Multispectral Imager Modeling

Jonathan Fanning[a], Carl Halford[a], Eddie Jacobs[b], Phil Richardson[b]
[a]University of Memphis, Memphis, TN, USA 38152;
[b]U.S. Army Night Vision and Electronic Sensors Directorate (NVESD), Fort Belvoir, VA, USA 22060

ABSTRACT

This paper describes the modeling of multispectral infrared sensors. The current NVESD infrared sensor model, NVTherm[1], models single spectral band sensors. The current NVTherm model is being updated to model third generation multispectral infrared sensors. A simple model for the target and its background radiance is presented here and typical results are reported for common materials. The proposed target radiance model supports band selection studies. Spectral atmospheric propagation modeling is accomplished using MODTRAN. Example radiance calculations are presented and compared to data collected for validation. The data supports rejecting the null hypothesis that the model is invalid.

Keywords: NVTherm, spectral radiance

1. INTRODUCTION

This paper presents a description of NVTherm[1], the current NVESD thermal sensor model, and suggests an extension to multispectral capabilities. NVTherm is designed to model single spectral band sensors. Third generation infrared sensors (FLIRs) currently under development will sense multiple spectral bands with a single detector array. Consequently, the current NVTherm model must be updated to model multispectral imager systems. A more detailed model of the target and background is required to incorporate spectral effects. One such model is presented. It uses planar surfaces in the form of a box sitting on a plane and located near a planar wall. The box is a tank-sized box and the wall can represent a building or a tree line, depending on what materials are specified.

This model is intended to give quick and useful spectral target radiance predictions without a high level of expertise in thermal prediction being required by the user. A complicated target/background scenario would require the use of more sophisticated codes such as Muses or ShipIR. This model is not intended to be a substitute for those codes.

To simplify the calculation of spectral radiance, some assumptions have been made about the materials and surfaces. All materials and surfaces are assumed to be opaque and Lambertian. The opaque assumption avoids the need to handle translucent materials. Assuming opaque materials allows the material properties to be fully specified by either reflectance or emittance. Very few materials are translucent in the infrared bands. The Lambertian assumption allows geometric calculations to be separated from spectral calculations. This greatly reduces the amount of calculation necessary. Most materials are close to Lambertian in the infrared. Handling non-Lambertian surfaces would greatly complicate the model.

An example system is treated in detail. Painted surfaces are used for the box surfaces and the ground plane is assumed to be asphalt. The wall is assumed to be brick. A data collection provides sufficient data to show agreement with the predictions of the model. That is, the data supports rejecting the null hypothesis that the model is invalid.

1.1. NVTherm

NVTherm is a sensor model designed to compare the performance of infrared sensors. The current version of NVTherm is designed to model single band infrared sensors in the MWIR (3μm to 5μm) and LWIR (8μm to 12μm) spectral bands. The current version of NVTherm calculates target and background radiance using effective blackbody temperatures furnished as input data.

To model multispectral sensors, more accurate spectral information is needed. The input to the new version of the model is spectral radiance of the target and background in W/cm^2/sr. This allows target to background contrast to be calculated accurately for arbitrary spectral bands. The radiance values are calculated at the target and background. The atmospheric transmission is handled by NVTherm, which uses MODTRAN internally to allow calculations at different ranges.

1.2. Model Scenario

A single target and background geometry with 4 look angles has been chosen to simplify the model as shown in Figure 1. This model is robust enough for sensor comparison and band selection studies. Users will be able to input their own scenario if desired. The assumed target consists of a roughly tank-size box 6m long, 3m wide, and 2m high. It is located 10m away from a 12m high wall of essentially infinite length. The 4 views are 0°, 0.1 radian declination, 45° declination, and 90° declination. The 0° and 0.1 radian views are typical of ground-to-ground engagements. The 45° view is intended to model an Unmanned Aerial Vehicle (UAV) view. The 90° view models UAV, aircraft, or satellite views. Figure 1 shows the geometry and the 4 views modeled.

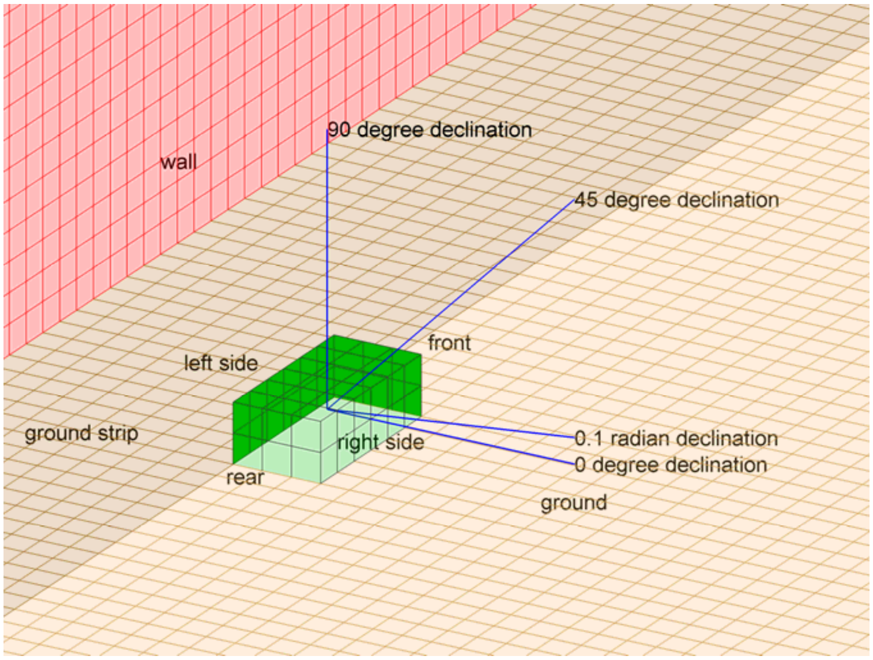

Figure 1: box and wall geometry

2. SOURCES OF RADIANCE

The 4 contributions to surface radiance in this model are:

1. Direct thermal emission (Planck’s Law)
2. Reflected direct solar radiation
3. Reflected sky radiance and scattering
4. Reflected radiance from surrounding surfaces

Direct thermal emission is the radiance due to blackbody radiation of all surfaces at temperatures greater than absolute zero. Thermal emission contributes the largest fraction of the total radiance in both the MWIR and LWIR bands with most materials. Reflected direct solar radiation is the radiance due to the sun which radiates similarly to a blackbody with a temperature of 5900°K. Solar radiation can contribute a large amount of radiance in the MWIR band, but contributes almost no radiation in the LWIR band. Reflected sky radiance and scattering is the radiance contribution due to thermal emission of the atmosphere plus radiation from the sun that is scattered by the atmosphere. Sky radiance and scattering usually add small amounts of radiance to the total radiance. The thermal emission of the atmosphere is usually small because the sky tends to be colder than objects at ground level and the atmosphere is translucent in the bands of interest to infrared sensors. Reflected radiance from surrounding surfaces characterizes the radiance from a surface that is due to reflections from surrounding surfaces. The reflected radiance contribution is generally fairly small but important in both the MWIR and LWIR bands. The surrounding surfaces tend to have total radiances close to the target surface, but the reflectivity of most materials in the infrared is small.

MODTRAN is a program used to calculate atmospheric data useful for imaging sensors. MODTRAN can calculate spectral direct solar irradiance, spectral sky radiance plus solar scattering, and spectral atmospheric transmission. MODTRAN can model almost any atmospheric conditions with high accuracy. Model parameters include latitude/longitude, time of day, time of year, cloud conditions, view angles and lengths, and air temperature. Most parameters can be specified very precisely if enough data is known. Reasonable defaults are included if very fine atmospheric control is not needed.

This project uses MODTRAN to calculate solar irradiance and sky thermal emission plus scattering. The atmospheric transmission from the target to the sensor is handled by NVTherm. Solar irradiance is calculated by MODTRAN in W/cm^2 versus wavelength in μm. The sun is treated as a point source in this model. Sky thermal radiance plus scattering is calculated in W/cm^2/sr versus wavelength in μm for a given view direction. This calculation is performed multiple times to get an accurate sampling of the entire sky. Preliminary results indicate that sampling every 10° in zenith/elevation and at a fixed azimuth value will give reasonably accurate results in the infrared region. Sky thermal emission is nearly uniform in azimuth. The zenith variation is mostly because of the differing path lengths through the atmosphere into space. Scattering is a small contribution in the infrared bands over the entire sky due to the wavelength dependence of scattering.

3. RADIANCE CALCULATIONS

The total radiance from a surface calculated by this model is summarized by equation 1. L_{Planck} is the direct thermal emission of the surface. L_{sun} is reflected radiance due to solar irradiance. L_{sky} is the radiance due to atmospheric thermal emission and scattered solar radiation. $L_{surroundings}$ is the radiance due to reflections from surrounding surfaces. All radiance components are functions of wavelength.

$$L(\lambda) = L_{Planck}(\lambda) + L_{sun}(\lambda) + L_{sky}(\lambda) + L_{surroundings}(\lambda) \tag{1}$$

The total radiance easily breaks down into these 4 components. Direct thermal emission is calculated using Planck's Law for blackbody radiation modified by the spectral emittance of the surface. Reflected solar irradiance is calculated by reflecting the solar irradiance obtained from MODTRAN using the spectral reflectance of the surface. Reflected sky radiance is calculated from MODTRAN data by integrating the reflected radiance over the area of the sky. The reflected radiance is calculated last using the other 3 radiance contributions from other surfaces.

3.1. Direct Thermal Emission

The direct thermal emission is calculated using Planck's Law. Many equivalent forms of Planck's Law exist for different input and output units. The specific form desired is radiance in W/cm^2/sr versus wavelength in μm. The equation used is taken from equation 5-11 in Driggers, et al[2]. This is shown as equation 2 with an additional factor added to handle non-blackbody emissivity. $\rho(\lambda)$ is the spectral reflectivity of the surface. T is the temperature of the surface in degrees Kelvin.

$$L_{Planck}(\lambda) = [1-\rho(\lambda)]\left[\frac{37418}{\lambda^5 \pi\left(e^{\frac{14388}{\lambda T}}-1\right)}\right] \tag{2}$$

3.2. Direct Solar Irradiance

The data for direct solar irradiance is obtained from MODTRAN. The direction of the sun must be input to MODTRAN when calculating solar irradiance. This direction will be calculated and output during a MODTRAN sky radiance run. The direction of the sun is also input to the spectral radiance model. The reflected radiance due to reflected direct solar irradiance is calculated using equation 3. $E(\lambda)$ is the irradiance data from MODTRAN. θ is the angle between the surface normal and the direction of the sun. The $\cos(\theta)$ factor accounts for the angle between the surface and the sun. This factor is easier to compute as a dot product as the direction of the sun and the surface normal are both known as vectors. The factor of $1/\pi$ converts between irradiance and radiance for the Lambertian surfaces.

$$L_{sun}(\lambda) = \rho(\lambda)\left(\frac{1}{\pi}\right)E(\lambda)\cos(\theta) \tag{3}$$

The sun is checked for obscuration by walls using the same method described in section 3.3.2 entitled Wall Effects. The sun is considered to be a point source and is described by a single vector. As such, the sun is either considered totally visible or totally blocked.

3.3. Reflected sky radiance plus solar scattering

Sky radiance and scattered solar radiation are calculated by MODTRAN at the same time. They are calculated for a given point in the sky. To get the total contribution to the surface radiance the sky radiance is integrated over the entire sky. The data used in the integration is generated by multiple MODTRAN runs with differing view directions. Several runs are necessary to sample the entire sky. Equation 4 shows the integral used to calculate the total reflected radiance from the sky. This integral must be evaluated numerically.

$$L_{sky}(\lambda) = \rho(\lambda)\left(\frac{1}{\pi}\right)\int_0^{\frac{\pi}{2}}\int_0^{2\pi} L_{sky\_direct}(\theta,\phi,\lambda)\cos(\theta_n)\sin(\phi)\,d\theta\, d\phi \tag{4}$$

L_{sky_direct} is the MODTRAN sky radiance data is a given direction. θ is the azimuth angle and ϕ is the zenith angle. θ_n is the angle between the normal of the surface and the part of the sky under consideration. θ_n is thus a function of θ and ϕ. The cos (θ_n) factor accounts for the angle between the surface and the part of the sky. The $\sin(\phi)$ term comes from the integration over the surface of a sphere.

3.3.1. Numerical Integration

The integral in equation 4 must be evaluated numerically. The sky radiance data obtained from MODTRAN is known only at discrete values of θ and ϕ. As indicated by the integral, a surface receives radiation from an entire hemisphere centered on the surface normal. The hemisphere is generated as a set of (θ,ϕ) vectors relative to the surface normal. This set of vectors is then rotated into the world coordinate system.

Surfaces with normal vectors that are not vertical do not receive radiation from the entire sky. The hemisphere visible from an example surface with a non-vertical normal is shown in Figure 2. Points marked with the symbol “x” represent vectors below the level of the ground. Points below the ground can be identified by a ϕ angle in world coordinates greater than $\pi/2$. Points behind the surface are never generated and do not need to be handled separately.

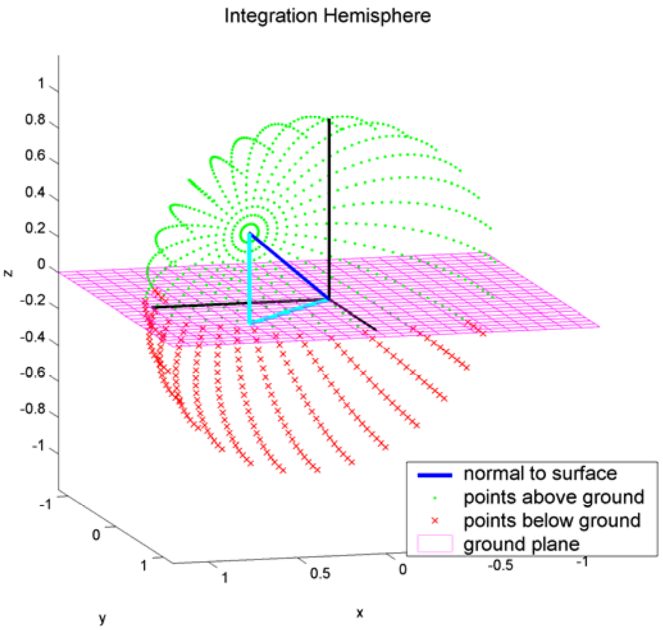

Figure 2: integration hemisphere

3.3.2. Wall Effects

Walls or targets will block parts of the sky from the view of other walls or targets in most scenarios, including the simple box target configuration. In most scenarios, all walls or other obstructions are vertical. This model is only designed to handle vertical walls. The location of a wall is specified by a distance (d) from the surface under consideration and the azimuth angle (θ). The size of the wall is specified by its horizontal (w_{left}, w_{right}) and vertical (h_{top}, h_{bottom}) extents from its center.

Handling the effects of walls is fairly straightforward because the integral over the visible sky is done numerically. The presence of walls blocks the radiation from the sky at certain angles. When a wall is defined, all vectors for the current surface are checked for intersection with the wall. Vectors that intersect the wall are marked as blocked. Blocked vectors are not included in the summation for total sky radiance.

The first step in checking a vector for collision with a wall is to calculate the distance from the surface to the wall. This distance is found using equation 5. θ_w is the azimuth angle of the wall in world coordinates θ and ϕ are the azimuth and zenith angles of the vector under consideration in world coordinates.

$$r = \frac{d\left[\sin(\theta_w) - \cos(\theta_w)\tan\left(\theta_w + \frac{\pi}{2}\right)\right]}{\sin(\phi)\left[\sin(\theta) - \cos(\theta)\tan\left(\theta_w + \frac{\pi}{2}\right)\right]} \tag{5}$$

A negative value of r indicates that the wall is behind the current vector and the vector cannot intersect the wall. The horizontal and vertical intersections of the vector with the wall are found using equations 6 and 7.

$$w = r\sin\left(\theta_w - \theta\right)\sin\left(\phi\right) \tag{6}$$

$$h = r\cos\left(\phi\right) \tag{7}$$

If w and h are within the horizontal and vertical extents of the wall, the vector is marked as blocked. All vectors are considered visible by default. Vectors that are not blocked by the current wall are unchanged to allow multiple walls to be defined. Figure 3 shows the vectors blocked by a sample wall. The center of the surface under consideration is located at the origin. One quarter of an integration hemisphere is shown for clarity. The “x” shaped points are blocked by the wall.

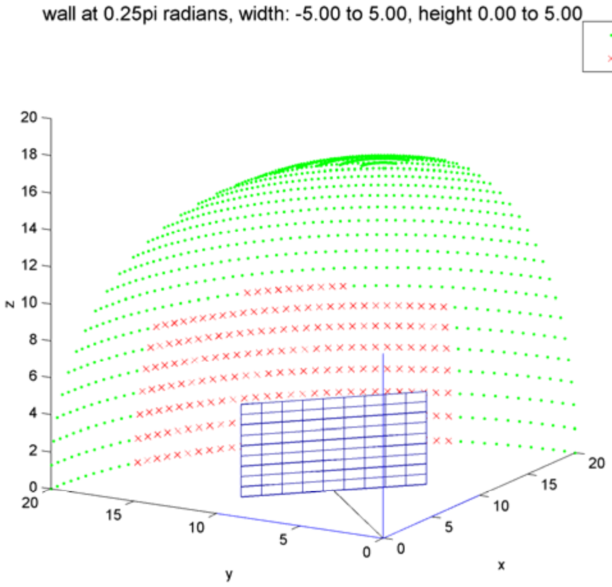

Figure 3: vectors blocked by a wall

3.4. Reflected Radiance from Surroundings

The most difficult component of the total radiance to calculate is the radiance due to reflections of surrounding surfaces. This model only considers a single bounce to simplify the calculations. The reflectivity of most materials is low in the infrared regions, so ignoring multiple bounces should not have much effect on the results. The single bounce radiance is calculated using the radiance of each surface ignoring all other surfaces. The components of the 0 bounce radiance are shown in equation 8.

$$L_0(\lambda) = L_{Planck}(\lambda) + L_{sun}(\lambda) + L_{sky}(\lambda) \tag{8}$$

The additional radiance contribution to surface 2 due to the reflection of the radiance of surface 1 is given by equation 9. A_1 is the area of surface 1 and A_2 is the area of surface 2. θ_1 is the angle between the normal of surface 1 and the vector between the two surfaces. θ_2 is the corresponding vector for surface 2. R is the distance between the two surfaces.

$$L_{2add}(\lambda) = \left[\frac{\rho_2(\lambda)}{\pi A_2}\right] L_1(\lambda) \int_{A_2}\int_{A_1} \frac{\cos(\theta_1)\cos(\theta_2)}{R^2}\, dA_1\, dA_2 \tag{9}$$

The total radiance of a surface when considering a single bounce is given by equation 10. This is an alternate form of equation 1 that shows the order in which the radiance contributions are calculated.

$$L_{total}(\lambda) = L_0(\lambda) + \sum_n L_{2add}(\lambda) \qquad (10)$$

Under the Lambertian assumption, the wavelength dependent parts of the reflected radiance can be separated from the geometric parts as shown in equation 9. This allows the geometric factors to be computed separately. A standard way to handle the geometric factors is to compute the view factor. This is an approach from heat transfer, as in Siegel and Howard[3]. The view factor from surface 2 to surface 1 is defined by equation 11.

$$F_{12} = \left(\frac{1}{\pi A_1}\right) \int_{A_2}\int_{A_1} \frac{\cos(\theta_1)\cos(\theta_2)}{R^2} dA_1 dA_2 \qquad (11)$$

Comparing equation 9 to equation 11, it is clear that the additional radiance can be calculated as shown in equation 12.

$$L_{2add}(\lambda) = \rho(\lambda)\left(\frac{A_1}{A_2}\right) F_{12} L_1(\lambda) \qquad (12)$$

When the area of surface 1 is infinite, it is convenient to calculate the view factor in the opposite direction, from surface 1 to surface 2. This is shown in equation 13.

$$L_{2add}(\lambda) = \rho(\lambda) F_{21} L_1(\lambda) \qquad (13)$$

View factor integrals for some configurations can be evaluated analytically. Most of these configurations involve infinite surfaces or surfaces with certain types of symmetry. Reference 3 gives the equations for many view factors that can be solved analytically.

In general, the view factor integrals must be evaluated numerically. The separability of view factors and the spectral calculations allows the view factors to be evaluated separately from the rest of the calculations. Currently, the view factors are evaluated using MATLAB to perform the numerical integration. There is a significant amount of work required to correctly evaluate all of the view factors. First, the basic surfaces used in the scenario are broken up into subsections. The choice of reasonable subsections depends upon which surfaces are able to view other surfaces and the specific view angle. For example, in Figure 1 notice that the front of the target can only view approximately half of the wall. The view angle affects which pieces of the surfaces are actually used to find the final radiance. The radiance of surfaces that are not visible from a given view direction does not need to be calculated.

4. MODEL SUBSTANTIATION

The model described in this paper has been compared to data obtained in a preliminary field data collection. This collection was performed to check the basic validity of the model. It is not an exhaustive validation of the model. A more thorough validation of the model is planned.

4.1. Material Selection

The model computes radiance of 3 surfaces: a target, a wall, and a background. Experimental data was needed for comparison to the model predicted results. The 3 materials chosen were green paint, brick, and asphalt. These materials were chosen because they were readily available to field test. Reflectance data for use with the model was also available on these materials.

The 3 materials used in the data collection and the model calculations are only approximate matches. The properties of all 3 materials will vary between different samples. The condition of the materials used in generating the reflectance data was not known. The materials used in the data collection were in good repair, but were fairly dirty.

4.2. Data Collection

The primary instrument used to collect field data was a CI Systems SR-5000 spectroradiometer. The SR-5000 is useable between 2.5µm and 14µm. The output of the instrument is uncalibrated and must be calibrated using external blackbodies. Liquid nitrogen is used to cool the SR-5000 detector and stabilize the detector temperature so the instrument should be consistent once calibrated.

A Raytek Raynger II infrared thermometer was used to measure the temperature of the surfaces during collection. This temperature data was then used as input to the model. The model assumes that the target and background surface temperatures are known.

4.3. Comparison

The data obtained from the SR-5000 was fairly noisy due to lack of data for calibration. The SR-5000 generates a signal that is proportional to the difference in radiance between the target and an internal blackbody. Calibrating the instrument precisely requires a hot blackbody preferably over 100°C that is very close to the instrument to give a large difference signal. The blackbody must be as close as possible to avoid atmospheric effects. The effect of the atmosphere can be very significant over a few meters when measuring small wavelength bands. The most suitable blackbody available during the data collection was approximately 40°C and was about 15m from the instrument. The small difference signal from this blackbody lead to a large amount of noise in the calculated instrument function. Any noise in the instrument function will corrupt the radiance data.

As a result, the measured response curve of the instrument has a large amount of noise. Figure 4 shows the measured instrument function of the SR-5000. The instrument function is unusable in the 5µm to 8µm range due to heavy atmospheric attenuation. The instrument function shown in the manual[4] is smooth and never drops below 0. However, the overall shape of the function matches that shown in the manual in the regions of interest.

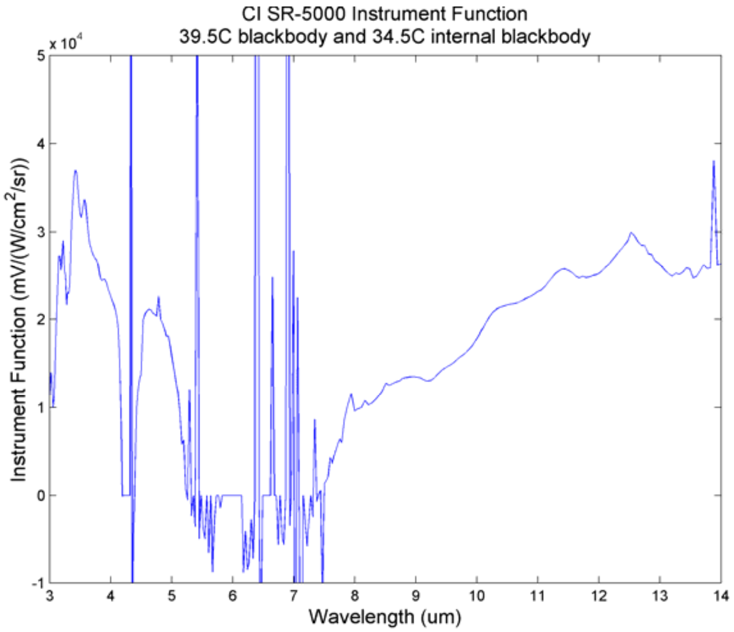

Figure 4: SR-5000 instrument function

The measured field data and the calculated data from the model are shown in Figure 5. The target curve is the model calculation using a green paint target. The background curve is the model calculation of a background consisting of approximately equal parts brick and asphalt. The model wall is brick and the ground is asphalt. The view angle causes the background to be a nearly equal mix of the wall and the ground.

The calculated data falls between the measured data through most of the MWIR and LWIR regions. The measured data between approximately 5µm and 8µm is meaningless due to atmospheric absorption. The model calculated data ends at 12.5µm due to a lack of reflectance data.

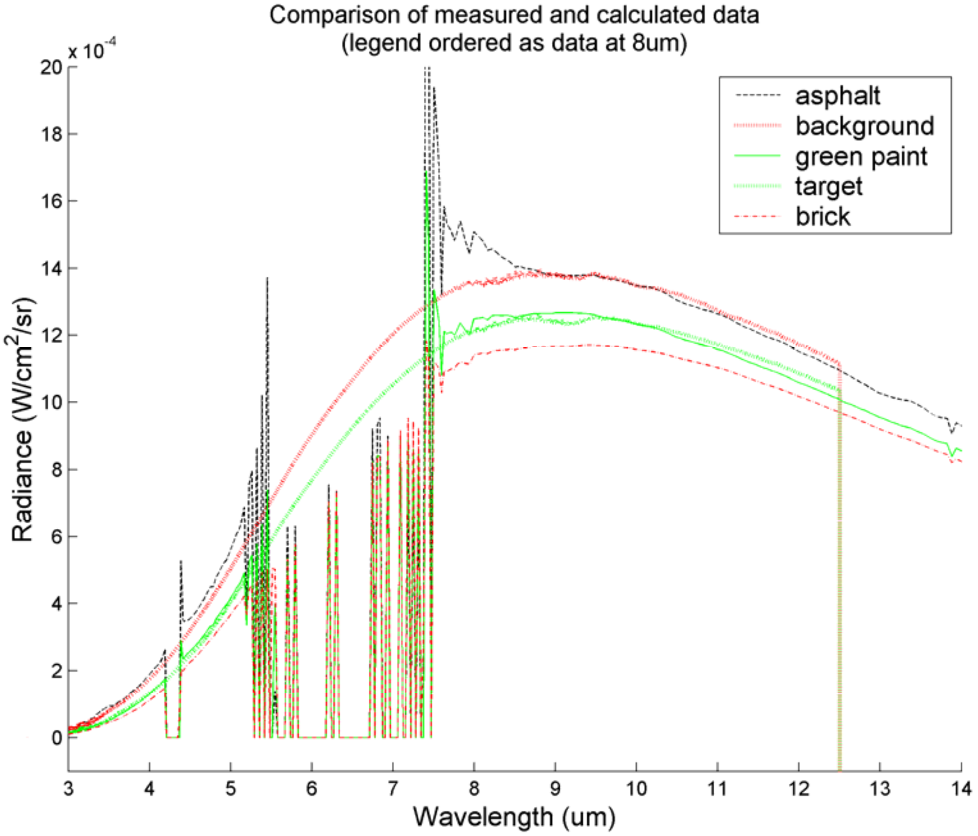

Figure 5: comparison of field data and model results

5. CONCLUSION

Figure 5 shows a comparison of the data calculated by the spectral model and data obtained from a field data collection. The legend is ordered to correspond to the order of the data at 8µm. The data agree well in the MWIR and LWIR regions of interest. The field data is too noisy to be used as a validation of the model. A more thorough data collection for validation purposes is planned. However, the currently available field data allows rejection of the null hypothesis that the model is invalid.

A spectral radiance model now exists for use in modeling third generation FLIRs. The spectral radiance can be input into a spectral version of NVTherm to allow comparisons between multispectral sensors. A major expected use of the spectral model is band selection.

The spectral radiance will also be used as input to an automatic target recognition (ATR) model currently under development. Some ATR algorithms are designed to use the additional information from multi-band imagers to better locate targets. The spectral radiance can be used to calculate the sensor response to a given target and background. The sensor response may then be input to a model of the ATR algorithm.

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