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Naval threat and countermeasures simulator

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ABSTRACT

A Naval Threat/Countermeasures Simulator (NTCS) capable of modelling the engagement between a naval ship and an infrared (IR) guided anti-ship missile is presented. The NTCS program is built upon previously developed naval ship signature software entitled Ship Infrared Simulator (SHIPIR) which produces 3-D graphical imagery of a ship in its sea/sky background for a wide range of operational, atmospheric, observer and spectral conditions. By adding models for an IR seeker head, missile flight dynamics and commonly deployed ship IR countermeasures, NTCS can effectively assess the IR susceptibility of naval platforms through calculation of target lock-on ranges and hit/miss distances. Current and future naval ships can be analyzed for IR suppression effectiveness in such areas as hot surface visibility, low emissivity paints and engine exhaust signature suppression. The various deployable countermeasures (flares, smoke screens, washdown and ship manoeuvres) and missile/seeker heads modelled in NTCS permit the assessment of ship survivability and development of tactics and countermeasures necessary to provide adequate IR protection. A description of NTCS is provided with emphasis on the missile and countermeasure models and overall engagement simulation. Some sample simulations to date on the Canadian DDH-280 tribal class destroyer are presented.

Keywords: naval threat, infrared simulation, countermeasures, naval engagement.

1. INTRODUCTION

Infrared (IR) guided missiles represent a major threat to military platforms, whether on land, at sea or in the air. With the development of more sophisticated imaging seeker technologies, this threat will only increase in the near future. Consequently, decoying such threats is more and more difficult as advanced imaging seekers are increasingly capable of distinguishing between decoy and target IR signatures.

To design adequate countermeasures for these advanced threats, one must have a modelling tool capable analyzing the intricate interactions between these two competing technologies. One must first predict the IR signatures of the target, its countermeasures and background and render these results to the high degree of resolution typical of IR imaging missiles, including the effects of atmospheric attenuation and background clutter. Secondly, the seeker head, its optics and image processing systems must be modelled in conjunction with the missile's flight dynamics and guidance control to accurately simulate the missile

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response to such IR imagery. Finally, these components must all be integrated into an interactive 3-D graphics environment to carry out the missile/target engagement.

The Naval Threat/Countermeasures Simulator (NTCS) is one such tool, using a previously developed Ship Infrared Simulator (SHIPIR) model[1,2,3] capable of simulating infrared images of ships at sea. NTCS has integrated SHIPIR with new models for IR countermeasures, an IR imaging seeker head, missile flight dynamics and missile guidance control to create a novel fully-integrated 3-D target/threat engagement simulator. The first part of this paper describes the overall design of NTCS. The remaining sections describe the seeker head model, missile flight dynamics and IR countermeasures in detail. Finally, the 3-D engagement simulation environment is illustrated with example outputs generated for a base-line engagement scenario.

2. NTCS OVERVIEW

NTCS is divided into four main categories: target, threat, countermeasures and engagement, as shown in Figure 1. Each category consists of various individual component modules which interact with each other as well as with those of other categories to form the principle data flow of the program.

2.1 Target modules

The target modules consist of all previously developed SHIPIR modules. *Characterize Ship* refers to the definition of all target parameters, including 3-D geometry, thermal and radiative material characteristics, user-specified thermal boundary conditions and the calculation of surface-to-surface radiation view factors. The *Simulation Conditions* module gathers all necessary inputs to simulate a specific IR scene. The *Background Model* computes the direct solar, direct atmospheric and total sea irradiances associated with a full hemispherical view of the background. The *Ship Thermal Model* calculates the ship surface temperatures using a steady-state algorithm based on both pre-defined and user-defined thermal boundary conditions (solar heating, wind convection, internal heat sources, etc). The *PLUMIR Model* computes the exhaust gas centre-line trajectory, temperature distribution and gas concentration for each exhaust stack, all of which are required to render an IR image of the exhaust gas plumes. The *IR Imaging* module integrates all the IR scene components into a single radiance-rendered image as viewed by the observer.

2.2 Threat modules

The threat modules consist of those components related to the missile including the seeker head, missile flight dynamics and control modules. Similar to the target, *Characterize Missile* refers to the input and selection of all missile parameters such as type (sea-skimming, rapid-descent, air-to-surface), their associated flight dynamics parameters and various seeker head parameters describing the optics, signal processing, detection/tracking algorithms and automatic gain control. The *IR Seeker Image Update* module refers to the generation of the seeker's field-of-view using the various resources of the *IR imaging* module. This module produces various seeker head-equivalent images. The *Seeker Head Model* processes the seekers image to identify and lock-on to any targets in the field-of-view. Once a target has been identified, it maintains target track by passing the lock-on coordinates to the *Missile Flight Dynamics/Control Model* which, in turn, simulates the response of the missile as it changes heading in order to maintain target lock. These together provide the input to the *Viewer Position and Direction Update Module* which directs both the *IR Imaging* and *IR Seeker Image Update* modules in the next simulation time frame.

2.3 Countermeasure modules

Starting with the *Characterize Countermeasures* module, this category of modules simulates any tactical decoy response to an incoming IR threat. The user specifies what type of countermeasures are available and the various configuration parameters associated with each countermeasure. The *Countermeasure Model* refers to the run-time module for each type of countermeasure, which simulates the IR countermeasure as it occurs in the IR Image.

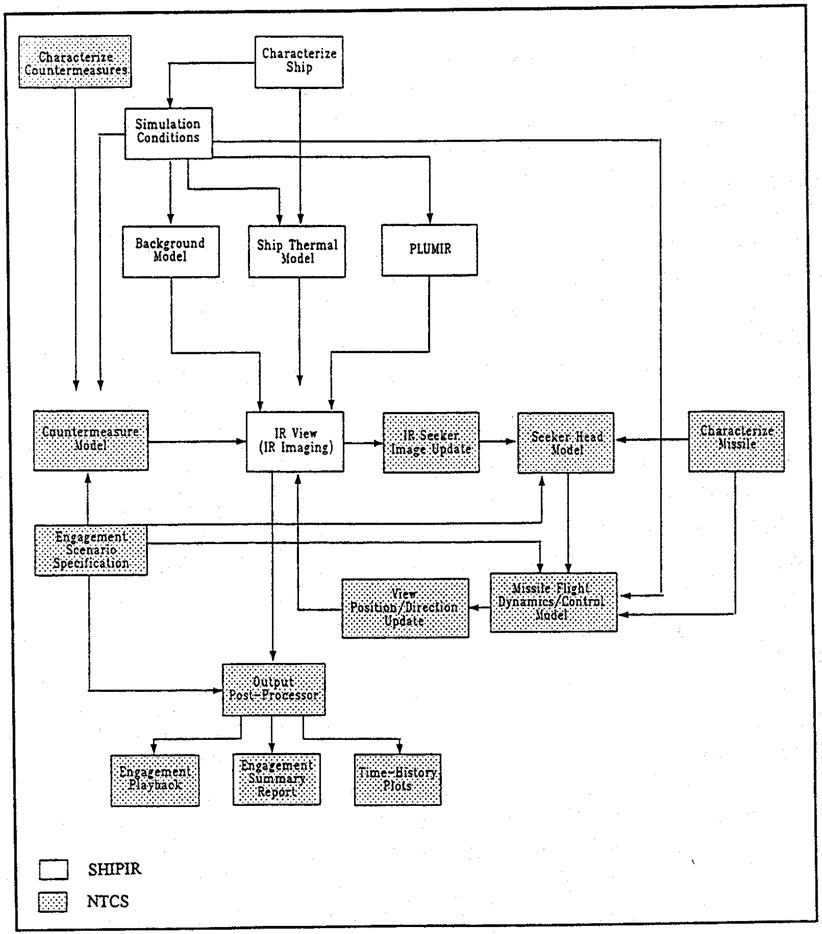

Figure 1: NTCS component flow diagram.

2.4 Engagement modules

This category of modules are responsible for the interactive engagement of all the above components before, during and after an NTCS simulation. The *Engagement Controller* handles the input specification of an NTCS simulation scenario via selection of pre-defined countermeasures (*Characterize Countermeasures*) and threats (*Characterize Missile*) to schedule the engagement scenario. Events are range-specified so that the user selects which of the various IR countermeasures on-board are to be deployed at what distance. With this schedule, the *Engagement Controller* proceeds with execution of the engagement through calls to the various component models in the proper sequence and with the appropriate data taken from each of the characterization modules. Following the engagement, the user can view any of three output options in the *Post-Processor* module. An interception point is calculated by representing the ship as a semi-ellipsoid with the missile intercepting it at some angular coordinate. If the simulation ended as a result of the missile flying out past the target, the miss distance is calculated. A *Summary Report* is generated for each engagement simulation consisting of all input variables defining the scenario and a table of output variables calculated during execution of the engagement. The user can also view the output as a *Time-History Plot* or using the *Engagement Playback* feature. The playback feature simply redraws the *IRView* and *IR Seeker* images at each simulation time frame based on the resultant missile, target and countermeasure stored data.

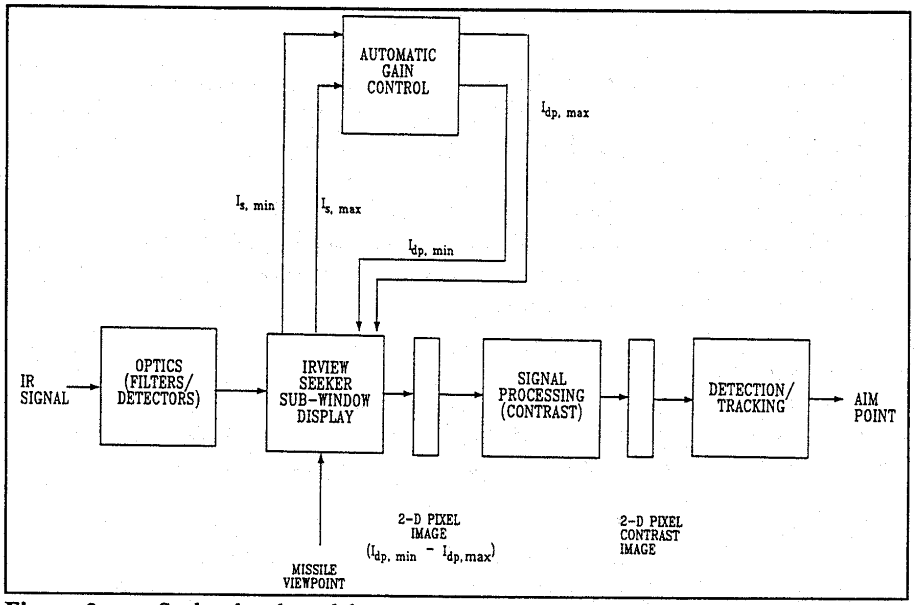

Figure 2: Seeker head model components.

3. SEEKER MODEL

The seeker head model has been devised based on the IR image generation capabilities of the *IRView* module, as illustrated in Figure 2. The most characteristic component of any IR imaging seeker head model is its detection and tracking algorithm. As taken from the IR E/O Handbook[4], the most common of theses algorithms are the following:

- binary centroid
- intensity centroid
- threshold intensity centroid
- fixed reference correlation
- adaptive reference correlation
- multi-mode

However, each missile has its own unique methods of minimizing the inherent deficiencies in these tracking algorithms. Some examples are the largest area centroid tracking, horizon/sky rejection and false alarm pulse detection. In order to accommodate all these various versions of the seeker, the model must be flexible enough to allow implementation of any specific seeker. Currently, only the first three centroidal imaging type seekers are implemented in NTCS which will serve as a template for later seeker models.

3.1 Optics

Optics refers to the lenses, filters and detectors which are located between the raw source IR image and the digital signal produced by the detector array. These devices are modelled using three basic design parameters[5]. A band transmission factor, τ_{opt}, which accounts for the attenuation caused by the lenses and filters. The detector array size (*mxn*) which is determined from the seeker field-of-view (FOV) requirements. The FOV is established by the length and height of the anticipated target at the minimum range of manoeuvrability (R_{min}), beyond which the missile cannot manoeuvre over the FOV to maintain lock. The number of detectors is based on the instantaneous field-of-view (IFOV) established by the anticipated minimum target size at the maximum range of detection (R_{max}). Finally, the detectivity of the seeker will depend on the detector material which varies with the IR waveband. Because of wide variations in detectivity for the same material and other variations imposed by the operating environment, NTCS uses only a single average detectivity ($\bar{D}^*_{hemi}$).

3.2 Seeker sub-window display

The seeker sub-window display consists of the raw IR image generated by *IRView* and corrected for any optical effects, seeker noise and intensity range-clipping by the automatic gain control (AGC).

3.3 Signal processing

The signal processing module is responsible for converting the raw IR image into contrasted and/or thresholded intensity image based on the particular seeker detection/tracking algorithm used. Two key parameters in signal processing are the frame rate (f_T) and the noise equivalent irradiance (NEI). The frame rate defines the overall manoeuvrability of the missile, based on the maximum allowable miss distance at the maximum missile acceleration and minimum target range. Its value not only establishes the overall simulation time step but is also used in calculating the seeker's NEI.

The NEI is used to render the raw IR image in the seeker sub-window display:

$$i_k = i_{(x,y)} = \frac{I_{p(x,y)}}{NEI}, \quad 1<k<Np \tag{1}$$

where i is an index to an irradiance colour map. In this manner, the NEI establishes the maximum resolution of the seeker image. All imagery is stored using the irradiance colour map to eliminate the need for converting between irradiance and voltage. The detectivity or irradiance to voltage relation is inherently implied in the definition of the NEI.

From, the raw IR image a contrasted IR image is computed using methods such as a simple average contrast:

$$\begin{aligned} \bar{i} &= \frac{1}{N_p}\sum_{k}^{Np} i_k \\ i_{c,k} &= \begin{cases} 0 & , \; i_k \le \bar{i} \\ (i_k - \bar{i}) & , \; i_k > 0 \end{cases} \end{aligned} \tag{2}$$

Thresholding further modifies the imagery to eliminate any low intensity signatures:

$$i_{c,k}^{T} = \begin{cases} 0 & , \; i_{c,k} < i^{T} \\ i_{c,k} & , \; i_{c,k} \ge i^{T} \end{cases} \tag{3}$$

In this way, i^T represents a signal-to-noise threshold ratio (SNT) which directs the tracker only to hot spots above SNT times the NEI. These are only examples of various signal processing schemes. Future versions of NTCS will implement more sophisticated signal processors as they become available.

3.4 Detection/tracking

Detection of a target is normally specified through a signal-to-noise ratio (SNR≈5) to eliminate any possible detector noise and ensure that an actual target has been acquired. Based on the detection of one such pixel value or that of multiple pixels, the detection algorithm would normally notify the signal processor to carry out centroidal calculations on either the contrasted or the threshold contrasted intensity values:

$$x_c = \frac{\sum_{k}^{Np} x_k \, i_{c,k}}{\sum_{k}^{Np} i_{c,k}} \qquad y_c = \frac{\sum_{k}^{Np} y_k \, i_{c,k}}{\sum_{k}^{Np} i_{c,k}} \;, \quad \begin{cases} 0<x_c<m-1 \\ 0<y_c<n-1 \end{cases} \tag{4}$$

These centroid coordinates are used to calculate the track angle for the missile guidance control system:

$$\Delta\theta_{LOS} = \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \\ \Delta\theta_z \end{pmatrix} = \frac{\cos^{-1}[c_z]}{\sqrt{c_x^2 + c_y^2}} \begin{pmatrix} -c_y \\ c_x \\ 0 \end{pmatrix} \quad , \quad \begin{cases} c_x = \dfrac{x_c - \dfrac{(m-1)}{2}}{m-1} \cos\left[\dfrac{\theta_{FOV,x}}{2}\right] \\ c_y = \dfrac{y_c - \dfrac{(n-1)}{2}}{n-1} \cos\left[\dfrac{\theta_{FOV,y}}{2}\right] \\ c_z = \sqrt{1 - c_x^2 - c_y^2} \end{cases} \tag{5}$$

where (c_x, c_y, c_z) are the aim point cosines and $\Delta\theta$ is the track angle in radians. The $\theta_{FOV,x}$ and $\theta_{FOV,y}$ are the seeker horizontal and vertical FOV angles, respectively.

3.5 Tracking gates

In order to exclude the effects of non-target background clutter and countermeasures, a tracking gate can be applied about the target image after lock-on is achieved. The tracking gate size can be either fixed or adaptive. A fixed tracking gate is defined as a percentage of the seeker's FOV. An adaptive tracking gate is sized slightly larger than the target at initial acquisition and is updated with missile-target range calculations by the seeker based on a user-specified anticipated target size.

3.6 Automatic gain control

The purpose of the automatic gain control (AGC) is to limit the seekers intensity range so that the image is neither saturated nor dominated by a single high intensity spot (ie., sun or flare). To increase the seeker image intensity range as the missile approaches the target, a low pass filter is used on the maximum raw IR image intensity, $I_{s,max}$:

$$I_{p,\max}(t+\Delta t) = I_{p,\max}(t) + \frac{I_{s,\max}(t) - I_{p,\max}(t)}{2^{\tau_{agc} f_T}} \tag{6}$$

A simple gain limiter on $I_{p,max}$ can ensure that a very hot spot does not cause the AGC to drown out the target.

4. MISSILE MODEL

The NTCS missile model is based on a generalized 6 degree-of-freedom (DOF) flight dynamics model which has been adjusted to fit the various flight modes and engagement characteristics of an anti-ship missile. Often the 6 DOF's can be reduced to that of specific anti-ship missile types (sea-skimming and rapid-descent - 4 DOF, air-to-surface - 6 DOF). When the missile begins its approach in NTCS, it is assumed to have been launched some time before and is travelling at a constant speed. For marine engagements, the missile speed will be somewhere near the speed of sound (≈341 m/s). Although there can be considerable change in mass of the missile due to long-term fuel consumption, this variation over the duration of the engagement can generally be neglected for anti-ship missiles.

4.1 Track angle error

Based on the track angle calculated by the seeker model, the track angle error or angular velocity of the line-of-sight is calculated between time frames as:

$$\Delta\dot{\theta}_{LOS} = \begin{pmatrix} \Delta\dot{\theta}_{LOS_x} \\ \Delta\dot{\theta}_{LOS_y} \\ \Delta\dot{\theta}_{LOS_z} \end{pmatrix} = \begin{pmatrix} \dfrac{\Delta\theta_{LOS_x}(t) - \Delta\theta_{LOS_x}(t-\Delta t)}{\Delta t} \\ \dfrac{\Delta\theta_{LOS_y}(t) - \Delta\theta_{LOS_y}(t-\Delta t)}{\Delta t} \\ \dfrac{\Delta\theta_{LOS_z}(t) - \Delta\theta_{LOS_z}(t-\Delta t)}{\Delta t} \end{pmatrix} \tag{7}$$

and passed on to the missile guidance module.

4.2 Guidance control

The missile guidance system utilizes proportional navigation to command the missile to turn (accelerate) at a rate proportional to the angular velocity of the line-of-sight:

$$a_{m,d} = K_p \, \Delta\dot{\theta}_{LOS} \, V_m = K_p \begin{pmatrix} \Delta\dot{\theta}_{LOS_x} \\ \Delta\dot{\theta}_{LOS_y} \\ \Delta\dot{\theta}_{LOS_z} \end{pmatrix} V_m = \begin{pmatrix} a_{m,d_x} \\ a_{m,d_y} \\ a_{m,d_z} \end{pmatrix} \tag{8}$$

The desired value of angular acceleration, $a_{m,d}$, must be limited to the maximum turning rate of the missile, $a_{m,max}$.

4.3 Flight dynamics

The purpose of the flight dynamics model is to duplicate the response of the missile to the changes in direction demanded by the seeker tracking algorithm:

$$\begin{aligned} \frac{a_{m,a_x}}{a_{m,d_x}} &= \frac{1}{s^2 + 2\zeta_{sh}\omega_{n,sh}s + \omega^2_{n,sh}} \\ \frac{a_{m,a_y}}{a_{m,d_y}} &= \frac{1}{s^2 + 2\zeta_{dr}\omega_{n,dr}s + \omega^2_{n,dr}} \\ \frac{a_{m,a_z}}{a_{m,d_z}} &= \frac{1}{s + \tau_{rs}} \end{aligned} \tag{9}$$

where $a_{m,a}$ is the actual missile acceleration achieved in the pitch (x), yaw (y) and roll (z) principle axes. The *sh*, *dr* and *rs* terms refer to the spiral divergence, dutch roll and roll subsistence flight mode characteristics which govern the missile's flight. The solution and integration of the above transfer functions are used to establish a new missile velocity vector and position at the next engagement time frame.

5. COUNTERMEASURE MODELS

The NTCS target countermeasures are classified into two categories: those which apply before the engagement (ie., target infrared suppression system (IRSS) and washdown) and those that occur dynamically during the engagement.

5.1 Ship IRSS

Ship IRSS refers to the infrared suppression systems incorporated in the target design which become an inherent part of the target IR model. These would include exhaust gas and hot metal suppression, low emissivity paints and thermal insulation. Their implementation is transparent to the user at NTCS run-time since they have been modelled off-line using various modules in SHIPIR.

5.2 Target washdown

Similar to ship IRSS, target washdown is an NTCS option which presets the thermal and IR condition of the target. The user simply specifies a uniform temperature and emissivity to be applied to all external ship surfaces which are then used in the target radiance calculations of the *IRView* module.

5.3 Target smoke screens

A target smoke screen is modelled as a 2-D ellipse applied to the IR image according to a user-specified size, maximum transmission factor, rise-time, and decay constant. The 3-D coordinate position of the cloud relative to the ship must be specified which is assumed to remain constant with respect to the earth fixed reference frame.

5.4 Flare decoys

Flare decoys are defined by a source area, maximum intensity, rise-time, and burn-time. Similar to the smoke screen, flares are applied to the 2-D IR image as varying intensity spheres. The 3-D coordinate position of the flare relative to the ship at activation is specified but with specified lift and drag coefficients, the flare is modelled to drift with the wind and fall with gravity.

5.5 Target manoeuvres

The target motion relative to its initial position can be specified in a number of ways. Either by specifying a constant speed and constant heading, a series of speeds and headings to be interpolated with time or by a 3-D path to be followed with time. The selections and entries made here should reflect the targets real manoeuvrability.

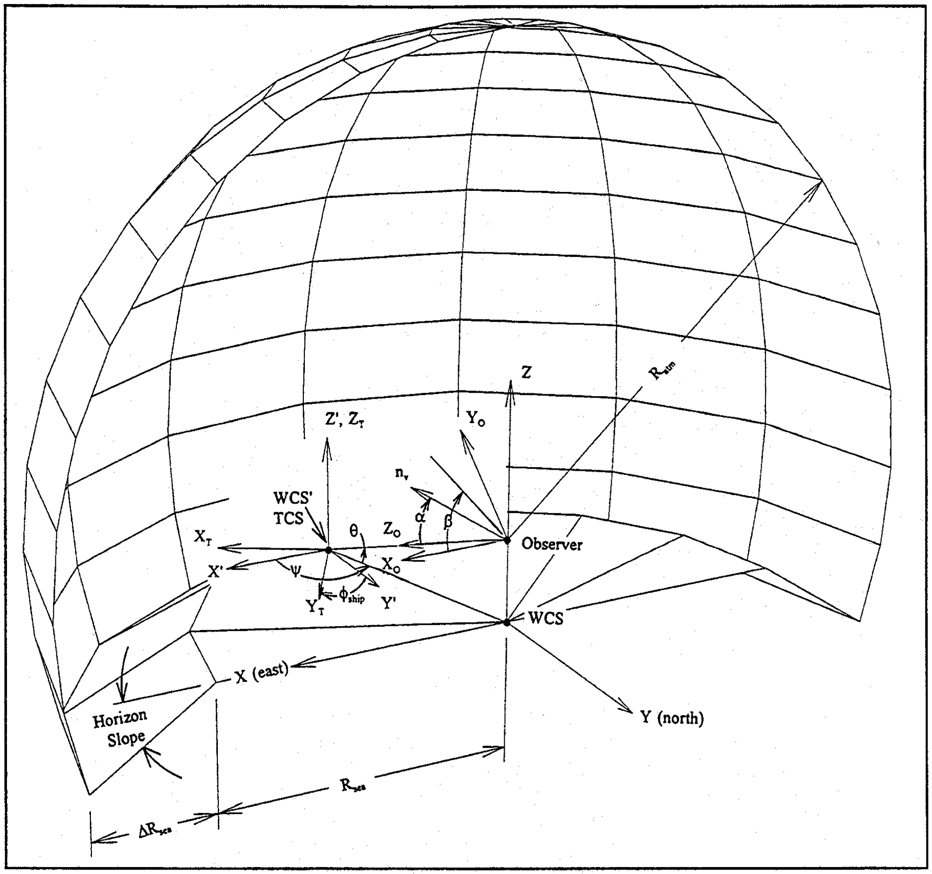

Figure 3: *IRView* 3-D coordinate geometry.

6. ENGAGEMENT SIMULATION

6.1 Scene components and relative motion

The 3-D coordinate geometry used for the target, background, and missile (observer) is illustrated in Figure 3. The atmospheric shell is generated as a radius (R_{atm}) about the observer's position. The origin of the world coordinate system (WCS) is located at the sea surface directly below the observer's position and moves with the observer. North and east are oriented as shown in the figure. The sea surface is modelled as a flat disk of radius, R_{sea}, about the world coordinate system origin. Curvature of the sea surface is modelled as a sloped extension of the sea surface radius (ΔR_{sea}). The target coordinate system (TCS) is defined by translating the world coordinate system to the target's location (WCS'), specifying target heading (ϕ_{ship}) in degrees east of north and observer azimuth (ψ) in degrees north of east. Observer elevation angle (θ) is defined with reference to the target coordinate system origin. The observer's look vector (n_v) can be shifted from the line of sight between the observer and the target by the application of twist (β) and offset (α) angles.

6.2 Sample engagement

In order to illustrate some of the key features of NTCS, this section will run through a hypothetical engagement scenario between an unsuppressed ship equipped with flare decoys and an IR-guided anti-ship missile. The seeker in this scenario utilizes a binary-centroid detection/tracking algorithm with no countermeasure rejection capability.

Figures 4 through 7 show a succession of IRView-driven graphics output screens as the simulation progresses. The simulation starts with the missile at a distance of 20 km from the target and heading in the direction of the target, see Figure 4. At this stage, the seeker is scanning its FOV in search of a target. The three sub-windows inset at the bottom of the image represent the seeker's FOV at various stages of signal processing. The sub-window on the right shows a pixel-rendered image of the scene in the seeker's FOV featuring automatic gain control and the introduction of noise into the signal. The centre sub-window shows the image in the seeker's FOV with the average background intensities removed by contrasting. The left sub-window shows the scene after a threshold has been applied to the contrasted image. At 20 km, with this particular seeker, the signature of the target occupies too small a portion of the seeker's FOV and is lost with the background during processing. Consequently, no lock is achieved and the circle representing the seeker's aim coordinates remains at the centre of the left seeker sub-window display.

Figure 5 shows the seeker locked on to the target at a range of 10 km. The aim point circle in the left sub-window moves to indicate the lock-on coordinates and the missile heading is adjusted accordingly. At a range of about 7 km, a flare decoy is deployed by the target. Figure 6 is a snap-shot at a range of 6.5 km. The addition of the flare decoy in the scene has caused the seeker's tracking algorithm to calculate new lock-on coordinates away from the target's centroid. Again, the missile heading is adjusted to maintain a target track.

Figure 7 shows the engagement at a range of 3 km. At this point the signature of the flare has caused the seeker's gain to be sufficiently lowered such that the target has disappeared along with the background during processing. The seeker is now locked on to the flare and will not strike the target. The engagement controller stops the simulation as the missile flies out past the target an displays the miss distance. Had the flare not successfully seduced the seeker, the simulation would have stopped as the missile intercepted the target and the hit location coordinates would have been displayed.

7. CONCLUSIONS

The NTCS model currently under development is a fully interactive 3-D graphical environment for naval IR threat and countermeasure simulation. It will be used in the future to assess the impact of both target IRSS and the deployment of decoys on the survivability of ships. It has been shown how models of the naval target and background signature (SHIPIR), an IR imager seeker head, missile flight dynamics and various IR countermeasures have been integrated into one simulation environment. NTCS could easily be extended to ground and air platforms by simply replacing the sea background with a terrain background model and incorporating the appropriate ground-to-ground and ground-to-air missile models.

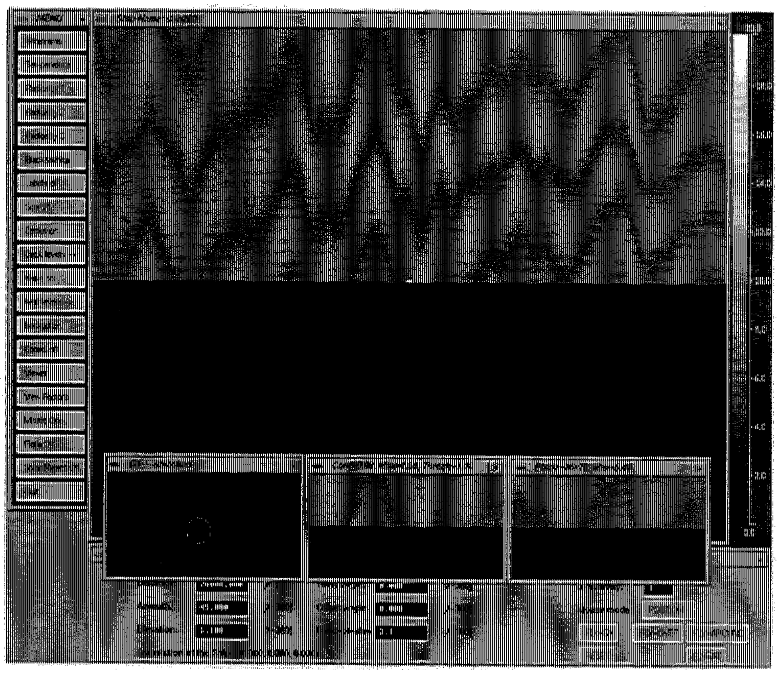

Figure 4: Hypothetical engagement at 20 km.

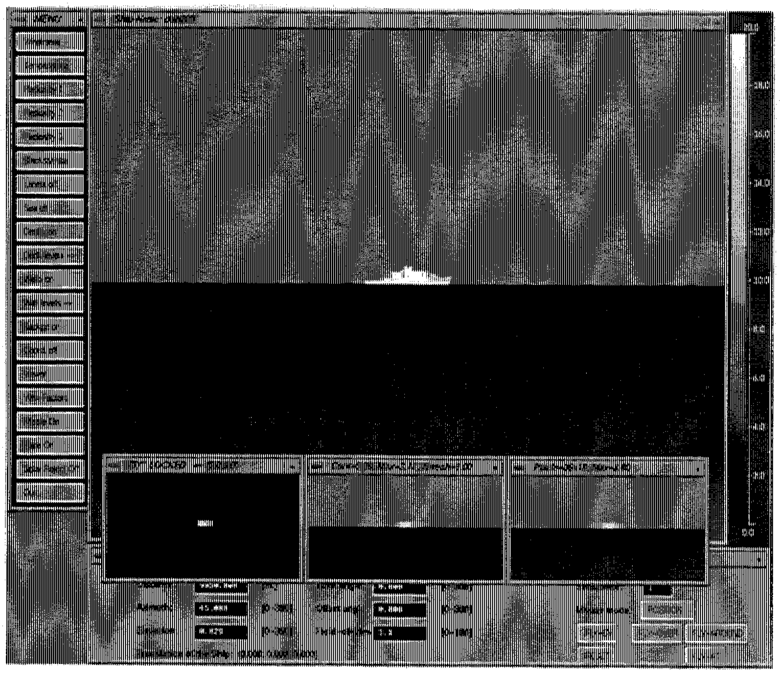

Figure 5: Hypothetical engagement at 10 km.

Figure 6: Hypothetical engagement at 6.5 km.

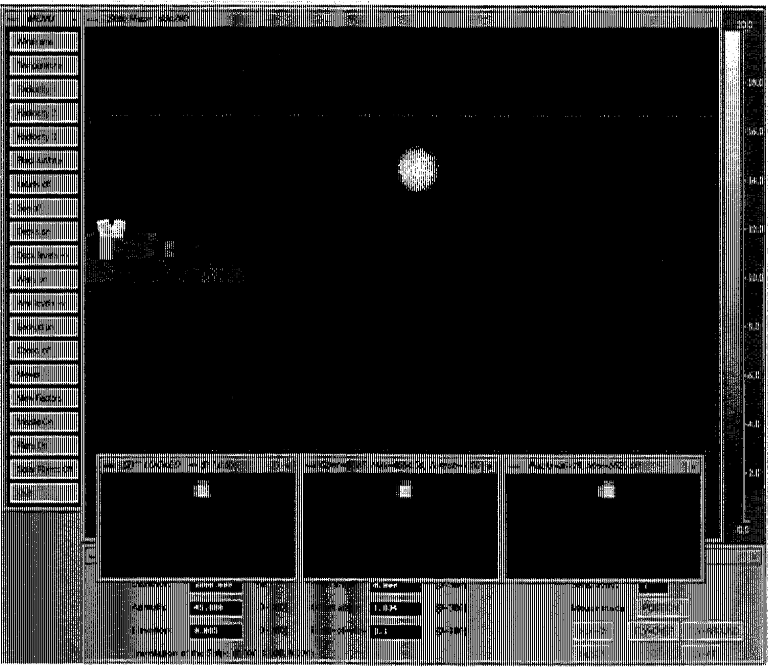

Figure 7: Hypothetical engagement at 3 km.

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