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An Integrated Radiance Throughput Model for Hypersonic Interceptor Seeker Performance Evaluation

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Abstract

Hypersonic endoatmospheric interceptors are presently under serious consideration for strategic and theater missile defenses. On board infrared seekers are planned for terminal guidance. It is desirable to perform seeker trade studies determining such things as expected S/N, tracking performance and optimum wavelength of operation. The dynamics of the interceptor/target trajectories combine with atmospheric interaction at both vehicles to degrade the infrared signal of the target. Because of this degradation, computation of this signal at the seeker focal plane and, consequently, performance of the seeker trade studies are made very difficult. These computations are usually performed piecemeal, for a limited number of trajectory points, and for very specific seeker configurations. An integrated radiance throughput model is under development that encompasses the trajectory dynamics and the atmospheric interactions. The model is intended for medium fidelity performance analysis to enable overall systems performance evaluations and trades. Performance of proposed window materials under a variety of aerothermal environments is an example of a typical trade space. Various existing codes are utilized integrally within the model, or are used to generate lookup tables for parameters over the range of trajectory and atmospheric variables. These include: the Optical Signature Code and the SIRRM Code for target signatures and bow shock radiance. The LOWTRAN 7 Code is used integrally to calculate atmospheric transmission and background. S/N and tracking performance will be estimated using a simple detector module. The model is described, and initial results are given that illustrate atmospheric transmission and window performance effects.

Introduction

A re-entering RV rapidly heats up comprising a dynamic target signature. The target signature propagates through a changing atmospheric path (with subsequent loss of energy through scattering and absorption) arriving at the hypersonic interceptor. This hypersonic interceptor also encounters a dynamic and extreme aerothermal environment. The interceptor seeker window heats up, and may require cooling by flowing cold gas over its surface. Simultaneously, the bow shock and the heated window of the interceptor radiate and produce background noise. All of these effects contribute to degradation of the target image in the seeker focal plane.

The dynamics described above comprise only a fraction of the effects that must be considered in evaluating the performance of a seeker on board an endoatmospheric hypersonic interceptor. Traditionally, the problem of determining the signal and background incident on a detector is done in piecemeal fashion, and often does not encompass all of the signal degrading factors. Furthermore, new technology development, ongoing research and test programs are shedding new light on many of the effects encountered when imaging from a hypersonic vehicle. Therefore, a need exists for a model which will examine all of the effects that degrade the interceptor seeker performance, and that can do so for a wide range of environments, and for a variety of seeker technologies and concepts.

The Integrated Radiance Throughput Model (IRTM) is being developed to quickly and efficiently provide an integrated radiance throughput analysis, considering all sources of signal degradation, for

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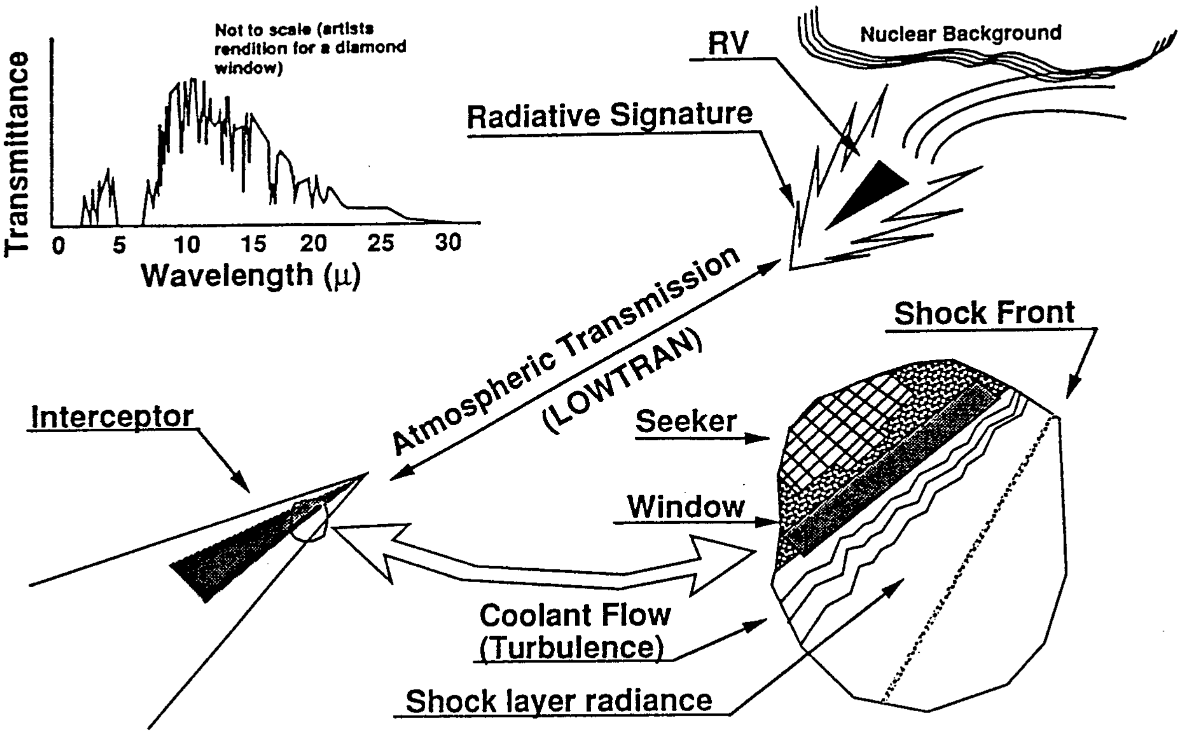

Figure 1 - Target To Detector Transmission

endoatmospheric interceptor vehicle seekers. The model will be used to examine the wavelength of operation of electro-optical (EO) seekers as new window and seeker technologies are being developed. Simultaneously, the model will incorporate data generated by new and innovative CFD and wave optic codes. Data from tests (such as the upcoming aero-optics tests at Calspan) can be used as inputs, and can help validate the model. The model is modular in nature, and includes options within various modules to provide analyses over a wide range of conditions, inputs and levels of fidelity.

The initial thrust of the program was to provide a means of evaluating diamond window and seeker technologies being developed under a Strategic Defense Command endo-technology effort. It has subsequently been expanded to include a wide range of window materials and technologies. The earliest version provides a basic throughput of the signal from a target, through the atmosphere, and through a window. It is presently being used to compare performance of various window materials over a range of target and atmospheric path parameters.

Later versions will include additional modules (i.e. consider more signal degrading sources), will have higher fidelity, and will calculate throughput for multiple points within the relative interceptor/target trajectories. The final version will have provisions for inputting seeker and aero-optic parameters derived from analysis or testing of actual hardware. The intent of this paper is to describe the overall model, discuss the present status of the model, outline the plans for completing the various modules, and to display initial results in which several window materials are compared.

Integrated Radiance Throughput Model Description

Figure 1 indicates a general picture of the target signature and sources of image degradation that are being incorporated in the model. As the target progresses through its trajectory it rapidly heats, and displays a distinct radiative signature that is primarily dependent on the temperature. The model can include background created from nuclear events as well as bow shock radiance background. Both of these are calculated by the SIRRM Code and are input into the model as look up tables. LOWTRAN is integral to the model and is used to calculate

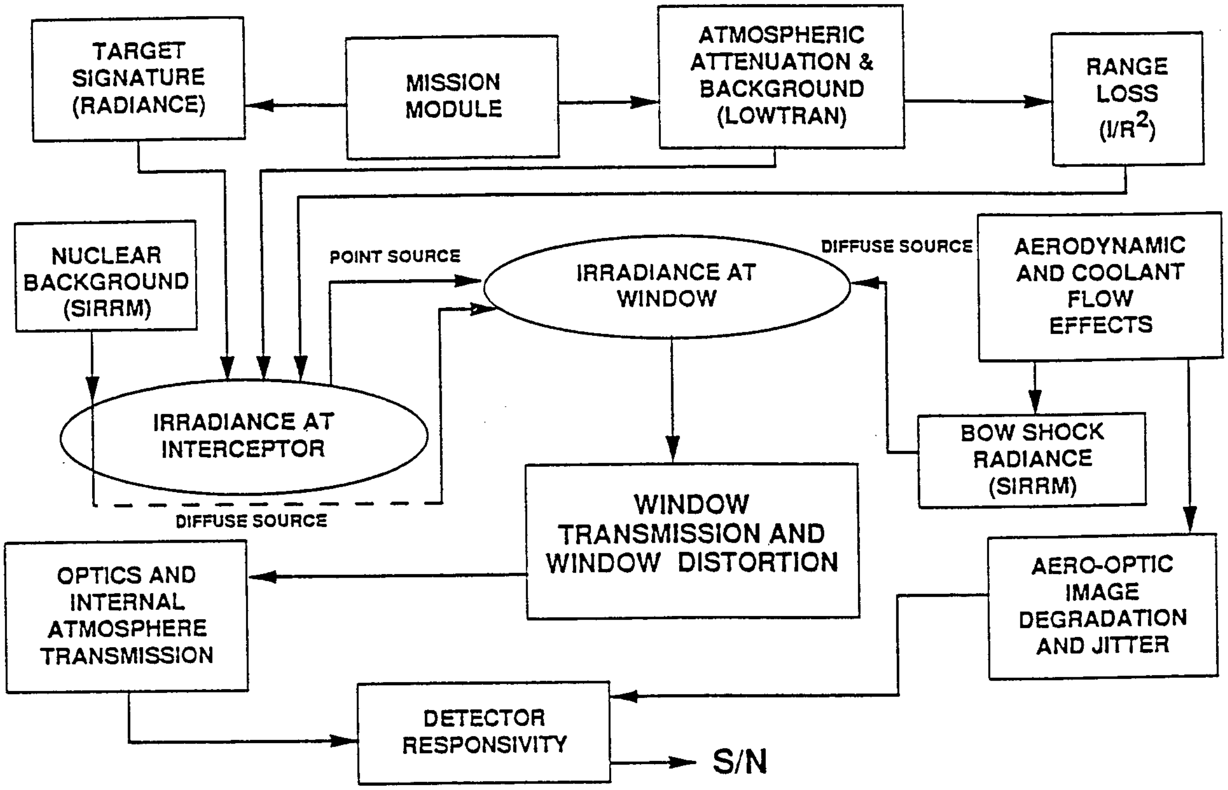

Figure 2 - Model Module Breakdown

atmospheric effects. Initially, very simple models will be used to simulate the aero-optics effects of the turbulent coolant flow. The inset to figure 1 illustrates multiple image degrading effects that take place at the interceptor.

Figure 2 illustrates all of the modules that will be included in the completed model. Note the several modules that are required to account for effects right at the interceptor. The window module must account for change in absorption as a function of heating, background caused by self-emission of the window, and distortion in the window. Bow shock radiance and aero-optics effects are accounted for by a combination of three modules: 1) the aerodynamic and coolant flow effects module, 2) the bow shock radiance module, and 3) the aero-optic image degradation and jitter module.

The modules will consist of either 1) industry standard computer codes, 2) data bases generated by computer codes or actual test data, or 3) algorithms based on the physics of the particular module. As an example: LOWTRAN is used to directly calculate atmospheric transmission. However, it is also used to generate data tables for representative atmospheric and earthshine backgrounds. It is necessary to do the latter as lookup tables because of very long run times of the LOWTRAN program when calculating background. It is desired that the model operate relatively quickly so that multiple points in a trajectory can be evaluated, and multiple technologies can be evaluated comparatively.

The target signal module is another example. Initial cases are run using Planck's black body equations to calculate radiance at a given target temperature. Later, higher fidelity models will use the Optical Signature Code to generate look up tables that more accurately represent target signatures under various velocity and altitude conditions.

The mission module serves as an input and coordination module. The multipoint version of the model will have relative trajectories input into the mission module. In turn, it will calculate altitudes, velocities and relative ranges between the interceptor and target. The RV altitude and velocity parameters will be used to access appropriate target signatures. The relative range parameters will feed the LOWTRAN program to enable appropriate transmission calculations.

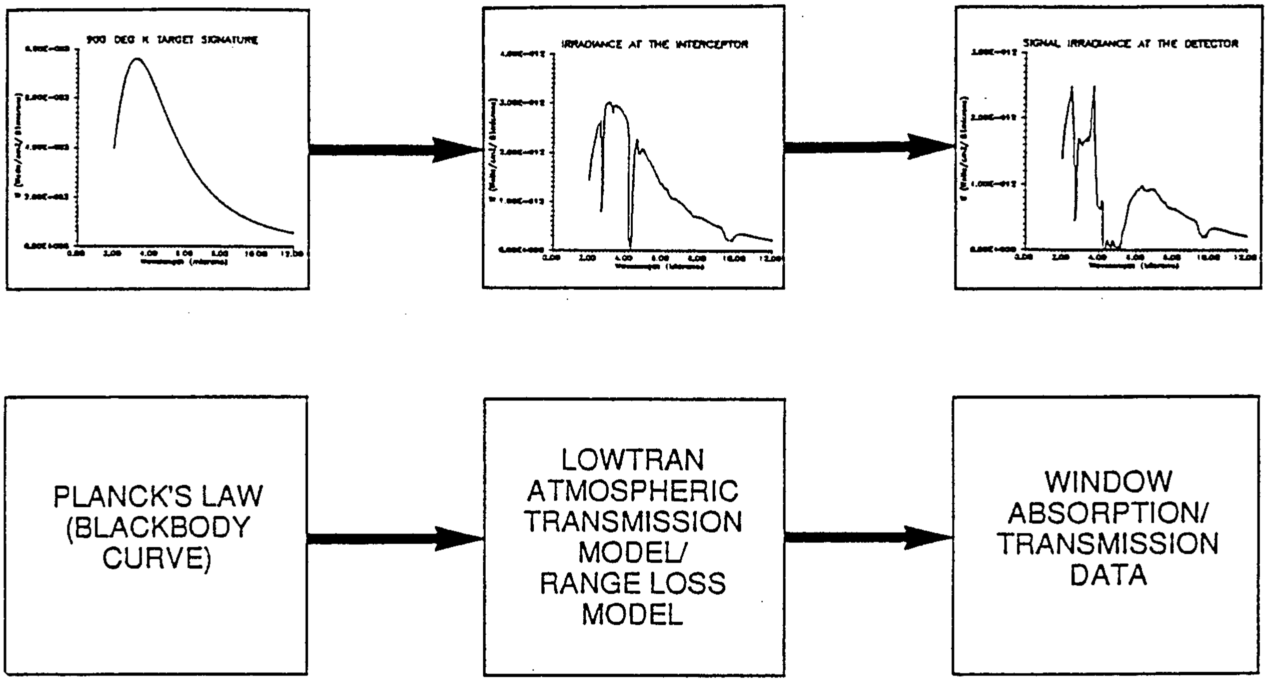

Figure 3 - Sample Throughput

Aerodynamic and coolant flow effects will be calculated off-line by CFD codes to establish inputs into the SIRRM code. The SIRRM code will also be run off-line to generate lookup tables that are accessed by using appropriate interceptor altitude and velocity parameters. CFD code outputs may also be used to generate inputs for various aero-optic codes. Aero-optic degradations indicated by these codes can be input into the throughput model as simple PSF degradation factors.

The detector module will consist of either a quadrant detector model with appropriate spectral and responsivity parameters, or may be implemented as a small staring array model with a simple centroiding algorithm.

Window distortion can be input as look up tables generated by using thermal modelling codes that in turn are fed appropriate temperature input parameters by CFD code results.

In general, industry standard codes that run sufficiently fast will be utilized directly in the model. Large codes that require extensive computational power will be used off line to generate lookup tables. This way, the overall model can operate rapidly and evaluate performance over a range of mission parameters, and can be used to evaluate several seeker technology combinations. The model is designed to operate on PCs. A Macintosh version is also planned.

Present Status and Module Implementation

The present version of the model is implemented to calculate signal throughput from a target, through the atmosphere, and through a seeker window. The intent of this version is to compare performance of various window materials given specific target signatures and atmospheric path geometries and conditions, and assumed window temperatures.

Figure 3 indicates the process involved in this simplified analysis. The target is modeled as a black body. The user chooses the desired target temperature, the RV and interceptor altitudes and the slant range. The desired atmospheric model is chosen within the LOWTRAN suite of options. The altitude and slant range information is used with LOWTRAN to calculate an atmospheric transmittance. The target signature undergoes a spectral multiplication by the calculated atmospheric transmittance factor. It is further multiplied by the $1/R^2$ factor to determine signal irradiance at the interceptor. Transmittance through the window is calculated and multiplies this signature. The resulting signature is then multiplied by the aperture area and the transmission factor of the optics. The result is a calculation of signal intensities resident on the detector.

Plots of the result from each step can be produced using the data tables generated by the model. Figure 3 specifically depicts a calculation for a hypothetical diamond window.

Figure 4 depicts the flow diagram for those modules implemented. As can be seen this is a subset of the full model illustrated in Figure 2. A final note on present status: initial window property calculations used lookup tables of absorption properties of materials found in literature or in various government contract reviews. We recently obtained a copy of the "PhononB" program [Mike Thomas, Johns Hopkins Applied Physics Laboratory], and will use it to generate new lookup tables.

The target module currently calculates signature using Planck's Black Body Law,

$$W_L = (K1 \times \Delta\lambda \times A_T)/(\lambda^5 (e^{K2/\lambda T}-1)) \qquad (1)$$

where $K1 = 37405$, $K2 = 14378.9$, A_T is the radiating area in cm^2, λ is wavelength in µm, T is temperature in K° and W_L is power radiated. The power radiated is calculated at each wavelength increment over the total waveband (which is specified as an input).

The atmospheric attenuation and background module uses the LOWTRAN computer code to determine the atmospheric transmission of the target signal over the same waveband and wavelength increment as specified in the target module. The interceptor altitude, target altitude and slant range are input using the LOWTRAN input screen. The atmospheric transmission values calculated by LOWTRAN are then multiplied by the power radiated, thereby calculating the amount of signal transmitted through the atmosphere. This value is also multiplied by the $1/R^2$ factor to account for the range between the target and the interceptor (eqn. 2).

$$W_I = (W_L \times t_a)/R^2 \qquad (2)$$

where W_I is the power incident at the interceptor, t_a is the atmospheric transmission value, and R is the range between the target and the interceptor.

The window module contains absorption data (vs. wavelength) for several different materials including diamond and sapphire, two materials being used for endoatmospheric interceptors. After choosing a window material and window thickness, the power transmitted through the window is calculated by

$$W_W = W_I \times e^{-(a \times t)} \qquad (3)$$

where W_W is the power transmitted through the window, a is the absorption coefficient of the win-

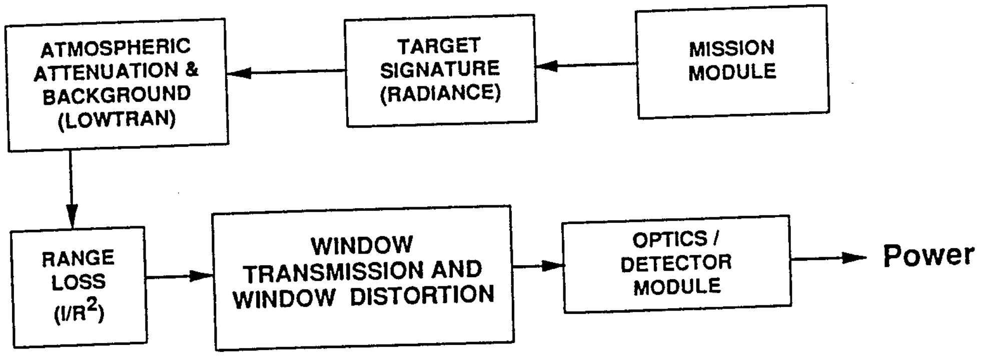

Figure 4 - Throughput Model Flow

dow material, and t is the thickness of the window.

The final module implemented in the throughput model, is the detector/optics module. It currently calculates the power received per quadrant of the detector by

$$W_D = A_r \times t_D \times W_W/4 \tag{4}$$

where A_r is the area of the receiver and t_D is the transmission factor of the optics. For the results shown in the following paragraph, the aperature diameter is 10cm and the transmission of the optics is assumed to be .8.

Figures 5-7 show a comparison of diamond and sapphire windows looking at a 900°K target from 50km away. The sapphire window represents a typical HEDI configuration and the diamond window represents a typical Endo LEAP configuration. Figure 5 shows the results for a target at 37km altitude and an interceptor at 7km altitude. As is expected, the sapphire window outperforms the diamond in the waveband from about 3μm - 5μm, but diamond performs much better across the full spectrum, excluding 4μm - 6μm. Figure 6 shows the results for the target at 40km altitude and the interceptor at 10km altitude. The irradiance for both window materials has improved considerably at these higher altitudes (because of the less dense atmosphere to transmit through), most notably for the diamond at the longer wavelengths. Figure 7 shows the diamond and sapphire windows for the target at 45km and the interceptor at 15km. Once again, the diamond performance is greatly increased at longer wavelengths. Figures 8 - 10 show the power received per quadrant of the detector for the same cases outlined in Figures 5 - 7. Three spectral bands were input: band 1 from 3-5μm, band 2 from 5-8μm and band 3 from 8-12μm. In each case, the diamond window outperforms the sapphire window at the higher wavelengths, (spectral bands 2 and 3), and the sapphire significantly outperforms the diamond in spectral band 1.

If one shifts to a 2-4 μm band as shown in Figure 11, more energy is available using a diamond window. However, sapphire still outperforms diamond, but the results are closer. Two things to keep in mind in making trades of this nature: 1) for targets of these temperatures there is plenty of power in these bands (2-4 & 3-5) using either window, 2) other trade factors may be more important, i.e., much superior material properties for diamond that may simplify other aspects of the overall interceptor/seeker design (diamond is stronger, much better thermal conductance, has lower emissivity, etc.).

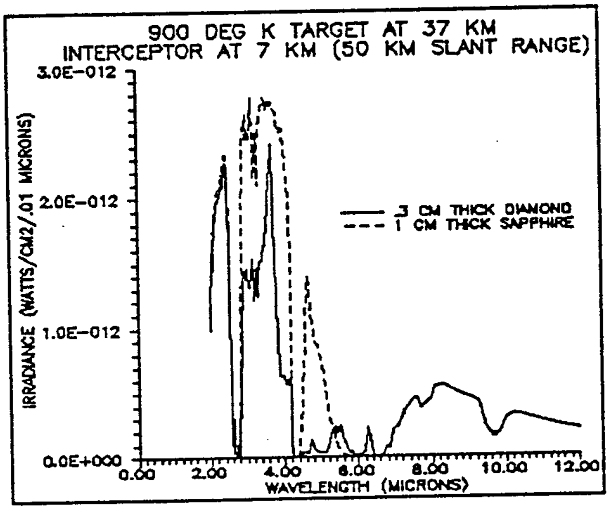

Figure 5 - 7km Interceptor Throughput

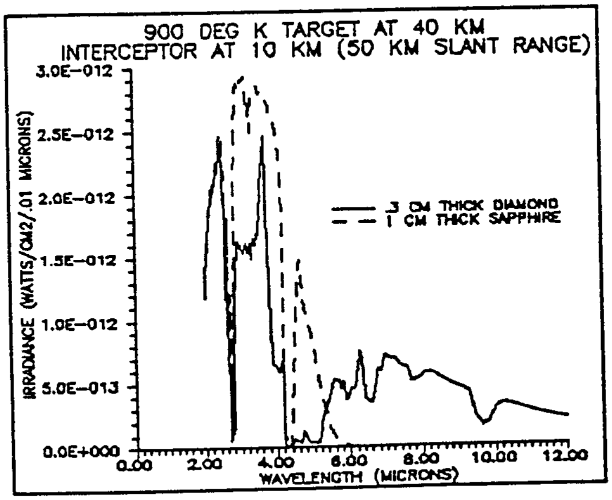

Figure 6 - 10km Interceptor Throughput

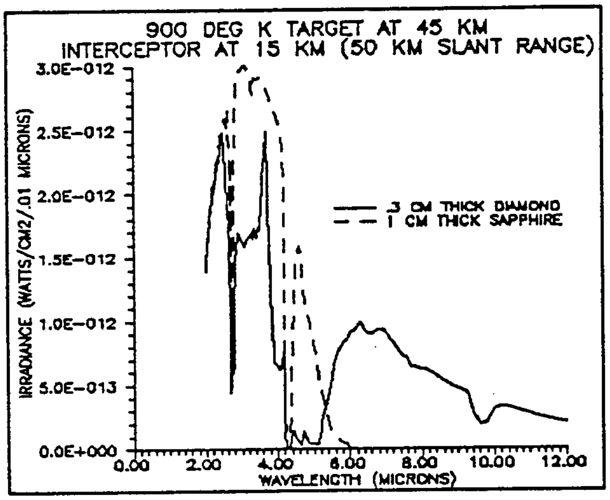

Figure 7 - 15km Interceptor Throughput

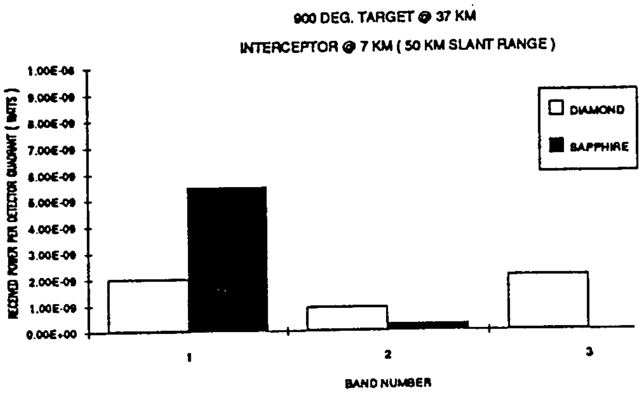

Figure 8 - 7km Interceptor Detector Power

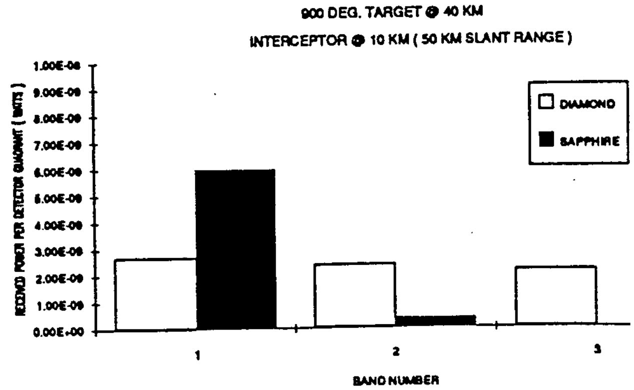

Figure 9 - 10km Interceptor Detector Power

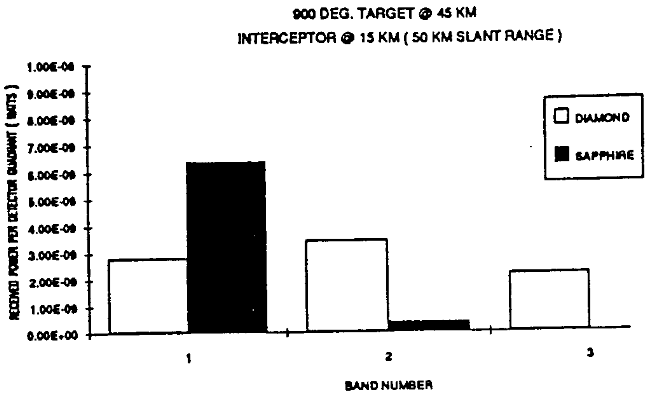

Figure 10 - 15km Interceptor Detector Power

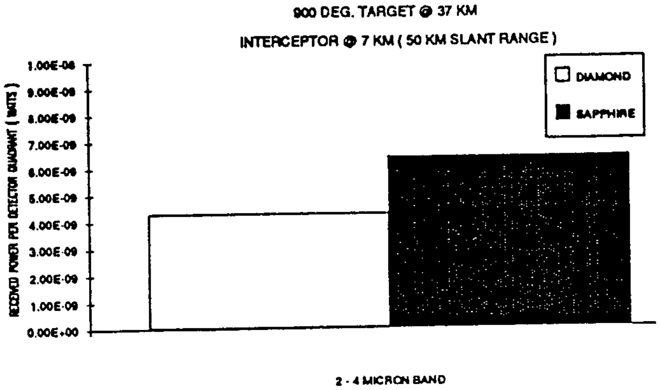

Figure 11 - Detector Power for 2-4 micron Band

Summary

An integrated radiance throughput model is under development. This model is intended for use as a performance evaulation tool for various seeker component and systems technologies. It can be used as a systems tool to provide a means of performing trade studies at a medium level of fidelity. It is already being used for comparative studies of possible window materials. The model is implemented to provide rapid results for numerous mission scenarios, and geometries using various emerging window and seeker technologies.