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Using SeaRad and MODTRAN to Improve the Ocean Background Model of the Electro-Optical Tactical Decision Aid (EOTDA)

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EXECUTIVE SUMMARY

OBJECTIVE

This report compares the predictions of ocean radiance and detection range from the unmodified Electro-Optical Tactical Decision Aid (EOTDA) version 3.0 with a modified version. The original EOTDA was developed by the U.S. Air Force, with only minimal attention applied to the complexities of the marine environment. The objective of this comparative study was to evaluate whether modifying the EOTDA would improve ocean background radiance predictions and ultimately improve detection range performance. The modifications involved replacing the original semi-empirical water background model with a rigorous geometric ocean radiance model, called SeaRad, and replacing the sky radiance model with the sky model from the MODTRAN 3 code.

RESULTS

A significant difference in behavior was noted between the original and modified EOTDA when comparing the zero-range ocean background temperature predictions of both models. The accuracy of the background temperature predictions was 57 percent better with the modified version than the original version for the cases studied. While background radiance and temperature predictions improved significantly, less improvement was realized in detection range predictions. The detection range error averaged about 17 percent in both the modified and original versions. The reason for this is that improvements in the background model tend to be diluted by atmospheric transmission loss and offset by errors in the target model. The greatest improvement was for the larger zenith angles and longer range cases.

RECOMMENDATIONS

Sufficient improvement was realized with the modified EOTDA employing the SeaRad ocean radiance model in combination with the MODTRAN sky radiance model that transition to the Navy fleet-ready version is recommended. All of the cases tested used zenith angles within 5 degrees of the horizon, because these were the cases for which detection range data were available. Future work should compare the two models with data having larger zenith angles. However, one would intuitively expect the near-horizon cases to be a more stressful test of the models and these data show the greater improvement as zenith angles increase. These modifications along with the improvements already implemented in the Navy EOMDA will make the decision aid more useful for marine applications.

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INTRODUCTION

The Electro-Optical Tactical Decision Aid (EOTDA) is a strike warfare mission planning tool developed by the U.S. Air Force throughout the 1980s. In the late 1980s, the U.S. Navy adapted the EOTDA to Navy applications by adding Navy sensors and targets. The EOTDA is currently installed in Navy fleet mission planning and support systems. Fleet experience with the EOTDA and previous studies have noted the need for improvement, especially for scenarios involving ocean backgrounds. In order to test and improve the ocean background model in the EOTDA, a modified version has been created that replaces the existing semi-empirical model with the SeaRad model that was developed by Space and Naval Warfare (SPAWAR) Systems Center, San Diego (SSC SD). The SeaRad model is a more rigorous solution based on the Cox-Munk wave-slope probabilities. During the April 1996 Electro-Optical Propagation Assessment in Coastal Environments (EOPACE) trials, data were collected to evaluate the effects of the SeaRad version of the EOTDA. Data were collected using a calibrated airborne infrared imaging system and an operational forward-looking infrared (FLIR) system against ship targets. A modified version of MODTRAN (Berk et al., 1989) containing the SeaRad model was used to correct the data for the influences of the atmosphere. This report uses these data along with the modified EOTDA to evaluate the effects of the SeaRad model on ocean background predictions under both clear and clouded skies. The results of this case study indicate the combined SeaRad and MODTRAN modifications improve performance enough to consider transition to fleet use. The reports detailing the modifications are included as an appendix.

BACKGROUND

The EOTDA is a strike warfare mission assessment tool for predicting the range performance of a pre-selected airborne sensor, target, and background for the forecast weather conditions. After the user inputs weather, target, background, and sensor information, the EOTDA predicts detection and lock-on ranges. The EOTDA output also includes thermal contrast information for the scene.

The EOTDA was originally developed for use on the IBM PC AT. In 1989, the U.S. Navy, under the direction of the Naval Research Laboratory, Monterey, CA (NRLMRY), adopted the U.S. Air Force EOTDA as a replacement for the outdated UFLIR program. NRLMRY added naval airborne FLIR sensors to the EOTDA sensor suite along with two ship targets, a Russian frigate (Krivak III) and a gunboat (R/V Pt. Sur). NRLMRY installed the EOTDA into the workstation platforms of the Tactical Environmental Support System (TESS) and the Tactical Automated Mission Planning System (TAMPS).

The EOTDA consists of three primary models: the sensor performance model, the atmospheric transmission model, and the target/background contrast model. These are depicted pictorially in figure 1. While the EOTDA predicts the performance range for several types of airborne sensors, including laser, night vision goggles, and long wave (8- to 12-micron) FLIR systems, this report focuses on the infrared FLIR performance.

The target-background contrast model has remained unchanged since the original EOTDA version 2.0 and is based on the Georgia Technology Research Institute computer model, TCM2. TCM2 is mainly a target model, so the selection of backgrounds is limited and the physics is considerably simplified. The TCM2 model was originally developed for the U.S. Air Force, so it is

not surprising that the attention to the water model is not as much as the U.S. Navy would have liked.
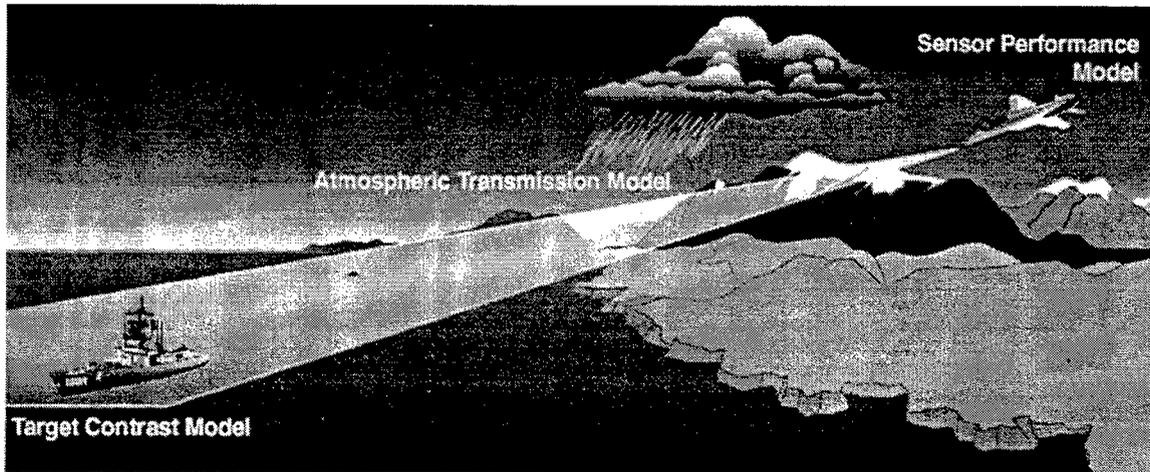
Figure 1. The EOTDA is a strike warfare decision aid consisting of three primary models: the sensor performance model, atmospheric transmission model, and target-background contrast model.

The atmospheric transmission model in the PC version of the EOTDA is a simplified, two-layer version of the LOWTRAN 7 (Kneiszys et al., 1988) code. NRLMRY has upgraded the transmission model in the Navy workstation version of the EOTDA to the full 33-layer version of LOWTRAN 7. They have also created a new graphical user interface and renamed the workstation version, EOMDA, for Electro-Optical Meteorological Decision Aid. The Navy PC version still contains the simplified transmission computer code and is used at many Naval Air Station facilities, while the workstation version in TESS and TAMPS contains the 33-layer code.

Since the sensor performance model relies on the Johnson criteria (Johnson, 1958) to transform the target critical dimensions and thermal contrast to detection range, one would expect the sensor performance model to be the primary source of prediction error. This is because of the inherent difficulties in making the Johnson criteria transformations and because of human performance differences in recognizing targets. However, experience has demonstrated the error often exceeds the expected 25 percent maximum allowed by the Johnson criteria when the EOTDA is tested under open-ocean or coastal marine scenarios. Validation tests conducted by NRLMRY (Dreksler et al., 1995) and SSC San Diego (McGrath, 1994) using marine target scenarios confirmed the need for an improved ocean radiance model. The U.S. Air Force also funded a study that investigated the background models. Their report (Shemine, 1993) showed satisfactory results with the soil and vegetation backgrounds, but confirmed deficiencies in the water background model. When the problems with the water background became evident, it was hypothesized that replacing the empirical water background wave slope prediction code with a rigorous geometric model might produce more accurate ocean background radiance predictions that would translate to more accurate detection range predictions. This report addresses this hypothesis by comparing the effect of replacing the current EOTDA water background model with the SeaRad ocean radiance model (Zeisse, 1995b) and the EOTDA sky radiance model with a more precise sky radiance model from the well-known MODTRAN 3 code.

The original water background model implemented in the EOTDA uses an empirical expression for the ocean background radiance computations (Shapiro, 1987). The basic equation used in the EOTDA for thermal irradiance, $W(\theta)$, emanating from the ocean surface from direction, θ, is given by

$$W(\theta) = (1 - \rho)f(T_0)\sigma T_0^4 + \rho W_{sky(8-14)} \tag{1}$$

where:

ρ	is the Fresnel reflectance of the water surface at view angle, θ;
T_0	is the surface temperature of the water in Kelvin;
σ	is the Stephan-Boltzmann constant, 5.6644×10^{-12} $Wcm^{-2}K^{-4}$;
$W_{sky(8-14)}$	is the long wave band sky radiation received at the surface; and
$f(T_0)$	is the long wave band fraction of total broadband energy radiated.

In practice, the variables for equation (1) are empirically derived using several simplifying assumptions. For example, the diffuse sky radiation is assumed to be isotropic and the same average sky dome infrared irradiance is used for all incidence angles less than 80 degrees, with correction factors used for larger view angles approaching the horizon. The basic empirical equations for reflectance, ρ, are taken from the work by Paltridge and Platt (1976) for initial undisturbed water with corrections based on simplifications of wind effects derived by Cox and Munk (1954). The clear sky radiation, $W_{sky(8-14)}$, is calculated from empirical equations from work the published by Idso (1981). The cloud effects are added algebraically to the clear sky radiance. Much of the complexity of these formulae are further simplified in the EOTDA by using correction factors and lookup tables.

It is a difficult problem to quantify the amount of reflected sky radiance and thermal emission reaching a sensor. Even under clear sky conditions, the direct and diffuse solar and sky irradiance arriving at a small area of the sea surface is complicated by turbulence, lack of homogeneity, aerosol and molecular scattering, and other factors, many of which have spectral dependencies. Once the incident radiation is determined, the actual amount that is reflected becomes complicated by surface characteristics (e.g., white caps, foam kelp, etc.) and by geometric dependencies due to solar zenith angle and wind ruffling of the surface and gravity waves. The emissivity and surface temperature of the water must be known. It is clear that a computer code destined for an IBM AT would need simplification to tackle such a problem. However, with the increased computing power of today's computers, it is time to take a more rigorous approach, like adding the SeaRad and MODTRAN models.

SeaRad is an ocean radiance model based on the Cox-Munk statistical model (Cox and Munk, 1954, 1956). SeaRad was originally developed as an ocean background add-on to the MODTRAN 2 atmospheric codes. The MODTRAN2/LOWTRAN-7 code is used to calculate atmospheric transmittance, and solar, sky, and path radiance values that serve as input for the SeaRad ocean radiance model. Given these inputs, SeaRad uses sea surface temperature, wind speed, and geometric relationships to determine the amount of radiation reaching the sensor.
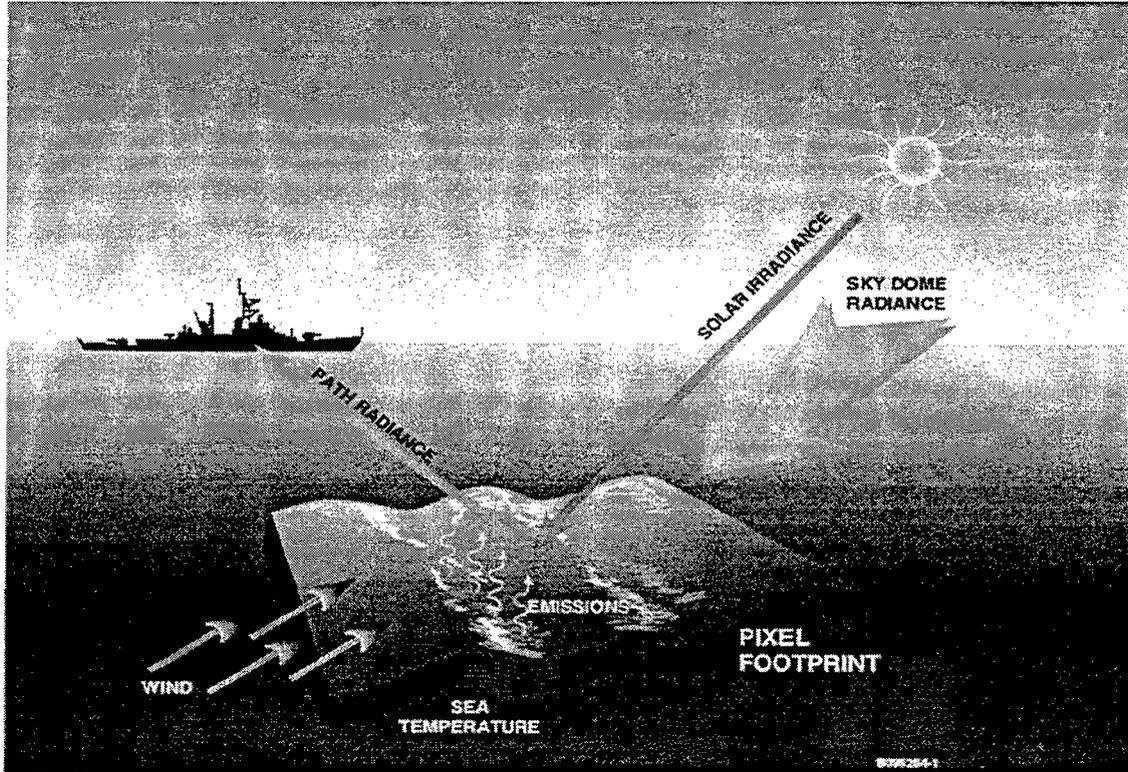
Figure 2. Primary infrared radiation components involved as a shipboard infrared sensor views downward towards the water, perhaps looking for a submarine periscope or incoming missile.

Figure 2 illustrates the contributions to the total radiance received at a sensor from each thermal source: the sky, the sea, and the intervening atmosphere. The main function of SeaRad is to determine the Fresnel reflectance, $\rho(\lambda,)$, and emissivity, $\varepsilon(\lambda)$, for the distribution of wave facets within the field of view of the sensor. SeaRad, in cooperation with MODTRAN/LOWTRAN, can then solve for the various radiance terms according to the equation,

$$N(\lambda) = \int F(\lambda)\left[\tau(\lambda)\rho(\lambda)\{N(\lambda)_{Sky} + N(\lambda)_{Sun}\} + \tau(\lambda)\varepsilon(\lambda)N(\lambda)_{Sea} + N(\lambda)_{Path}\right]d\lambda \qquad (2)$$

where:

$N(\lambda)$	is integrated spectral radiance responded to by a sensor;
$F(\lambda)$	is the spectral response of the sensor;
$\tau(\lambda)$	is the atmospheric transmittance at wavelength λ;
$\rho(\lambda)$	is the Fresnel reflectance at wavelength λ;
$\varepsilon(\lambda)$	is the Fresnel emissivity, $(1-\rho)$, at wavelength λ;
$N(\lambda)_{Sky}$	is the incident sky radiance at wavelength λ;
$N(\lambda)_{Sun}$	is the direct & scattered incident radiance of the solar disk;
$N(\lambda)_{Sea}$	is the emitted sea radiance; and
$N(\lambda)_{Path}$	is the emitted atmospheric path radiance.

In finding the solution of equation (2) for a given scenario, SeaRad must find the values of reflectance, $\rho(\lambda)$, and emissivity, $\varepsilon(\lambda)$. SeaRad uses crosswind angle, upwind angle, and wind speed to determine a wave facet probability distribution based on the Cox-Munk theory. The facet slopes are then applied to the standard Fresnel equation for specular reflections to determine $\rho(\lambda)$ and $\varepsilon(\lambda)$. The formulae for this computation are complicated and described in the SeaRad report (Zeisse, 1995b) and in more detail in the journal article (Zeisse, 1995a). The SeaRad output strongly depends on accurate radiance inputs for $N(\lambda)_{Sky}$, $N(\lambda)_{Sun}$, $N(\lambda)_{Sea}$, $N(\lambda)_{Path}$. The sky radiance routine in the original EOTDA is a fairly simple model that uses an integrated clear sky value for the sky dome, with correction factors for zenith angles greater than 80 degrees and then adds radiance values for cloud conditions. A more precise sky radiance model is required to gain the full benefit from the SeaRad algorithm. Consequently, the EOTDA has been further modified to include the sky model from the MODTRAN 3 code. The rationale for a precise sky model is made clear by the following discussion.

As discussed earlier, the wave facet geometry determines the proportions of reflected sky and sea surface radiant energy according to the Fresnel equation. It is important to note that the facet geometry also determines what geographical area of the sky is acting as the source of the radiant energy reaching the sensor. As an example, consider the pixel footprint represented in figure 3 by the small square area just below the horizon. Corresponding to this footprint is an elliptical area of the sky dome that radiates and will be reflected by the water toward the sensor. The majority of the received radiance always emanates from the center portion of the ellipse (represented by the darker shading within the ellipse). As the wind speed increases, the area of the ellipse also increases, because the greater wind produces larger facet angles which pick up a larger area of the sky dome. Given enough wind in our example in figure 3, the ellipse would widen to the point that some of the facets would reflect the sun, thus producing glitter on our footprint. It should be obvious from this example that it is absolutely essential that the sky radiance model accurately predict the irradiance of the specific geometric area of the sky being reflected. It is possible to have an accurate model for determining the total integrated sky dome radiance and still have errors because of failure to properly model the local area radiance. This is the rationale for a more rigorous approach to both the sky and sea radiance models of the EOTDA. If the sky model is not improved concurrently with the water background model, SeaRad might work perfectly but still produce erroneous results due to erroneous sky radiance input data. The MODTRAN 3 sky model met the need for area-specific sky dome radiance and was used to replace the original EOTDA sky model for our evaluation.

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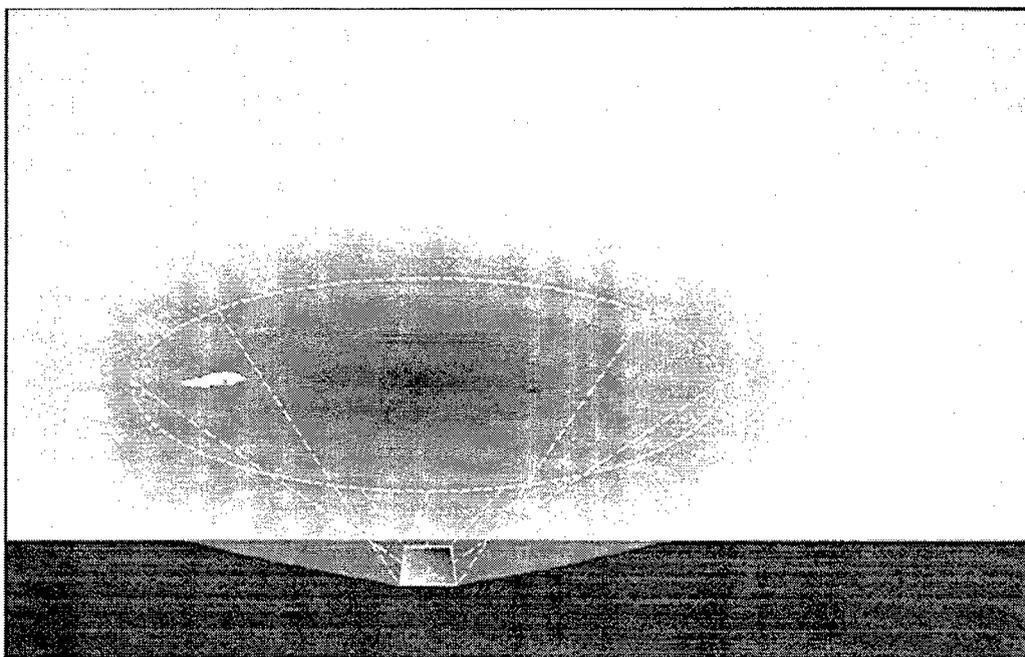
Figure 3. The wave facet geometry not only determines ratio of reflected sky and emitted sea radiance reaching the sensor, but it also determines what area of the sky dome dominates the reflected sky contribution. As the wind speed increases the area of the ellipse increases and the dominance of the center area decreases.

MEASUREMENTS

The accurate empirical data required for testing the modifications were obtained from field measurements that leveraged on larger measurement campaigns, such as the successful Electro-Optical Propagation in Coastal Environments (EOPACE) effort. A calibrated infrared imaging system manufactured by AGEMA Infrared Systems, Inc. collected infrared target and background data from an airborne platform, a twin-engine Piper Navajo. These data were supplemented with supporting meteorological and navigational data.

Three primary types of measurements were made. First, vertical profile data were collected by flying in a vertical upward spiral starting at an altitude of 15 meters, climbing to 1500 meters. These data are for input into the MODTRAN and EOTDA codes. The second type of measurement is close-up imaging of the target and background, as shown in the upper left frame of figure 4. These images were later corrected to zero-range values by using the MODTRAN code for removing the atmospheric influence. The third type of measurement is the detection range of the target, which is determined by flying away from the target until the target is barely discernible against the background and then noting the distance on the distance measuring equipment (DME) onboard the aircraft that receives the tactical aircraft navigation beacon (TACAN) signal from the ship. Figure 4 shows infrared images (8- to 12-micron band) of a ship target fading from view as the distance from the camera increases. The small, bright spot representing the thermal signature of the ship is barely visible at the 20-kilometer range and just disappears at about 23 kilometers. This detection range is compared to the EOTDA prediction. Although, target resolution diminishes with distance, resolution is not a concern because the EOTDA operates primarily on total average temperatures over the entire

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target area, rather than hot spot detection. Meteorological data are continuously recorded during the radiometric imaging.
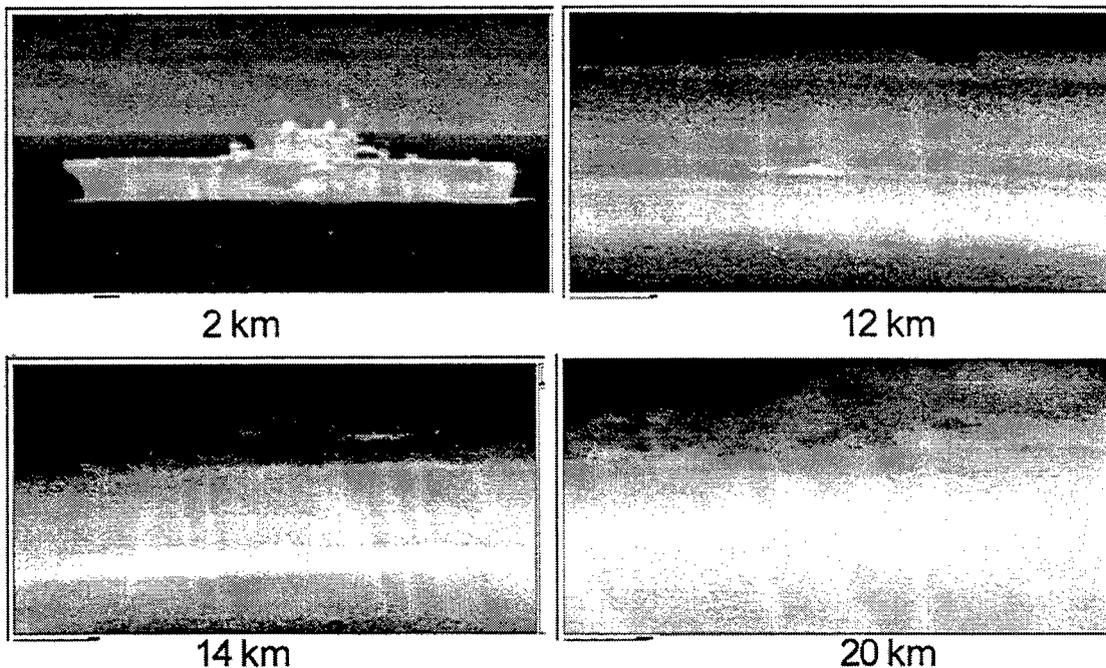
Figure 4. After completing close-up measurements, detection ranges were determined. In this case the ship was barely visible at 20 km and disappeared at 23 km.

The AGEMA 900 system provides several tools for analyzing the recorded images. The total integrated radiance is of primary interest in evaluating the target and background models of the EOTDA. The total integrated radiance is found by using the area analysis capability of the AGEMA system. The system provides the capability of defining an irregular area and then performing statistical analysis on that area.

Figure 5 shows long wave ship images of the port and starboard sides of a ship where the areas of interest have been defined by the area analysis tools of the AGEMA infrared system. In this example, there is a significant difference between the two sides. The thermal contrast is significantly greater for the starboard view (15.8°C compared with 6.9°C), making the ship much more vulnerable to an attack at the starboard side. An attack aircraft could conceivably locate and deliver weapons at more than twice the stand-off range by approaching toward the sunlit (starboard) side instead of the shaded and wind-cooled side. It is crucial that decision aid software be able to accurately predict these tactical conditions.

Because the distances from the camera to the target (500 to 3000 meters) include a significant atmospheric influence, the image temperature values require correction to obtain zero-range equivalent blackbody temperature. The atmospheric contribution to the scene displayed by the calibrated AGEMA 900 imaging system is shown in equation (3). Each side of the equation represents the total radiance upon the detector for a given pixel. An AGEMA system frame image is displayed as a 272 x 136 pixel array of spot temperatures determined in accordance with Plank's black body formula.

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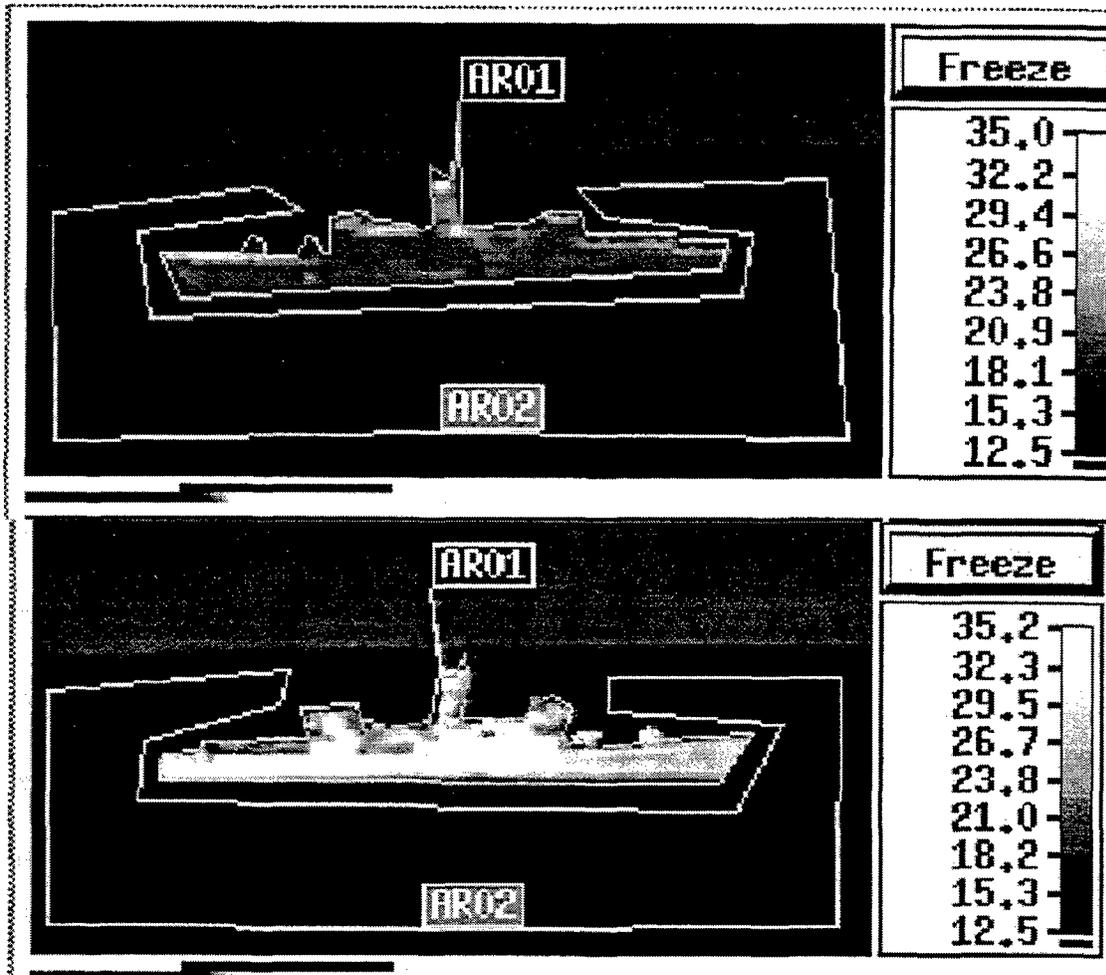
Figure 5. Target/background analysis. The port view (top) and starboard view (bottom) are both 8- to 12-micron images of same ship at same time.

Equation (3) can also represent the total integrated scene radiance arriving at the AGEMA detector for the set of pixels corresponding a target area. The left side shows the total radiance in terms of the apparent target temperature, T_A. The right side shows the breakdown of the apparent temperature, T_A, into its atmospheric components and the actual (zero-range) target temperature, T_S, which is the desired result:

$$\frac{1}{\pi}\int_{v_1}^{v_2} W(T_A, v) F(v) dv = \int_{v_1}^{v_2}\left[\varepsilon(v)\tau(v, R)\left(\frac{1}{\pi}\right)W(T_S, v) + N_P(v, R) \right] F(v) dv. \quad (3)$$

The target emissivity, ε, is estimated from empirical data and assumed constant over the 8- to 12-micron band (wavenumbers 1250 cm^{-1} to 830 cm^{-1}). The AGEMA system relative spectral response, $F(v)$, is a measured parameter that is inserted into MODTRAN by modifying the code. Certain meteorological parameters, such as air mass parameter and visibility are operator-determined

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rather than instrument measured. The slant-path range, R, transmittance, τ, and path radiance, N_P, and the zero-range target radiance, N_S, are determined directly from the output of MODTRAN. The final zero-range temperature, T_S, is calculated from the zero-range radiance, N_S, using Plank's black body formula.

The general procedure for correcting the apparent spot temperatures or area averaged temperatures to zero-range values is a trial-and-error method that iteratively runs MODTRAN with different values of zero-range boundary temperature (the TBOUND parameter) until the result matches the measured values from the AGEMA system. The meteorological data, path geometry, target emissivity, and estimated target temperature are entered into the MODTRAN input file prior to running the program.

RESULTS

The corrected measurement data described above are needed for evaluating the performance of the SeaRad model and original EOTDA. However, before comparing with measured data, it is instructive to compare the two models with each other to see how they each behave under various weather conditions. Figure 6 compares the background predictions for SeaRad with the original EOTDA version 3.1 (Shapiro model) for 29 cases representing a variety of weather conditions. These data do not show which model, if any, is correct. They only show that the two models behave differently in some scenarios and behave nearly the same in many others.

SeaRad is a geometric model that heavily depends on an accurate sky radiance model for input. When a more geometrically rigorous model, such as the MODTRAN 3 sky radiance algorithm is added to the EOTDA in conjunction with the SeaRad model, the relative behavior of water background models differs significantly between the two models. Figure 7 shows the difference between the original EOTDA water background predictions and the modified EOTDA containing both the SeaRad ocean radiance model and the MODTRAN sky radiance model. Figure 7 shows the same cases as figure 6 except the sky model is added in figure 7, and much greater difference is apparent between the two models.

Each case is from a separate measurement day, time, and condition unrelated to the others. There is no phenomenological significance to the order, since they are arranged chronologically. Cases 18 through 20, 22, and 24 through 29 are under clear sky conditions (SKC). Cases 1 through 4 , 9, 12 through 17, and 21 are under scattered clouds (SCT), and cases 6 through 8 and 23 are under broken clouds (BKN). Cases 5, 10, and 11 are under marine stratus cloud conditions (OVC).

In general, there is better agreement between the models under the clear sky conditions. The SeaRad model seems more sensitive to changes in wind speed and sensor angle. However, the Shapiro model showed greater sensitivity in the high-altitude cases, which are shown as case numbers 14 through 17. The depression angle for these high-altitude cases was between 4 and 5 degrees, while all the other cases were viewing the ocean surface near the horizon at depression angles between 0.5 and 1.5 degrees.

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Background Model Comparison
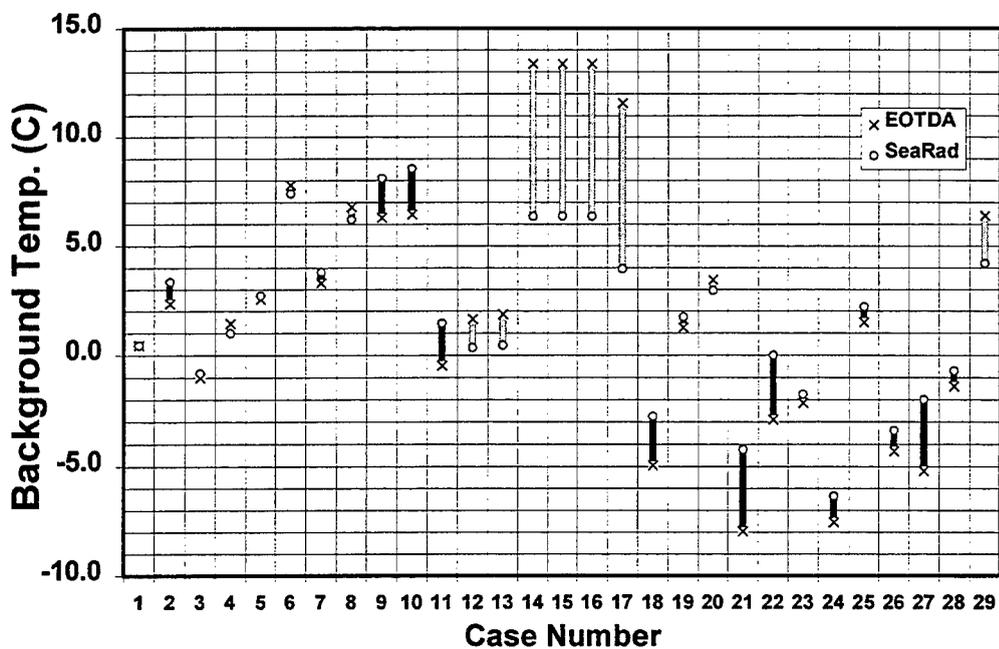
Figure 6. Behavior comparison of the SeaRad radiance model to the original EOTDA background model.

Background Model Comparison
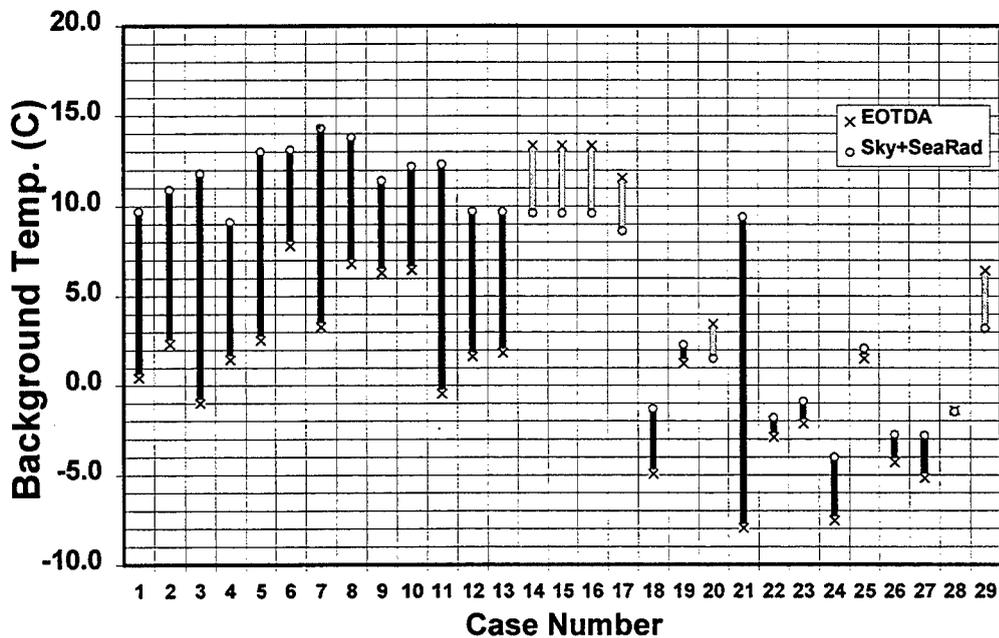
Figure 7. Behavior comparison of the SeaRad radiance model to the original EOTDA background model with an additional modification that replaces the original sky radiance model with the MODTRAN 7 sky radiance model.

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Figure 8 compares the model predictions with the corrected measured values of scene background temperatures. The drop bars show the difference between the measured values and the original EOTDA predictions. In the majority of near-horizon cases, the EOTDA under-predicted the background temperature. However, in the high-altitude larger zenith angle cases (14 through 17), the EOTDA over-predicted the zero-range ocean background temperature. The background temperature predictions of the modified EOTDA show much better agreement with the measured values. Thus, these data show significant improvement by replacing the semi-empirical models with a geometrically more rigorous solution using the SeaRad ocean radiance model and the MODTRAN sky radiance model. The greatest benefit is obtained under clouded sky conditions.

Comparison of Modeled and Measured Background Temperatures
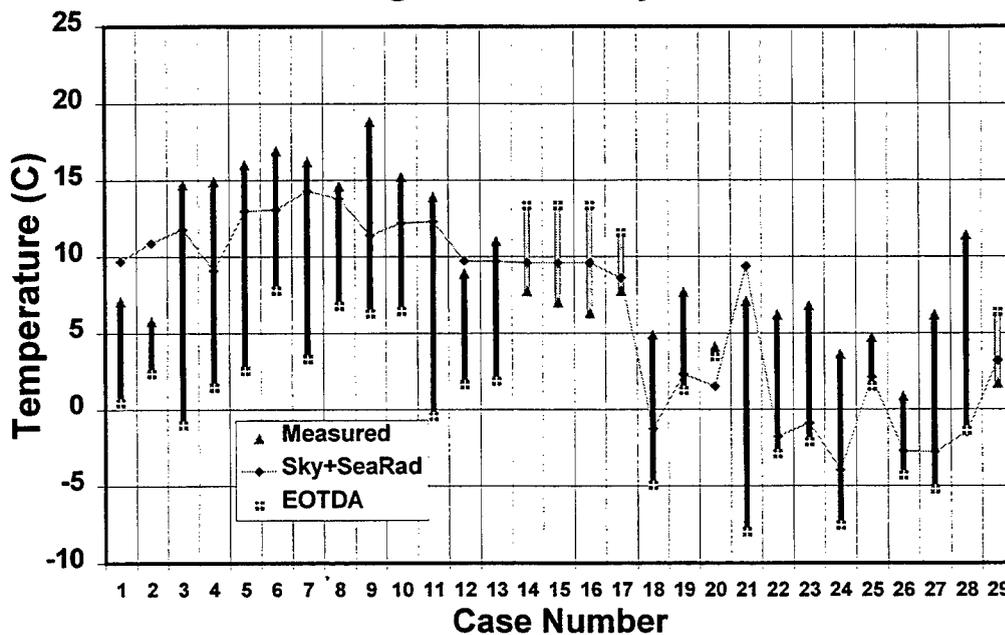
Figure 8. Comparison of the measured data to the model predictions. The predictions of the modified model are connected to make them stand out for easier comparison with the measured (diamond symbol) values.

While the main objective of this effort is to improve the water background model predictions, the primary output of the EOTDA is detection range predictions. It is, thus, of interest to observe the effect of the modified version on detection range performance. In fact, the selection of the data set for this study was made on the basis of having corresponding detection range measurements; much more data were available if the only interest were the ocean backgrounds. Figure 9 is a scatter plot of measured detection range versus predicted range. Ideally, both numbers should agree, so the data points should lie on the diagonal line. The dashed lines are 25 percent error limits. Points above the diagonal line are over-predictions of detection range, while those below are under-predictions of range. The greatest improvement is with the points on the far right of the graph within the 50 to 60 km measured detection range area. These are the long-range, high-altitude, larger zenith angle cases.

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In most of the other cases, there is only slight improvement in detection range predictions. In general, there is a large improvement in background temperature modeling and a notable shift in the detection range data toward more accurate predictions.
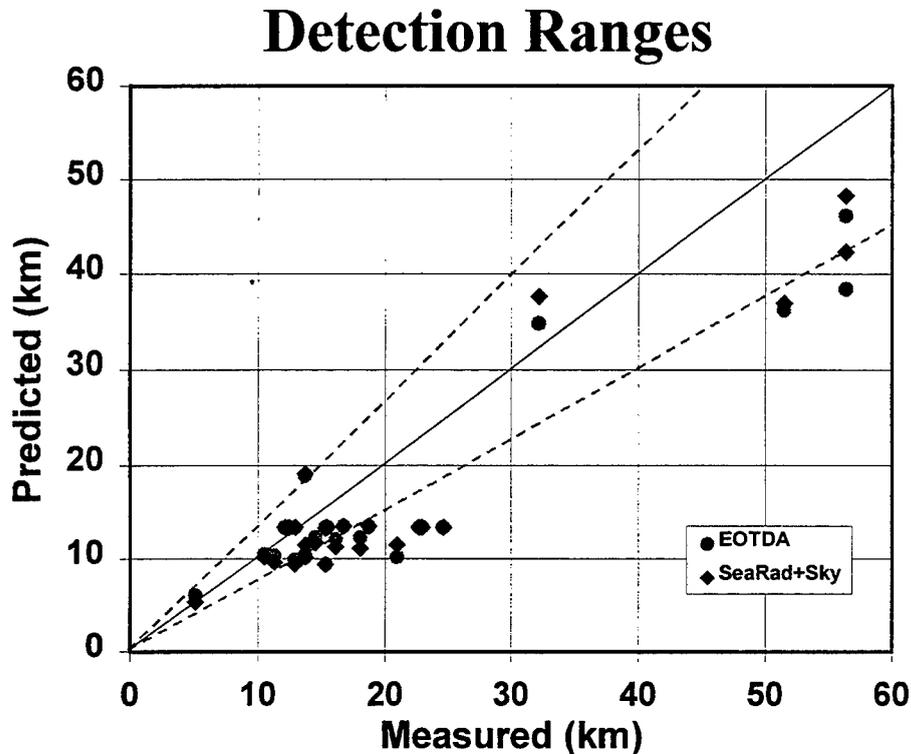
Detection Ranges

Figure 9. Measured detection range versus predicted range scatter plot.

The significance of the SeaRad modification on detection range performance would be more noticeable if there were no other offsetting factors within the EOTDA. For example, errors in sky temperature and solar loading will cause miscalculations in both the target and background radiance values, but these errors will tend to cancel when subtracting for target-background radiance contrast. Therefore, making the background model more accurate without improving the target model could make the target-background contrast less accurate. This depends, of course, on whether the inaccuracy of the background model would have been in the direction of canceling the target model prediction error. Additionally, the transmission loss from the intervening atmosphere tends to attenuate the contrast errors, thus masking some of the benefit of the modifications, especially in the long-range cases.

Figure 8 indicates significant improvement in ocean background predictions is realized with the modified EOTDA employing the SeaRad ocean radiance model in combination with the MODTRAN sky radiance model. Improvement in overall performance of the EOTDA is sufficient enough to recommend transition to a Navy fleet-ready version as an interim measure until a complete replacement for the EOTDA is available. As suggested in the above paragraph, future improvements to the target models would be another recommended step toward improving the overall range performance that would complement the improved water background model. However,

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the EOTDA ultimately needs to be replaced with a more sophisticated model that includes surface layer phenomenology (such as, turbulence, refraction, white-capping, and shadowing effects), accurate scene rendering (including feature cueing), complex background modeling, and multi-spectral sensor capability. Developments in weapons system sensor technology and improvements in computer performance justify replacing the outdated EOTDA with a model more suited to the complex problem being addressed.

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APPENDIX A

THERMOANALYTICS FINAL REPORT ON IMPLEMENTING SEARAD

IMPLEMENTATION OF AN EFFICIENT AND ACCURATE MARINE RADIANCE MODEL INTO THE ELECTRO-OPTICAL TACTICAL DECISION AID (EOTDA)

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15 January, 1998

Final Report
July 1996 - October 1996

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PREFACE

1.   INTRODUCTION

The Cox-Munk ruffled ocean radiance estimates have been included in Version 3.1 (β) of the EOTDA. The thermal model itself is unchanged. That is, no changes have been made in the way target and background temperatures are computed. Changes have been made in the way ocean background radiances are calculated, and in the corresponding equivalent black body temperatures for those backgrounds. The target-ocean background temperature contrasts held in the IROUT.DAT file are now computed using Cox-Munk radiances. New NRAD.DAT files are generated to record ocean background radiance component information as a function of time, wind-speed, and position.

The new inputs required to drive the EOTDA are (1) ocean temperature for each of the specified ocean backgrounds, (2) integration step size for integrating radiance over the sky dome and (3) the number of intervals to break the wave number band into when integrating over all the wave numbers. The user is asked for this information when an ocean background is specified and default values can be chosen if desired. All other needed information is already in the EOTDA - sun and receiver positions, wind speed, equivalent black body sky temperature, and direct and diffuse solar radiation.

2.   SUBROUTINES

New Subroutine SKY

Reflected Sky Radiance

In the unmodified EOTDA, an equivalent black body sky temperature, Tskyir, and a radiance relation are used to arrive at a sky radiance, Rsky, with units $W/(m^2\,sr)$. This radiance is scaled by a dimensionless factor, AFAC, that depends on the zenith angle of the part of the sky doing the radiating. AFAC is obtained from the subroutine SKYDIR and is about 1.0 at a zenith angle of 60°C.

The NCCOSC modified EOTDA uses the black body sky temperature, Tskyir, and the function BB(wavenumber, temperature) to generate spectral radiance with units $W/(m^2 sr\,cm^{-1})$. This radiance is then multiplied by the sky dome interaction probability density and the product is integrated over the sky dome and over the wavenumber interval v_1 to v_2. When this product is being integrated over the sky dome, SKYDIR1 is called (see section 2.4). SKYDIR1 returns a factor AFAC used to scale the product based on the portion of the sky doing the radiating. The resulting integrated radiance has units $W/(m^2 sr)$.

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2.2.2 Reflected Diffuse Solar Radiance

In the unmodified EOTDA, a total diffuse solar radiance, in W/m^2, is adjusted for the orientation of the surface on which the radiation is incident. This adjustment depends on both the azimuth and zenith of the surface normal. In effect, the total diffuse solar irradiance DIFF is scaled like DIFFT = DIFF $\times$ f(θ,ϕ), where DIFFT is the zenith and azimuth dependent diffuse solar irradiance and f(θ,ϕ) is the scaling function, dependent on the zenith θ, and the azimuth ϕ.

In the NCCOSC modified EOTDA, a black body spectral radiance $W/(m^2 sr\ cm^{-1})$, at sun temperature, is integrated over a wavenumber interval to obtain the black body radiance, $W/(m^2 sr)$ between v_1 and v_2. This is scaled by the fraction DIFFT/SOLAR_IRRAD, where DIFFT is the total (wide band) diffuse solar irradiance from a given direction (W/m^2) and SOLAR_IRRAD is the wide band black body irradiance at the temperature of the sun (W/m^2).

The idea is that if the black body spectral radiance were integrated from $v = 0$ to $v = \infty$, SOLAR_IRRAD would be obtained, and we would recover the wide band diffuse solar irradiance, DIFFT. Integration over a limited band followed by multiplication by the ratio DIFFT/SOLAR results in that portion of DIFFT within the band of interest - the desired, band-limited diffuse solar radiance. When integration is carried out over the sky dome, the variation of DIFFT with θ and ϕ adjusts the radiance falling on the sloping sea facet much as AFAC does in the case of sky radiation - with the additional dependence on azimuth.

2.1.3 Sky Dome Integration

Calculation of the reflected sky radiance requires 'spatial' integration over either the sky dome or over the range of wave slopes. The approach taken here has been to integrate over the sky dome, i.e. to evaluate the sky radiance at specified azimuth and zenith angles, multiply it by the wave slope probability distribution function for the given receiver and sky point angles and by the sea reflectivity and sum up these products over the range of zenith and azimuth angles and the range of wave numbers.

In an attempt to speed up the sky radiance calculation, we exploit the fact that under some conditions only portions of the sky contribute significantly to the reflected sky radiance. For example, if the wind is very light, the sea is nearly flat and with (assumed) specular reflection, the sea behaves like a mirror and reflects only the part of the sky near zenith angle $\Theta_{sky} = \Theta_{sensor}$ and azimuth angle $\Phi_{sky} = \Phi_{sensor} + 180°$. A lookup table has been generated specifying limits on zenith and azimuth angle integration ranges so that integration is not carried out over parts of the sky not contributing to the integral. This table is a function of receiver zenith angle and wind speed. The user has the option to integrate over the full sky dome, ignoring the precomputed limits if he wishes. In many conditions there will be no speed/accuracy improvement in specifying limited zenith and azimuth ranges, since much of the sky **will** contribute to the reflected sky radiance.

In order to allow the user to trade between speed and accuracy in the radiance estimation, he is asked to specify the zenith angle increment to be used in the integration. The integration routine then computes the appropriate azimuth angle increment so that the incremental zenith arc length ΔS_Θ is approximately equal to the incremental azimuth arc length ΔS_Φ. For example, if the user specifies a 5 degree zenith angle increment, the zenith arc will be divided into 90/5 = 18 intervals, each with incremental arc length $\Delta S_\Theta = \pi / 36$ (on a unit sphere). At the 7th zenith angle step, $\Theta_{zenith,7} = 32\frac{1}{2}^\circ$ and the azimuth angle increment should be such that $\pi / 36 = SIN(32\frac{1}{2})\Delta\Phi_{azimuth}$. This results in $\Delta\Phi_{azimuth} \approx 9.3^\circ$ and the azimuth, at the zenith angle of $32\frac{1}{2}^\circ$, being divided into 360/9.3 $\approx$ 38 intervals. So, at the 7th zenith angle step there will be 38 azimuth angle steps. The total number of integrand evaluations in the spatial integration, with a 5 degree zenith angle increment, is about 820. This must then be carried out for each step in the wavenumber integration. The number of integrand evaluations goes up quickly with decreasing zenith angle increment - with $\Delta\Theta_{zenith} = 1^\circ$, there are about 20,580 integrand evaluations in the reflected sky radiance spatial integration alone.

The EOTDA calculates detection range for a given sensor by adjusting the slant range between the sensor and the target. Since the sensor is held at a constant elevation while the slant range is varied, the sensor zenith angle varies during detection range estimation. If zenith and azimuth angle limits are used in the sky dome integration during this estimation, they too may vary with slant range. In order to hold reflected sky radiance estimation speed and accuracy approximately constant as the sensor zenith angle varies, we hold the total number of integrand evaluations, N_{total}, constant, but vary the zenith and azimuth angle increments so that $\Delta S_\Theta \approx \Delta S_\Phi$. In order to do this we write

$$N_{total} = \sum_{i=1}^{N_\Theta} \frac{N_\Theta(\Phi_{max} - \Phi_{min})SIN(\Theta_i)}{\Theta_{max} - \Theta_{min}}$$

where $\Phi_{min}, \Phi_{max}, \Theta_{min}$ and Θ_{max} are lower and upper integration limits on the azimuth and zenith angles (the 'precomputed limits' mentioned above), respectively. Here N_Θ is the number of integration steps in the zenith angle direction and N_{total} is the total number of integrand evaluations in the sky dome integration. We can write,

$$\Theta_i = \Theta_{min} - \left(\frac{\Theta_{max} - \Theta_{min}}{2N_\Theta}\right) + i\left(\frac{\Theta_{max} - \Theta_{min}}{N_\Theta}\right) \quad \text{where } i \in (1, N_\Theta)$$

We also approximate

$$SIN(\Theta) \approx \alpha\Theta^2 + \beta\Theta + \gamma$$

where a curve-fitting routine was used to find α, β, and γ for $\Theta \in (0, \pi/2)$. Substituting equations 2 and 3 into equation 1, we then solve for N_Θ. Having N_Θ and the zenith and azimuth angle integration ranges allows us to divide these ranges into integration steps where N_{total} is held constant and $\Delta S_\Theta \approx \Delta S_\Phi$. N_{total} is determined by the choice of zenith angle increment mentioned above, where full sky dome integration is assumed for the purpose of calculating N_{total}. For the case where the zenith angle increment is 5 degrees, discussed above, N_{total} is about 820.

2.2 New Subroutine SEA

2.2.1 Sea Emission Radiance

The NCCOSC modified EOTDA uses a sea temperature to compute a black body spectral radiance $W / (m^2 sr\ cm^{-1})$ for the water and then multiplies this radiance by an emissivity that depends on the angle between the water surface normal and the direction to the receiver. The sea temperature can either be specified by the user and held constant, or be taken from within the EOTDA model and vary with time. The radiance $\times$ emissivity product is multiplied by the wave slope distribution and integrated from -4σ to $+4\sigma$, in both the X and Y slope directions - where σ is the slope deviation. The slope space integration is done in polar coordinates and the integrand evaluation points are clustered with more points near zero wave slope - where the slope probability distribution function is steepest. This results in good accuracy with relatively few integrand evaluations - another attempt to speed up the integration. This slope space integration is in turn integrated over the specified wave band.

2.3 New Subroutine GLINT

2.3.1 Solar Glint Radiance

In the unmodified EOTDA, the estimate of the sun glint off the water background uses a model derived estimate of the wide-band direct solar irradiance, BEAM, and computes an incident irradiance adjusted for the slope of the water surface using a value for the RMS slope of the surface, BETA, that depends on the wind speed over the water. The incident irradiance is multiplied by the water reflectivity and a scaling factor, SPFAC, to correct for the desired limited bandwidth of the reflected radiance.

In the NCCOSC modified EOTDA, the sun is taken as a black body at 5900 degrees K and the function $BB(T_{sun}, \nu)$ is used to find the spectral radiance, $W / (m^2 sr\ cm^{-1})$, at a given wavenumber. This result is scaled by the ratio BEAM/SOLAR_TOP, which is an estimate of the atmospheric transmission coefficient τ, and integrated over the wave band ν_1 to ν_2 and over the solar disk. The result is the band-limited radiance, $W / (m^2 sr)$ due to the solar glint.

In computing the radiance at the sensor due to sky emission and direct and diffuse solar radiation, the reflectivity of the water at each wavenumber and angle of incidence is used to calculate the reflected radiance.

2.4   New Subroutine SKYDIR1

This subroutine is a slight modification of SKYDIR, currently in the unmodified EOTDA. Given an average black body equivalent sky temperature and the corresponding sky radiance, SKYDIR1 computes a scaling factor for that radiance based on the season and the zenith angle of the part of the sky doing the radiating. For example, if the average sky temperature (obtained from the EOTDA model) is 200 degrees K, then the average sky radiance is about

$$\text{Rad}_{sky,av} \approx \frac{\frac{11910.62}{\lambda^3}}{e^{\frac{14387.86}{\lambda T}} - 1} \approx 5.52 \times 10^{-3} \quad W/(m^2 sr\ cm^{-1})$$

at $\lambda = 9.0\mu$ meters. If it's summer and the sky source point zenith angle is 80 degrees, SKYDIR1 would return a scaling factor of AFAC = 1.10. The sky radiance at zenith = 80 degrees, and all azimuths, would then be $\text{Rad}_{sky,80°} \approx 5.52 \times 10^{-3} \times 1.10 \approx 6.07 \times 10^{-3}$ $W/(m^2 sr\ cm^{-1})$. The scaling factor table is taken from an STX report by Ralph Shapiro (Scientific Report No. 36 plus 1988 addendum, AFGL-TR-87-0254).

2.5   New Subroutine SOLCOMP1

This is a modification of the SOLCOMP subroutine currently in EOTDA. SOLCOMP is called with solar and sensor zenith angles adjusted for reflection from a sloping (wavy) water surface with a parameter (BETA) describing the RMS slope of the water. Also passed to SOLCOMP are solar and sensor azimuths, and direct and diffuse (variable DIFF in the EOTDA code) solar irradiances in W/m^2. Given sensor position and wave slope, SOLCOMP assumes a specular reflection and determines the part of the sky being reflected into the receiver.

DIFF is the total diffuse solar radiation falling on a horizontal surface. Using a procedure described in Report AFGL-TR-87-0200, Appendix B, SOLCOMP divides the total diffuse solar radiation into portions due to radiation from the half of the sky with the sun (DIFS) and the half without the sun (DIFA). It then computes a weighted average of these two components based on the position of the sky source point relative to the sun's position. If the part of the sky being reflected into the receiver is near the sun, DIFS contributes more to the average, otherwise DIFA does. Although SOLCOMP also computes the radiance due to reflected direct solar irradiance, we do not include this in SOLCOMP1 since it is carried out in the GLINT subroutine using the Cox-Munk slope distribution.

2.6   New Subroutine TESTRAD

This subroutine drives the SKY, SEA, and GLINT subroutines when comparing NCCOSC and EOTDA calculations of solar glint, reflected sky, and sea emission radiances. It is called from routine IR3. The OCEAN.IN file is opened in IR3 but read and closed in TESTRAD. TESTRAD reads the wavenumber in cm^{-1}, the solar zenith and azimuth in degrees, the dimensionless atmospheric transmission coefficient, the fitted curve coefficients for the $Ns(\Theta_{zenith})$ function and the ocean temperature in degrees C - all from the OCEAN.IN file. TESTRAD follows the EOTDA convention of assigning north to an azimuth of 0 and east to an azimuth of 90 degrees. After TESTRAD closes the OCEAN.IN file, it asks the user to input, via the keyboard, receiver position zenith and azimuth, day of the year (for the EOTDA model) and wind speed in m/s.

Subroutines SKY, SEA, and GLINT are next called with a single wavenumber specifying the lower and upper limits of the wavenumber integral. This indicates to SKY, SEA, and GLINT that no spectral integration is to be carried out - only spatial integration. After SKY, SEA, and GLINT return the radiance estimates, TESTRAD writes the result to the terminal for the user to inspect.

2.7   Changed Subroutine RDIROP

In this subroutine the OPS.DAT file is read and the number of requested ocean backgrounds is counted. If this number is greater than zero, the user is asked if he wants to compute background radiances at a single wavenumber for comparison with similar computations with stand-alone programs. If yes, the user inputs the name of the 'OCEAN.IN type' file, holding wavenumber, $Ns(\Theta)$ function coefficients (see section 4.2), sea temperature and solar azimuth and zenith. RDIROP then calls TESTRAD to carry out the computation. After TESTRAD is finished, the user is asked whether to use constant sea temperatures or EOTDA estimated sea temperatures in the EOTDA background radiance model. He is also asked whether or not to integrate over the whole sky dome or to use the precomputed limits in zenith and azimuth integration, as discussed in section 2.1.3. Finally, the user is asked for the zenith angle integration angle step size in degrees.

2.8   Changed Subroutine OUTPUT

When output is to be written to IROUT.DAT, the background type is checked - if it's an ocean background, subroutines SKY, GLINT, and SEA are called to get the reflected sky and sun radiances and the emitted sea radiance. These radiances are summed and used to compute an equivalent black body temperature which is in turn used to find the temperature contrast between the target and the background. This contrast is written to the IROUT.DAT file, replacing the contrast computed the old way. As OUTPUT loops

through the specified backgrounds, points of view, and targets, an internal record of background of point-of-view/background combinations is created and used to avoid redundant computation of target-background contrasts. That is, if two contrasts share the same ocean background but have different targets, ocean radiance will be computed only once and used in both contrast calculations. As these background radiances are computed for use in calculating temperature contrasts, they are also saved to radiance arrays RSKY, RSUN, and RSEA along with the corresponding azimuths and ranges for the points of view. These quantities are written to NRAD#.DAT files - one for each specified ocean background.

2.9   Changed Subroutine ANGDEP

Subroutine ANGDEP calculates water background radiance for use in determining target/background contrast and in the iterative estimation of detection range. It now calls subroutines SKY, SEA, and GLINT to determine water background radiance.

2.10   Changed Routine IR3

IR3 initializes a flag, NRAD_FLAG, used to indicate the presence of ocean backgrounds. This flag is later changed in RDIROP if there are ocean backgrounds. IR3 also closes the new NRAD.DAT files when the EOTDA is completed.

2.11   Optional New Subroutines

These subroutines are included but not called. They may be called with simple changes in the source code.

PLANK_NRAD: An optional addition to EOTDA (in the file FT4.FOR) to integrate the Planck function over a specified band at a specified temperature. The EOTDA currently uses a polynomial function of the temperature to make this estimate, but is independent of band. PLANK_NRAD was added to include band dependence in the integrated Planck function. If the band of interest is that implicit in the polynomial curve fit, subroutine PLANK may be used instead. Calls to subroutine PLANK are made in files FT3.FOR, FT5.FOR, and FTBKGDB.FOR.

APPRNT_NRAD: This subroutine (in file FT5.FOR) inverts the function evaluated by PLANK_NRAD. Given a radiance and a specified band, APPRNT_NRAD finds the corresponding black body temperature. Again, EOTDA currently carries this out with a polynomial (in Radiance$^{1/4}$) that is band-independent. APPRNT_NRAD was included to restore band-dependence to the calculations. Calls to subroutine APPRNT_NRAD are made in files F3.FOR, FT3.FOR, FT4.FOR, FT5.FOR, and FTBKGDB.FOR.

3. FUNCTIONS

This section is included to mention a new function added to the EOTDA not due to NCCOSC, RDT&E - though it is derived from one originating there.

3.1 New Function BB_INVERT

This function inverts the function BB(v,T). That is, where BB provides a black body spectral radiance (W/(m^{2}sr cm^{-1})) given temperature and wavenumber, BB_INVERT returns a temperature when given a spectral radiance and a wavenumber. This function is used when comparing the EOTDA and NCCOSC sky radiance estimates. See section 4.2.

4. ON COMPARING EOTDA AND NCCOSC RADIANCES

The EOTDA modifications are based on code developed by C. Zeisse at the R.D.T. & E. division of NCCOSC. In order to allow a comparison between the two (slightly different) radiance estimates, the driver routine TESTRAD was written to perform sky dome integration of solar glint radiance, sky radiance and sea emission at a given wavenumber. Information needed to carry out the calculation is held in the 'OCEAN.IN' type file and input at the keyboard.

4.1 Solar Glint

The NCCOSC developed solar glint radiance code is essentially embedded in the EOTDA except for the estimate of τ, the atmospheric transmission coefficient. The NCCOSC code reads τ from the OCEAN.IN file, while EOTDA provides an estimate of the broad-band solar irradiance at the ocean surface using the variable BEAM. If we assume a solar irradiance at the top of the atmosphere of 1370 W/(m^2), we may then approximate the transmission coefficient with the ratio BEAM/1370. In this way, a time varying transmission coefficient is provided, as BEAM is taken from a time varying weather file.

4.2 Sky Radiance

NCCOSC uses a fitted curve function of the zenith angle Θ to estimate the sky radiance. EOTDA uses an equivalent black body temperature to estimate an average sky radiance and then scales this radiance with a function that depends on zenith angle. In order to make a reasonable comparison between the NCCOSC and EOTDA sky radiance estimates, an appropriate average black body sky temperature must be determined. Since the EOTDA zenith angle dependent scaling function is nearly equal to 1.0 at Θ = 60 degrees, the NCCOSC fitted curve, function Ns(Θ) is used to find a spectral radiance at zenith angle Θ = 60 degrees. Function BB_INVERT is then used to find the

corresponding equivalent black body temperature for the sky, the wavenumber specified in the OCEAN.IN file. This temperature is then used to find the sky radiance during integration over the sky dome. The NCCOSC sky radiance function is,

$$Ns(\Theta) = A_{ns} + B_{ns}e^{\frac{\Theta}{C_{ns}}} \quad W/(m^2 sr\ cm^{-1})$$

Where the parameters A_{ns}, B_{ns}, and C_{ns} are provided by the user in the OCEAN.IN file. With values of $A_{ns} = 1.779 \times 10^{-2}$, $B_{ns} = 5.841 \times 10^{-5}$ and $C_{ns} = 2.254 \times 10^{-1}$ then $Ns(\Theta = 60^{\circ}) \approx 1.786 \times 10^{-2}\ W/(m^2 sr\ cm^{-1})$. At a wavenumber of 945 cm^{-1}, this corresponds to a sky temperature of about 214.6 K. The EOTDA then uses this value to determine the sky radiance at a zenith angle of 60 degrees and scales it with factor AFAC at other angles. AFAC is determined in subroutine SKYDIR1.

4.3   Sea Emission

The code provided to ThermoAnalytics by NCCOSC had the sea emission estimate carried out within the sky dome integration that also computed the reflected sky radiance estimate. In order to speed up the emission calculation, it was separated from the reflected sky radiance calculation and integrated in slope space. The change in integration domain has resulted in small changes in the emission estimate - less than about ½ % in example estimates where the sky dome integration used about 800 integrand evaluations and the slope space integration used 100 integrand evaluations.

5.   NEW OUTPUT

The unmodified EOTDA currently generates a binary output file, IROUT.DAT, that includes an entry stating the apparent temperature contrast between the target and the background. When there are no ocean backgrounds in the model, the file will be unchanged. If an ocean background is specified, the temperature contrast will be calculated using the Cox-Munk radiance calculations.

If ocean backgrounds are specified, new output files will be generated - one for each of the ocean backgrounds. For example, if two ocean backgrounds are being modeled, files NRAD1.DAT and NRAD2.DAT will be produced. A sample output is displayed below:

```
Under the following conditions:
      Latitude             =            43.000000
      Longitude            =            74.000000
      Year                 =               1992
      Month                =                  7
      Day                  =                  9
      Temperature of Ocean =           288.150000
      Wave Band (microns)  =             8.000000 to    12.000000
```

```
The band integrated radiances (W/m**2 sr) are :

Time =   600               Wind Speed =    7.98
  Az     Zen   Tapp   Rtot        Remit       Rsky        Rglint      Rdiff
240.00  77.12 283.91 .3058E+02   .2577E+02   .4817E+01   .0000E+00   .0000E+00
240.00  75.80 283.69 .3046E+02   .2617E+02   .4286E+01   .0000E+00   .0000E+00
240.00  74.17 283.47 .3034E+02   .2663E+02   .3710E+01   .0000E+00   .0000E+00

Time =   700               Wind Speed =    7.98
  Az     Zen   Tapp   Rtot        Remit       Rsky        Rglint      Rdiff
240.00  77.12 283.91 .3058E+02   .2577E+02   .4817E+01   .0000E+00   .0000E+00
240.00  75.80 283.69 .3046E+02   .2617E+02   .4286E+01   .0000E+00   .0000E+00
240.00  74.17 283.47 .3034E+02   .2663E+02   .3710E+01   .0000E+00   .0000E+00
```

In the above excerpt, we see that the model conditions, Latitude, Longitude, etc. are reported. Following this information are the time varying quantities, wind speed, sensor azimuth and zenith, and the computed radiances and apparent temperatures for each of the sensors. The azimuth is clockwise positive when looking along the nadir, with north being azimuth = 0. Remit, Rglint, and Rdiff are the sea emission, reflected sky, reflected solar glint, and reflected diffuse solar radiances, respectively. All are in units of $W / (m^2 sr)$. Rtot is the sum of these radiances and Tapp is the associated black body temperature, degrees K. Wind speed is in m/s.

6. SPEEDUP CHANGES

The addition of the Cox-Munk ocean radiance model involves the integration of sky radiance either over the sky dome or over the range of slopes of the ocean surface. This integration requires many evaluations of sky and water radiance and has slowed the EOTDA down considerably. Previous attempts to mitigate this loss in performance included precomputed azimuth and zenith angle integration limits over the sky dome that depended on wind speed. Low wind speeds result in a limited range of wave slopes and reflection of a limited portion of the sky dome into the sensor. These precomputed limits were used to limit the number of integrand evaluations in the sky dome integration.

In an attempt to speed up the water emission radiance estimate, slope space integration was carried out in polar coordinates. More integrand evaluations were performed where the rate of slope change was greatest - near the origin. In this way fewer total integrand evaluations were needed for comparable accuracy - when compared to uniformly spaced points of integrand evaluation.

Despite these efforts, the ocean radiance estimates still slowed the EOTDA down unacceptably. In a particular example with one water background, using default values for integration step size and four intervals in the wave number integration, 90% of the total time was spent in subroutine SKY - evaluating the contribution of sky emission and scattered solar radiation to the reflected ocean radiance. Of that 90%, about 40% of the time was spent evaluating the ocean reflectivity - in subroutine RHO1. Given the large amount of time spent in subroutine SKY, it was clear that it was necessary to reduce the number of times SKY was called and improve the execution speed of the routine itself.

The first step was to reduce the number of calls to SKY. The approach taken is described in section 6.1. The second step, speeding SKY itself up, is described in section 6.3. The net result, for the case investigated, was a speed improvement by a factor of about 10.

When we initiated this research contract, the 16 bit Windows 3.11 was the standard operating system used on PC's. It has since been primarily replaced by the 32 bit Windows 95 operating system. The Microsoft FORTRAN 5.1 compiler could no longer be used and was replaced with the newer (32 bit) Microsoft PowerStation FORTRAN Compiler. This conversion required substantial changes throughout the EOTDA in order for it to compile. These changes, along with Pentium class PC's, have also resulted in substantial improvements to the runtime.

6.1   Subroutine RANGER

The sensor performance model uses calculations of the target/background contrast to estimate the range at which a target is detectable. The sensor is held at a specified height, but moved toward and away from the target - changing its slant range - until the target detection threshold range was determined. This required many evaluations of the total ocean radiance with constant sensor azimuth angle but varying sensor zenith angle. The previous EOTDA would recompute the radiance at each iteration. The current EOTDA evaluates the ocean radiance at the given azimuth and for the current meteorological conditions throughout a range of zenith angles and holds the results in an array. When the slant range is being solved for, ocean radiance is determined by an interpolation into the zenith angle vs. ocean radiance array rather than by re-evaluating the sky dome and slope space integrals - this is significantly faster. The algorithm used in RANGER to compute detection range uses a numerical root finding technique called Binary Search. We attempted to improve the solution speed by replacing it with the Newton-Raphson iteration method. Although in many cases it reduced the number of iterations, it was not fool-proof due to inherent discontinuities in the Range algorithm; and thus, we elected to keep the original Binary Search method.

6.2   Subroutine OUTPUT

Subroutine OUTPUT also evaluates the ocean radiance for output to the NRAD.DAT file. The user now has the option to specify that the Cox-Munk radiance be computed at every output (which will produce a table that includes each component of the total radiance) or interpolated from the above mentioned radiance versus zenith angle array (which will output a table that includes just the apparent temperature).

The user is asked:

Do you want full diagnostics for water backgrounds?

Enter <y>es for full or <return> for minimal default:

Answering *yes* to this question results in the water background radiance being computed for output to the NRAD.DAT file. Interpolation into the radiance array is the default result.

6.3   Subroutine SKYSLOPE

Since most of the time spent computing the ocean radiance was in subroutine SKY, a method was sought to speed up the integration carried out there. The approach taken was to use a modified version of subroutine SKY in NRAD Technical Report 1702, "SeaRad, A Sea Radiance Prediction Code." In this routine, integration is carried out over wave slopes rather than over the sky dome. It uses a function, $Ns(T_s, v)$, to find the sky radiance incident on the ocean surface at zenith angle T_s and wavenumber v. The modified version of SKY (called SKYSLOPE in the EOTDA) calls subroutines SOLCOMP1 (a function of zenith and azimuth angles) and SKYDIR1 (a function of zenith angle) to get the diffuse solar radiance and the sky emission at the ocean surface. The integration of radiance over wave slopes is placed inside a loop to integrate over wave number to produce the total sky irradiance reflected from the ocean surface. Subroutine SKYSLOPE is faster than subroutine SKY by a factor of about 2.

7.   Future Work

We propose to complete the integration of LOWTRAN/MODTRAN routines into the EOTDA to improve skyshine and solar incidence modeling. The EOTDA currently models the skyshine incident on the ocean surface without the option to change spectral range or resolution - the scattered solar component is modeled using a single radiance value between 8 and 14 micrometers (held in the weather file) and the sky emission is 'hard-coded' for the 8 - 14 micrometer band also. Spectral dependence is included only in the ocean surface reflectance.

The incorporation of LOWTRAN/MODTRAN routines in the EOTDA would introduce spectral dependence into the direct and diffuse solar radiance and the sky thermal emission. The range of LOWTRAN/MODTRAN options - model atmosphere, type of extinction, seasonal dependence of the troposphere and stratosphere aerosol profiles - could be included in the EOTDA. This would require additional inputs to specify the options to be used.

Simply replacing the current EOTDA skyshine estimation routines with some subset of the LOWTRAN/MODTRAN model would greatly increase the complexity of the sky radiance code - slowing down the EOTDA. Phillips Laboratory report PL-TR-95-2007, "Phenomenology Studies in Support of Aircraft IR Signature Modeling", provides a means to reduce the impact of the additional complexity on modeling time. This report describes an algorithm for approximating the skyshine at all parts of the sky (at a given wavelength) using the results of LOWTRAN/MODTRAN modeling at only four points of the sky dome. The values at these four points are then used to interpolate values throughout the sky - with zenith and azimuth angle dependence.

The EOTDA then need only call the LOWTRAN/MODTRAN routines four times for each wavenumber, and only when the meteorological conditions change. All other values of skyshine would be obtained by using the interpolation algorithm. The increased complexity of the LOWTRAN/MODTRAN based skyshine routines would thereby be offset by the limited number of times the routines would need to be called.

THERMOANALYTICS FINAL REPORT ON THE SKY MODEL
MODIFICATION

The Addition of the MODTRAN 3/LOWTRAN 7 Sky Model to the Electro-Optical Tactical Decision Aid (EOTDA)

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PREFACE

1. INTRODUCTION

The Electro-Optical Tactical Decision AID (EOTDA) is a computer code used to predict electro-optical system performance for a given set of targets and backgrounds. The existing EOTDA was developed for the U.S. Air Force at a cost of several million dollars over 15 years and several contracts. The Air Force developed EOTDA has been adapted to U.S. Navy platforms and is used in the Navy Tactical Mission Planning System (TAMPS 6). However, the existing EOTDA has been found inaccurate for marine applications. An improved radiance model for ocean scenarios, called SeaRad was developed by Dr. Carl Zeisse at NRaD based on the Cox-Munk method and implemented in the EOTDA by ThermoAnalytics Inc., Calumet Michigan. The addition of the ocean radiance model has uncovered deficiencies in the EOTDA sky model that provides input to the ocean radiance model. The current model tends to underestimate sky radiance under both clouded and clear sky conditions. This task involved replacing the existing EOTDA sky and cloud infrared radiance models with the more widely accepted MODTRAN /LOWTRAN model.

2. APPROACH

The ocean radiance model addition to the EOTDA requires estimates of thermal path radiation, scattered solar radiation and direct solar radiation at all points of the sky dome. The unmodified EOTDA uses two modules to calculate this radiation - subroutines **SKYDIR** and **SOLCOMP**. In order to minimize changes to the EOTDA, code from the MODTRAN/LOWTRAN suite of modules was integrated with the EOTDA code to allow direct substitution of calls to MODTRAN/LOWTRAN derived subroutines for calls to **SKYDIR** and **SOLCOMP**.

A further modification was needed to prevent unacceptable slowdown of the EOTDA, since the increased sophistication of the MODTRAN/LOWTRAN based radiation estimates also greatly increased run-time. The modification was based on a 4 sky-point interpolation scheme described in Robertson [1]. Rather than calling the MODTRAN/LOWTRAN sky radiance routines for each point in the sky - when integration over the skydome was carried out, the MODTRAN/LOWTRAN routines were required for only 4 points: (1) at 90 degree zenith and 180 degree azimuth from the sun, (2) at 70 degree zenith and 180 degree azimuth, (3) directly toward the sun and (4) 20 degrees off the solar zenith and 0 degrees off the solar azimuth. The thermal path radiance and scattered solar radiance were then estimated for all points of the sky dome using values of spectral transmittance, thermal radiance, scattered solar radiance and molecular optical depth at these 4 points.

User provided MODTRAN/LOWTRAN input for the modified EOTDA is held in the 'TAPE5' file, as in normal MODTRAN/LOWTRAN runs, although only certain MODTRAN/LOWTRAN options are permitted in the EOTDA, since we are restricting our attention to the application of the MODTRAN/LOWTRAN code to sky/solar radiation estimates for paths from sea-level to space.

The MODTRAN/LOWTRAN modules were modified only to suppress standard MODTRAN/LOWTRAN output, save out radiances, transmittances and optical depth estimates for use in the interpolator and to disallow MODTRAN/LOWTRAN options not needed for the sea radiance application. Some user specified variables ordinarily taken from the **TAPE5** file to drive MODTRAN/LOWTRAN are instead taken from the EOTDA inputs.

3.   DIRECTIONAL SKYSHINE IRRADIANCE

Skyshine radiation exhibits two features that we wish to capture in the sea radiance calculations - a strong solar peak in the direction towards the sun and an increase in radiance towards the horizon in the half of the sky opposite to the solar direction. This structure is seen at both shorter wavelengths (solar only) and longer wavelengths (thermal emissions only). The four MODTRAN runs used to characterize this structure are:

(1) Horizontal path near 90 degree zenith, 180 degree azimuth from the sun.

(2) Path at 70 degree zenith, 180 degrees from the sun.

(3) Path directly towards the sun.

(4) Path at 20 degrees from solar zenith, 0 degrees from solar azimuth.

The skyshine estimate based on these four points is divided into three components:

(1) Thermal emissions, which include the thermal skyshine component calculated by MODTRAN for viewing the horizon opposite to the sun.

(2) Indirect solar skyshine, which includes direct and multiply scattered sunshine that is determined by looking at the horizon opposite to the sun, and

(3) Scattered solar skyshine, including the more directly scattered solar component with a peak in the solar direction.

Skyshine Near the Horizon

Thermal and indirect solar components are well approximated by

$$f(\theta) = \frac{E_\lambda}{\Delta_\lambda + \cos(\theta)}$$

(1)

where θ is the zenith angle and the constants E_λ and Δ_λ are determined at each wavenumber by MODTRAN runs (1) and (2). Equation (1) is fitted to the thermal and solar components separately. This simple fit has problems at the edge of the molecular absorption bands for the solar component due to the interplay between atmospheric absorption and scattered solar radiation. Adding a component to the solar scattering algorithm helps account for this absorption. The solar component is then given by

$$E_1(\lambda,\theta) = \frac{E_{\lambda\tau}\tau_\lambda + E_\lambda}{\Delta + \cos(\theta)} \tag{2}$$

Here, τ_λ is the transmittance from space to the observer along the observer's look direction and $E_{\lambda\tau}$ is a second solar energy term.

The second solar energy term is only used when the skyshine near the horizon is significantly modified by molecular absorption. Equation (2) is used (rather than equation (1)) when the solar irradiance at the horizon is equal or less than that calculated at 70 degree zenith. The value of Δ is then set at 0.5 and τ_λ is calculated as follows:

(1) Estimate optical depth. The optical depth for the atmospheric path is estimated from MODTRAN calculations at 70 and 90 degree zenith angles. For a zenith angle less than 70 degrees, the MODTRAN optical depth for molecular scattering at 70 degrees is scaled based on the plane parallel atmosphere approximation. For zenith angles between 70 and 90 degrees, equation (1) is used to interpolate the optical depth.

(2) Calculate transmittance. The spectral transmittance is given by

$$\tau_\lambda = \exp\left[-\left(k_\lambda x / \sqrt{1 + a_\lambda k_\lambda x}\right)\right] \tag{3}$$

where x is the estimated optical depth , and k_λ and a_λ are curve-fit parameters determined from the MODTRAN scattered radiances at 70 and 90 degrees. These parameters are calculated for each wavenumber and then used for all directions. When the calculated τ_λ at 90 degrees is less than 10^{-7}, the following expression is used instead:

$$\tau_\lambda = \exp\left[-\left(k_\lambda x / a_\lambda\right)^{1/2}\right] \tag{4}$$

Skyshine Near the Sun

The skyshine component near the sun includes solar radiation scattered by the atmosphere and excludes the direct solar component, which is calculated separately as simply attenuated sunlight. The scattered radiation is calculated by MODTRAN as the single and multiple scattered atmospheric radiance. As with the horizon case we introduce a scaling function to describe the angular width of the scattered solar radiation. The form used is:

$$E_{2\lambda} = \frac{E_{sol} - E_1}{\varepsilon^2 \cos^2(\alpha) + \sin^2(\alpha)} \tag{5}$$

where E_1 is the component of scattered solar radiation from the horizon, E_{sol} and ε are the model parameters, and α is the scattering angle between the solar direction and the incident direction for the skyshine. One MODTRAN run is along the observer-to-sun path and a second run uses a zenith 20 degrees off the solar zenith, both with a 0 degree relative zenith angle. When the scattering angle α is greater than 90 degrees, the direct scattered solar component is assumed to be zero. See Robertson [1] for more details concerning the directional skyshine model.

Despite the use of this four point curve fit to speed skyshine estimates, the additional computational burden due to the use of the MODTRAN/LOWTRAN routines may slow the EOTDA down, depending on the options used. Use of MODTRAN routines appear to slow calculations down more than do LOWTRAN routines. The computation of multiple scattering radiance - particularly usage of the DISORT algorithm for multi-stream multiple scattering calculations - significantly slows the EOTDA down.

2. THE MODTRAN 3/LOWTRAN 7 RADIANCE ESTIMATES

New Inputs

The addition of the MODTRAN/LOWTRAN routines to the EOTDA required the addition of new inputs to drive the routines. These new inputs are held in a **TAPE5** file, a sample of which is included in the delivered software . Since this application of the MODTRAN/LOWTRAN routines is for ocean radiance estimation, certain restrictions apply to the options allowed in the **TAPE5** file:

(1)   The file must specify two MODTRAN/LOWTRAN runs - one for thermal radiation and scattering calculations and another for direct solar radiance calculations. The thermal and scattered radiance calculations will be carried out for points 1 through 4 and the direct transmitted solar calculation is carried out for point 3.

(2)   The MODTRAN/LOWTRAN variable specifying 'mode of execution' must be IEMSCT=2 for the first run and IEMSCT=3 for the second run. These two modes correspond to thermal and scattered radiance calculations and direct solar calculations, respectively.

(3)   Restriction (a) also forces the first occurrence of IRPT = 1 and the second occurrence, IRPT = 0.

(4)   Since we are interested in radiance at the ocean surface, we want ITYPE = 3, specifying a MODTRAN calculation for a vertical or slant-path to space.

(5)   The MODTRAN variable IPARM must be = 2. This keeps the specification of observer/sun geometry similar to that used in the EOTDA. This value for IPARM forces further requirements on the **TAPE5** file according to the MODTRAN/LOWTRAN manual.

Note: As indicated in restriction (5) above, certain **TAPE5** options affect the way the MODTRAN/LOWTRAN routines read the **TAPE5** file. For example, if IVSA=1, variables ZCVSA, ZTVSA and ZINVSA will be read. MODTRAN/LOWTRAN will fail if these variables are not in **TAPE5** - and the MODTRAN/LOWTRAN routines in the modified EOTDA will fail as well. That is, the MODTRAN/LOWTRAN routines have not been modified to trap out user input errors.

Ignored TAPE5 Inputs

Some variables are retained in the **TAPE5** file to keep the file of the same form as the standard MODTRAN/LOWTRAN **TAPE5** file, but are ignored when the MODTRAN/LOWTRAN routines are called.

(1)   The solar zenith angle is supplied by the EOTDA calling routines and ignored in **TAPE5**.

(2)   Day of the year is supplied by the EOTDA.

(3)   Instantaneous wind speed is supplied by the EOTDA. A 24 hour average wind speed is supplied by **TAPE5**. It is MODTRAN/LOWTRAN variable WHH. WHH is only used when IHAZE =3.

(4)   Observer zenith and azimuth angles are supplied by the EOTDA - ignored in **TAPE5**.

(5)   **TAPE5** variables IV1, IV2 and IDV are the initial wavenumber, the final wavenumber and the wavenumber increment used in MODTRAN calculations. These inputs are ignored and equivalent variables are taken from the EOTDA and substituted for the **TAPE5** inputs. Since MODTRAN allows only integer specification of these quantities and has a maximum wavenumber increment of $50 \ cm^{-1}$, the EOTDA specification of these quantities may not be exactly those used in MODTRAN. The actual wavenumbers used in the MODTRAN calculations will be output to the **MTRN.dat** file.

TAPE5 Read Warnings

(1)   If GNDALT ≠ 0, the user is warned that ground altitude is not at sea-level. Since this application of MODTRAN is intended to be used to estimate skyshine at the sea surface, the user is warned that sea-level is not at sea-level, but execution may continue if the user wishes.

(2)   If ISOURC ≠ 0, the user is warned that the extraterrestrial radiation source is not the sun - again, execution may continue.

New Output

An additional file is now generated to allow the user to examine the MODTRAN/LOWTRAN radiance calculations for the 4 sky points used in the interpolator and the results of integration of the interpolated radiances over the sky dome and the wavenumber band. This file, **MTRN.dat,** also reproduces the header portion of MODTRAN/LOWTRAN **TAPE6** output file. Each time the sensor performance model is called the MODTRAN/LOWTRAN routines are called and the results written to **MTRN.dat.** A skydome/wavenumber integration routine is also called, using the 4 point interpolator to calculate radiances throughout the skydome, and the integrated radiances also written to **MTRN.dat**. A sample portion of a **MTRN.dat** file is reproduced below.

```
*** MODTRAN3 Version 1.5 4/96 ***
0 CARD 1 *****F  6  3  2  0  0  0   0  0   0  0  0  0  0 283.000  .40
0 CARD 2 *****  0  1  0  1  0  0    .000    .000    .000    .000    .000
0 CARD 3 *****    .000    .000    .000  400.000    .000    .000  0
0 CARD 3A1*****  2  2  1  0
0 CARD 3A2*****  1.000  5.000    .000    .000    .000    .000    .000    .000
0 CARD 4 *****   833   1250    41    2
0 PROGRAM WILL COMPUTE RADIANCE+SOLAR SCATTERNG
0 ATMOSPHERIC MODEL
        TEMPERATURE =  6   1976 U S STANDARD
        WATER VAPOR =  6   1976 U S STANDARD
        OZONE    =  6   1976 U S STANDARD
             M4 =   6 M5 =   6 M6 =   6 MDEF =   1
0 SLANT PATH TO SPACE
        H1   =    .000 KM
        HMIN =    .000 KM
        ANGLE =    .000 DEG
0 SINGLE SCATTERING CONTROL PARAMETERS SUMMARY

        RELATIVE AZIMUTH =        1.000 DEG EAST OF NORTH
        SOLAR ZENITH =       5.000 DEG
        TIME (<0 UNDEF) =       .000 GREENWICH TIME
        PATH AZIMUTH =       .000 DEG EAST OF NORTH
        DAY OF THE YEAR =        1
0 EXTRATERRESTIAL SOURCE IS THE SUN
0 PHASE FUNCTION FROM MIE DATA BASE
0 FREQUENCY RANGE
        IV1 =      830 CM-1  (   12.05 MICROMETERS)
        IV2 =     1250 CM-1  (    8.00 MICROMETERS)
        IDV =       40 CM-1
        IFWHM =      2 CM-1
0 CARD 5 *****   1
 *** MODTRAN3 Version 1.5 4/96 ***
0 CARD 1 *****F  6  3  3  0  0  0   0  0   0  0  0  0  0 283.000  .40
0 CARD 2 *****  0  1  0  1  0  0    .000    .000    .000    .000    .000
0 CARD 3 *****    .000    .000    .000  0      .000  0    .000
0 CARD 4 *****   833   1250    41    2
0 PROGRAM WILL COMPUTE TRANSMITTED SOLAR IRRAD.
0 ATMOSPHERIC MODEL
        TEMPERATURE =  6   1976 U S STANDARD
        WATER VAPOR =  6   1976 U S STANDARD
        OZONE    =  6   1976 U S STANDARD

             M4 =   6 M5 =   6 M6 =   6 MDEF =   1
0 SLANT PATH TO SPACE
        H1   =    .000 KM
        HMIN =    .000 KM
        ANGLE =    .000 DEG
0 FREQUENCY RANGE
        IV1 =      830 CM-1  (   12.05 MICROMETERS)
        IV2 =     1250 CM-1  (    8.00 MICROMETERS)
        IDV =       40 CM-1
        IFWHM =      2 CM-1
```

MODTRAN radiances at time   900 sun at zenith angle   94.763950
Point 1 at 180 degree solar az., 89.5 degree zen.
Point 2 at 180 degree solar az., 70.0 degree zen.

Radiances(Watts/(m2-ster-(cm-1)))

	Point1		Point2		Point3		Point4		Direct Solar
WavNmbr	Thermal	Scattered	Thermal	Scattered	Thermal	Scattered	Thermal	Scattered	Watts/(m2-(cm-1))
830.	1.07E-01	0.00E+00	3.53E-02	7.54E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
870.	1.00E-01	0.00E+00	2.87E-02	9.78E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
910.	9.30E-02	0.00E+00	2.40E-02	1.38E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
950.	8.58E-02	0.00E+00	2.17E-02	1.87E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
990.	7.76E-02	0.00E+00	1.76E-02	9.39E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1030.	7.34E-02	0.00E+00	3.35E-02	2.75E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1070.	6.52E-02	0.00E+00	1.95E-02	5.80E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1110.	5.76E-02	0.00E+00	1.41E-02	3.23E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1150.	5.39E-02	0.00E+00	1.64E-02	3.54E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1190.	4.99E-02	0.00E+00	1.90E-02	4.81E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1230.	4.61E-02	0.00E+00	2.40E-02	3.84E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Radiances integrated over skydome (steradians) and wavenumber (cm-1)

WavNmbr	Thermal	Scattered	Thermal	Scattered
cm-1	Watts/(m2 cm-1)	Watts/(m2 cm-1)	Watts/m2	Watts/m2
830.	7.63E-02	2.06E-12	1.53E+00	4.12E-11
870.	6.16E-02	2.61E-12	3.99E+00	1.46E-10
910.	5.10E-02	3.63E-12	6.03E+00	2.91E-10
950.	4.60E-02	4.91E-12	7.87E+00	4.87E-10
990.	3.73E-02	2.51E-12	9.36E+00	5.88E-10
1030.	7.56E-02	1.13E-14	1.24E+01	5.88E-10
1070.	4.18E-02	1.65E-12	1.41E+01	6.54E-10
1110.	2.99E-02	8.52E-12	1.53E+01	9.95E-10
1150.	3.53E-02	9.67E-12	1.67E+01	1.38E-09
1190.	4.17E-02	1.36E-11	1.83E+01	1.93E-09
1230.	5.55E-02	1.22E-11	1.94E+01	2.17E-09

MODTRAN radiances at time   1000 sun at zenith angle   85.451680
Point 1 at 180 degree solar az., 89.5 degree zen.
Point 2 at 180 degree solar az., 70.0 degree zen.
Point 3 at 0 degree solar az., 85.452 degree zen.
Point 4 at 0 degree solar az., 65.452 degree zen.

Radiances(Watts/(m2-ster-(cm-1)))

	Point1		Point2		Point3		Point4		Direct Solar
WavNmbr	Thermal	Scattered	Thermal	Scattered	Thermal	Scattered	Thermal	Scattered	Watts/(m2-(cm-1))
830.	1.07E-01	3.56E-11	3.53E-02	1.16E-10	8.15E-02	1.71E-10	3.07E-02	1.05E-10	3.18E-04
870.	1.00E-01	7.53E-11	2.87E-02	1.65E-10	7.03E-02	2.92E-10	2.49E-02	1.48E-10	4.51E-04
910.	9.30E-02	1.41E-10	2.40E-02	2.29E-10	6.10E-02	4.54E-10	2.07E-02	2.04E-10	5.88E-04
950.	8.58E-02	2.35E-10	2.17E-02	3.00E-10	5.42E-02	6.38E-10	1.88E-02	2.67E-10	6.95E-04
990.	7.76E-02	3.68E-10	1.76E-02	3.09E-10	4.53E-02	7.70E-10	1.53E-02	2.75E-10	7.09E-04
1030.	7.34E-02	7.85E-12	3.35E-02	1.19E-11	5.73E-02	2.30E-11	3.06E-02	1.28E-11	1.71E-05
1070.	6.52E-02	4.27E-10	1.95E-02	3.34E-10	4.20E-02	8.15E-10	1.73E-02	3.02E-10	5.47E-04
1110.	5.76E-02	1.27E-09	1.41E-02	7.15E-10	3.24E-02	1.91E-09	1.25E-02	6.31E-10	1.12E-03
1150.	5.39E-02	9.99E-10	1.64E-02	7.60E-10	3.45E-02	1.78E-09	1.47E-02	6.79E-10	9.03E-04
1190.	4.99E-02	8.15E-10	1.90E-02	8.51E-10	3.56E-02	1.73E-09	1.72E-02	7.66E-10	7.66E-04
1230.	4.61E-02	3.06E-10	2.40E-02	6.78E-10	3.83E-02	9.70E-10	2.21E-02	6.30E-10	3.74E-04

Radiances integrated over skydome (steradians) and wavenumber (cm-1)

WavNmbr	Thermal	Scattered	Thermal	Scattered
cm-1	Watts/(m2 cm-1)	Watts/(m2 cm-1)	Watts/m2	Watts/m2
830.	7.63E-02	3.76E-10	1.53E+00	7.52E-09
870.	6.16E-02	5.11E-10	3.99E+00	2.80E-08
910.	5.10E-02	6.92E-10	6.03E+00	5.56E-08
950.	4.60E-02	8.94E-10	7.87E+00	9.14E-08
990.	3.73E-02	9.90E-10	9.36E+00	1.31E-07

1030.	7.56E-02	4.85E-11	1.24E+01	1.33E-07
1070.	4.18E-02	1.04E-09	1.41E+01	1.74E-07
1110.	2.99E-02	1.99E-09	1.53E+01	2.54E-07
1150.	3.53E-02	2.33E-09	1.67E+01	3.47E-07
1190.	4.17E-02	2.60E-09	1.83E+01	4.51E-07
1230.	5.55E-02	2.43E-09	1.94E+01	5.00E-07

Below the header of the MTRN.dat file follow the tables of the MODTRAN/LOWTRAN calculated radiances at the 4 sky points, at the indicated simulation time and solar zenith angle. The 4th sky point is at 0 degree azimuth from the sun and 20 degrees off the solar azimuth - this zenith is noted above the radiance table. Since MODTRAN calculated quantities (scattered radiances, transmittances, optical depth) at points 3 and 4 are used together to interpolate the near sun component of scattered solar radiation, and point 4 is directly toward the sun, if the sun is below the horizon, MODTRAN calculations are not carried out for points 3 or 4 and all radiance entries will be zero. When this occurs, only the interpolations based on evaluations at points 1 and 2 are used in EOTDA calculations.

The second table of radiances at each output time are the thermal emissions and scattered solar radiances integrated over the sky dome and across the wave band. The first column is the wave number in 1/cm. The second and third columns are the radiances integrated over the sky dome - using the 4 point interpolator to estimate radiances over the dome. The fourth and fifth columns are the intermediate sums in the integration over the wave band - with the last number in each column representing the total integrated radiance over the full sky and wave band.

2.   REFERENCES

[1] Robertson, D. C., P. K. Acharya, A. Berk, W.M. Cornette, and J. H. Gruninger, *Phenomenology Studies in Support of Aircraft IR Signature Modeling,* Phillips Laboratory Report PL-TR-95-2007

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13. ABSTRACT *(Maximum 200 words)*

This report compares the predictions of ocean radiance and detection range from the unmodified Electro-optical Tactical Decision Aid (EOTDA) version 3.0 with a modified version. The original EOTDA was developed by the U. S. Air Force, with only minimal attention applied to the complexities of the marine environment. The objective of this comparative study was to evaluate whether modifying the EOTDA would improve ocean background radiance predictions and ultimately improve detection range performance. The modifications involved replacing the original semi-empirical water background model with a rigorous geometric ocean radiance model, called SeaRad, and replacing the sky radiance model with the sky model from the MODTRAN 3 code. A significant difference in behavior was noted between the original and modified EOTDA when comparing the zero-range ocean background temperature predictions of both models. Because sufficient improvement was realized with the modified EOTDA employing the SeaRad ocean radiance model in combination with the MODTRAN sky radiance model, transition to the navy fleet-ready version is recommended.

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