speed and detection ranges associated with some operational anti-ship missiles, 20 seconds represents a significant portion of the time which is available for a countermeasure response in anti-ship missile defence.

A three dimensional surface plot showing “Time To Reach 15 Degrees Angle Error” as a function of Swept Audio sweep rates and sweep limits was generated. The results of these simulation trials (for those combinations of Swept Audio sweep rate and sweep width which gave rise to 15 degree angle errors in less than 20 seconds) are shown in Figure 7 below.

The three regions of “Slow Sweep, Large Error”, “Fast Sweep, Large Error” and “Small Quasi-Cyclical Error” which were analyzed previously (and shown in Figure 4) are superimposed on the three dimensional simulation results in Figure 7 and are seen to provide a reasonable match. This match would indicate that the analysis and the simulation are self consistent and provides some measure of validation for the simulation.

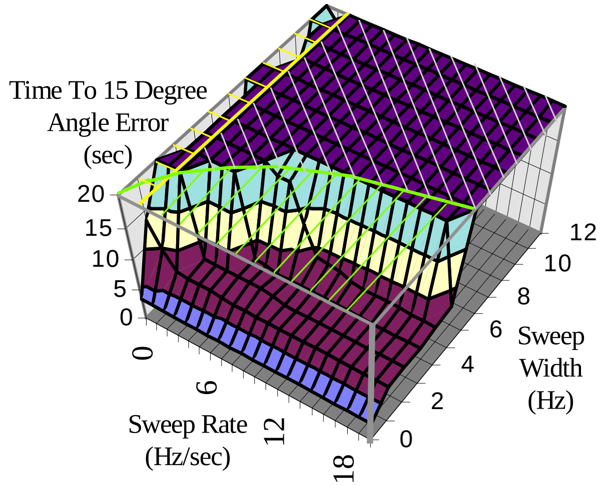

Figure 7. Regions of Swept Audio Effectiveness as a Function of Sweep Width and Sweep Rate

The results shown in Figure 7 indicate the combinations of Sweep Audio sweep rate and sweep width which cause large seeker angle tracking errors in less than 20 seconds. Results not included in Figure 7 are those for which longer than 20 seconds were required to attain an angle error of 15 degrees. Figure 7 provides a useful tool for choosing Swept Audio sweep rate and sweep width to successfully cause large angle tracking error in a LORO seeker. The successful combinations of sweep rate and sweep width are primarily dependent on the threat seeker's angle servo bandwidth.

Missile Miss Distance

The static analysis indicates that large seeker angle tracking errors do not necessarily lead to large missile miss distances. To demonstrate the impact of various Swept Audio sweep rates and sweep limits on the Missile Miss Distance numerous simulation runs were carried out using the combinations of sweep rate and sweep limit which were used in the plots for Time to Generate Large Angle Error. A simple engagement scenario was used in these simulation runs. The missile's cruise velocity used was 270 m/sec (high subsonic). The missile lock-on range was approximately 4 Km from the ship. The Swept Audio sweep asymmetry was 0.1 Hz, with all other parameters being as used in the generating the Time To Large Angle Tracking Error results of Figure 7.

A typical missile flight profile in plan view is shown in Figure 8. In this figure the weave in the missile trajectory is a result of the relative phase of the asymmetric sweep of the Swept Audio signal (relative to the seeker's lobing reference frequency) migrating several times through the angle servo's positive and negative antenna drive directions during the flight of the missile.

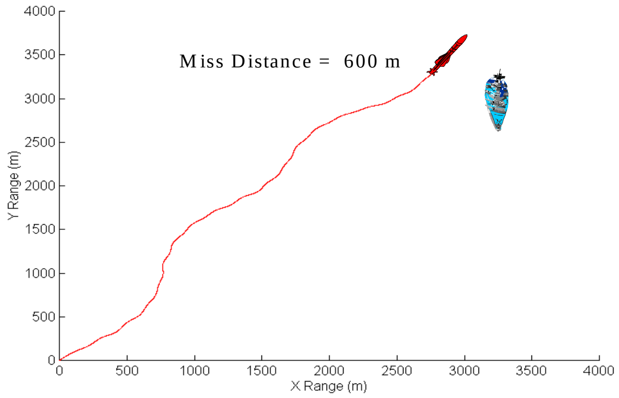

Figure 8. Typical Sea Skimming Missile Fly-out Plan View Trajectory With Miss Distance

A three dimensional plot of Missile Miss Distance as a function of various combinations of Swept Audio ECM sweep rate and sweep limits is shown in Figure 9

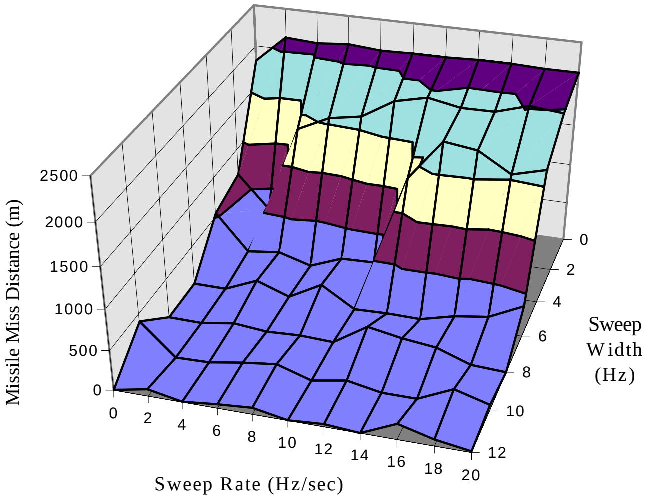

Figure 9 Missile Miss Distance As a Function Of Swept Audio ECM Sweep Width and Sweep Rate

Conclusions

From the above analysis and simulation results it is indicated that, using the Swept Audio ECM technique, large Missile Miss Distances can be generated in a subsonic, sea skimming anti-ship missile which uses the LORO angle tracking technique. However, substantial engineering knowledge underlies the selection of appropriate Swept Audio ECM parameters (particularly Sweep Rate and Width) which give rise to large Missile Miss Distances. The determination of appropriate ECM parameter combinations is directly related to two key seeker parameters:

- the seeker's LORO reference frequency, and,
- the seeker's angle servo bandwidth.

The static analysis and dynamic simulation results indicate that the optimum Swept Audio jamming waveform parameters are generally as follows:

- the sweep rate exceeds 10 Hz/sec,
- the sweep is approximately centered on the LORO reference scan frequency with a mean offset of less than one half of the angle servo bandwidth of the radar; and,
- the sweep width is less than 5 Hz.

With the above Swept Audio ECM parameters, angle tracking errors of the order of several antenna beamwidths should be generated in the radar or seeker within five to ten seconds of commencement of jamming and, more importantly, missile miss distances of many hundreds, even thousands, of meters can be created.

This paper, while specific to the Swept Audio ECM and LORO seeker engagement, indicates that engineering analysis methods and tools can be applied to the evaluation of the effectiveness of electronic countermeasures. Such evaluation methods and tools are not suggested for replacement of Hardware-In-The-Loop field trials, but rather as a supplement to such trials to assist in focusing on critical parameter combinations in pre-trial preparation and in analysis of data in post-trials report preparation.