This report contains a detailed description of the research work completed over the October 2006 – September 2007 fiscal year. The work involved research related to the Mechanical Draft Cooling Tower project through contract number DE-AC09-96SR18500. An executive summary of the work performed thus far is provided along with the current direction of the research.

Each of the following sections focuses on a different area of the project. A summary of the discussed topics is as follows:

- Section 1 – Apparent Temperature Dependence on Localized Atmospheric Water Vapor
- Section 2 – Beard-Maxwell NEFDS Implementation in Matlab
- Section 3 – Spectral Measurements of MDCT materials
- Section 4 – DIRSIG Model of the Apparent Temperature / Effective Emissivity for Multiple Internal Reflections for Closed and Open Cavities
- Section 5 – MDCT DIRSIG rendering with BRDF Materials
- Section 6 – Future work
Executive Summary

The problem of determining the temperature of a MDCT can be separated into two parts: the radiance leaving the tower and the radiance reaching the sensor.

The radiance leaving the tower is dependent on the optical properties of the tower materials and also on the internal geometry of the tower. Simulations using the DIRSIG software developed by the DIRSIG laboratory at RIT were used to investigate the dependence on the optical properties of the tower materials and on the number of internal reflections taking place inside the tower on the exiting radiance. The results of these simulations (see Section 4) indicate that, assuming the material has a relatively high emissivity and is somewhat specular in the longwave infrared, the tower radiance approaches the blackbody radiance given at least three internal reflections have occurred. In other words, the tower behaves like a blackbody if the previously mentioned assumptions hold.

Measurements of actual tower construction materials (see Section 3) indicate that most materials have a very low reflectance (0.10 or less) in the longwave infrared. This data is consistent with the assumption of a high emissivity material in Section 4. The directional characteristics of a material are described by its bidirectional reflectance distribution function (BRDF). There are several semi-empirical models used to approximate a true physical BRDF. The Nonconventional Exploitation Factors Data System (NEFDS) is an example of a BRDF model based on several measured parameters. These parameters for several hundred materials are stored in the NEF database. This model was incorporated into the DIRSIG software for use in simulations (see Section 2). The Ward BRDF is another BRDF model. It is a simple model with only three free parameters. The simplicity of the Ward model makes it ideal for case studies of radiometric phenomena. The studies completed over the past year into the radiance leaving a MDCT show that the material properties (BRDF) and internal geometry of the MDCT do not contribute significantly to the error in the apparent temperature of the tower (see Section 5).

The tower-leaving radiance discussed above must then be propagated through the exhaust plume of the tower and through the atmosphere to arrive at the sensor. The tower exhaust consists of a warm plume with a higher water vapor concentration than the ambient atmosphere. The MODTRAN software was used to study the effect of this plume under a variety of conditions. The result of this preliminary study demonstrates that the plume will be the largest source of error when attempting to derive the temperature of the MDCT (see Section 1). The current direction of this research is to expand this initial study and focus on performing a detailed analysis into the effects on the apparent temperature error due to the exhaust plume and the ambient atmospheric conditions. Techniques must be developed to compensate for the error introduced by the atmosphere.
Section 1
Apparent Temperature Dependence on Localized Atmospheric Water Vapor
Tech Report # RIT-30571-0007

Summary

The amount of water vapor in the atmosphere greatly affects the transmission along the target-to-sensor path. The MODTRAN atmospheric propagation tool was used to model how the water vapor concentration affects the transmission through the atmosphere in the long wave infrared region. The apparent temperature of the target will be underestimated (when the MODTRAN tool is run in transmission mode) since the transmission losses will result in less radiance recorded at the sensor.

Two atmospheric layers were defined in MODTRAN. The first layer extended from the ground to a specified height. This layer was representative of the exhausted water vapor plume from a mechanical draft cooling tower. The second layer extends from the first (plume) layer up to an observation altitude of one hundred meters. The air temperature and dew point depression in the plume layer and the thickness of the plume were varied to observe the effect on the total transmission through the air column between the sensor and target. In addition, the general atmospheric conditions were varied between two standard MODTRAN atmospheres to study any effect of ambient conditions on the transmission.

MODTRAN calculates the spectral transmissions for each set of atmospheric parameters that were varied. These spectral transmissions along with the Planck equation were used to convert the radiance reaching a thermal infrared sensor from a blackbody into an estimate of the apparent temperature of the blackbody. A temperature error was then defined as the difference between the transmission-affected estimated temperature and the actual apparent temperature of the blackbody.

The results demonstrate that the transmission through the air column decreases as the water vapor concentration increases. In terms of temperature errors, the errors increase as the air temperature increases, dew point depression decreases, plume height increases, and when the general atmospheric conditions are relatively warm and moist.
The transmission through the column of air between a target and a nadir-looking thermal sensor was investigated. The exhaust plume from a mechanical draft cooling tower (MDCT) would introduce heat and moisture into the area immediately above the tower. Radiance emitted within the tower must pass through this plume to reach an airborne sensor. Water vapor is the most important atmospheric constituent influencing the transmission through the air column. Knowledge of the atmospheric transmission is very important since it will influence the apparent temperature of the MDCT. Transmission values of less than unity will result in a lower radiance measured by the sensor. Therefore, the apparent temperature of the tower will be less than the actual tower temperature. Note that emissivity effects are not taken into account.

![Figure 1-1: Radiance from the tower passes through the exhaust plume to reach the sensor.](image)

The transmission value of the air column will depend on the amount of water vapor in the column. As illustrated in Figure 1-1, the target-to-sensor path can be divided into two segments. The first segment falls within the exhaust plume of the tower. The plume contains excess heat and moisture that was expelled from the tower. The second segment is the free atmosphere not influenced by the plume. The first segment would contain a higher water vapor concentration than the second segment (in most cases) and would therefore contribute more to transmission losses in the air column.

The MODTRAN atmospheric modeling tool was used to simulate the above situation. The transmission through the air column between 8 and 12 microns was investigated. The dew point depression and air temperature were chosen as measures of the water vapor concentration in the column due to their feasibility of measurement on site. The air column was divided into two layers in MODTRAN. The first layer extends from the ground to a height of z meters to represent the exhausted plume. The second layer extends from the first layer up to an observation altitude of 100 meters. The second layer was assigned standard atmospheric conditions. The first layer was also assigned standard conditions for all parameters except the air temperature and the dew point depression which were varied. Figure 1-2 below illustrates this layout.
Several MODTRAN runs were conducted under a variety of conditions. The air temperature in the first layer was varied in increments of 5K from 280K to 310K. For each temperature, dew point depressions of 0, 2, 5, 10, and 20K were used. The observation altitude was held fixed at 100m. The thickness of the first layer, z, was set to values of 1, 5, 10, and 20m. The above parameters were run for standard mid-latitude summer conditions and then repeated for sub-arctic winter conditions representing relatively wet and dry atmospheres, respectively.

The intent of the simulation was to model an air column containing a high water vapor concentration in the lower layer followed by a sharp fall off in water vapor concentration at the second layer. Mimicking this sharp fall off in MODTRAN is not straightforward. MODTRAN allows the user to set the height, pressure, temperature, dew point, etc. of each layer of the atmosphere. These exact values are only set for the exact heights specified. For intermediate heights, MODTRAN interpolates the atmospheric parameters. For this simulation, the first layer was to have a uniform air temperature and dew point. Standard conditions were set in the second layer. MODTRAN looks up the standard conditions for the altitude specified and assigns them to that layer. There is a sharp contrast in the temperature and dew point between the two layers. In order to reproduce this contrast, a small one meter thick layer was inserted between the two layers. This extra layer provided the necessary buffer to allow a sharp fall off in temperature and dew point depression between the first and second layers. Figure 1-3 demonstrates the required MODTRAN simulation scenario.
For each situation modeled above, MODTRAN calculated the spectral transmission of the atmosphere between 8 and 12 microns. MODTRAN was run in transmittance mode so that only the transmission was calculated. The path radiances were not calculated in this mode by design to isolate only the effects of transmission and eliminate the false reduction in error due to increase path radiance due to upwelling. The spectral transmissions were then put in terms of errors between the apparent temperature recorded by the sensor and the actual temperature of the target.

The target was chosen as a blackbody of temperature 306K. The Planck blackbody equation was used to generate the target's blackbody spectral radiance, \( L_\lambda \). The spectral radiance was then integrated between 8 and 12 microns to arrive at an integrated radiance of \( L_{BB} = 28.3891 \text{ W/m}^2\text{sr} \). For each MODTRAN run, the spectral transmission curve, \( \tau_\lambda \), was used to modify the blackbody spectral radiance. The integrated radiance of this modified curve, \( L'_{BB} \), is less than the integrated radiance of the blackbody, \( L_{BB} \), because of the effects of atmospheric transmission.

Given the integrated radiance as measured by the sensor, the approximate temperature of the blackbody can be calculated by inverting the Planck equation,

\[
T = \frac{hc}{\lambda k} \left[ \ln \left( \frac{2hc^2 \Delta \lambda}{L \lambda^5} \right) \right]^{-1} \quad [K], \quad (1.1)
\]

where \( \lambda \) is the average wavelength in the spectral region, \( \Delta \lambda \), that the radiance, \( L \), was integrated over. The integrated radiances described above, \( L_{BB} \) and \( L'_{BB} \), were converted into apparent temperatures, \( T_{BB} \) and \( T'_{BB} \), using equation (1.1)

The temperature error between the actual temperature, \( T_{BB} \), and the estimated temperature, \( T'_{BB} \), is the difference between the two,

\[
T_{error} = T_{BB} - T'_{BB} \quad [K]. \quad (1.2)
\]

Since the estimated temperature will always be less than the actual temperature due to the transmission losses, the temperature error will always be greater than zero.
The following plots are the results of the above MODTRAN runs and subsequent processing into temperature error. Each plot represents the theoretical temperature error for a given air temperature, dew point depression, first layer (plume) thickness and standard atmosphere conditions at a fixed observing altitude of 100 meters. The sensor had a flat, unit spectral response function between 8 and 12 microns and zero response outside that region.

**Figure 1-4** Temperature errors for a plume thickness of 1m (top left), 5m (top right), 10m (bottom left) and 20m (bottom right) under mid-lat summer conditions at a 100m obs. altitude.
Figure 1-5 Temperature errors for a plume thickness of 1m (top left), 5m (top right), 10m (bottom left) and 20m (bottom right) under sub-arctic winter conditions at a 100m obs. altitude.

In the above plots, the air temperature, dew point depression, first layer thickness, and standard atmospheric conditions were varied to observe their effect on the temperature error derived from the sensor radiance. The first layer (labeled water layer above) thickness represents the exhaust plume of the tower (see Figure 1-2). The air temperature and dew point depression were only varied in the first layer. The standard atmospheric conditions indicated were applied in the second layer. The variable first layer thickness was meant to represent various plume heights. A dew point depression close to zero indicates near saturated air while a large depression indicates dry air. Standard mid-latitude summer and sub-arctic winter conditions were chosen to mimic relatively wet and dry general atmospheric conditions, respectively.

Several trends are apparent in the plots above. The temperature error increases as the dew point depression decreases and as the air temperature increases. Since the dew point depression is an indicator of water vapor concentration, this trend indicates that the temperature error increases as the water vapor concentration increases. This conclusion is expected since a greater number of photons will be absorbed as a result of the increased number of water molecules in the atmosphere. In other words, the transmission decreases.

The temperature errors also increase as the first layer thickness increases. This is expected since the first layer represents the exhaust plume of the tower. A thicker layer would therefore represent more of the plume in the air column and will produce a greater effect on the radiance reaching the sensor.
Finally the overall temperature errors are greater under mid-latitude summer conditions than for sub-arctic winter conditions. A mid-latitude summer atmosphere contains a greater amount of water which leads to a decreased transmission. Conversely, a sub-arctic winter atmosphere is much drier and therefore contributes less to transmission losses.

The other atmospheric constituent gases, such as ozone, carbon dioxide, etc. also decrease transmission through the air column. These constituents were not varied in this study and were always present in the simulated atmosphere. The temperature errors never reach zero for all plots due to the presence of these constituents even for a very dry, cold atmosphere.

A comparison of all plots can be made by graphing the temperature error for a single air temperature for all conditions. Figure 1-6 is a composite plot of the temperature error for an air temperature of 300K. The upper set of curves represents the four plume heights under mid-latitude summer conditions. Similarly, the lower set of curves represents the four plume heights under sub-arctic winter conditions. The two sets are very similar except that the summer set has a larger bias than the winter plot. This again is due to the other atmospheric constituents and additional water vapor in the second layer affecting the transmission more in the mid-latitude summer case. The summer curves also have a curiosity that they cross each other around a dew point depression of about 10K. The rather large dew point depressions greater than 10 K force the first layer to be drier than the moist second layer. As a result, the temperature errors for a thick first layer are actually less than a thin first layer since there is less water vapor in the sensor path. This does not happen for the winter atmosphere because the second layer is always drier than the first layer. While not a likely scenario, these results were included in this study for completeness.

![Figure 1-6](image)

**Figure 1-6** Temperature errors at an air temperature of 300K at a 100m obs. altitude. The lower set of curves represent a sub-arctic winter atmosphere while the upper set of curves represent a mid-latitude summer atmosphere. Plume heights of 1, 5, 10, and 20 meters are represented by the solid, dashed, dotted, and dashed-dotted lines, respectively.
The result of this analysis reveals that knowledge of the water vapor content in the target-to-sensor path is very important to accurately derive the temperature of the MDCT. The transmission through the atmosphere in the long wave infrared decreases as the air temperature increases and the dew point depression decreases. The radiance (transmission) for a nadir-pointing sensor also decreases as the plume height increases. The overall transmission is less under mid-latitude summer conditions than for sub-arctic winter conditions. These lower transmission values translate into higher temperature errors produced when deriving the apparent temperature of the target from the radiance recorded by the sensor.

These simulations may be used to predict the temperature errors that might be observed on a typical summer day at the Savannah River Site (SRS). A plume height of 5 meters and a plume temperature and dew point depression of 305K and 2K, respectively, were chosen as typical values. This would translate into a plume at about 90°F and 90% relative humidity. The temperature error under these conditions is approximately 2.6K.
Section 2
Beard-Maxwell NEFDS Implementation in Matlab

Tech Report # RIT-30571-0010

Summary

The angular distribution of flux reflected from a material surface may greatly affect the radiance incident on a sensor. The distribution of reflected radiance into the hemisphere from a given source geometry is described by the bidirectional reflectance distribution function (BRDF) of the material. The BRDF is dependent on the incident ray angles, the reflected ray angles, and the wavelength. Bidirectional reflectance functions are very difficult to measure directly since spectral measurements must be taken over all incident and reflected angles. In practice semi-empirical models are used to approximate the BRDF based on several measured or estimated parameters.

The Beard-Maxwell model is one example of a model designed to approximate a BRDF [1]. The model requires seven input parameters that adjust the scatter from the first surface and from beneath the surface. These parameters are usually fit to measured data. This model serves as the basis for the Nonconventional Exploitation Factors Data System (NEFDS) [2]. The NEF database contains measured input parameters for several hundred materials. The Beard-Maxwell model, along with NEF materials, provide a powerful way to generate reflectance models from a few measured parameters for several hundred materials.

The NEFDS v9.5 Beard-Maxwell model was implemented in Matlab. The BRDF may be calculated for all incident and reflected angles above the hemisphere and for wavelengths ranging from the visible to the longwave infrared. The Matlab results were compared to the NEFDS v9.5 results generated from the BRDF program provided with the NEFDS.
Introduction

The incorporation of the NEFDS model into DIRSIG will provide a powerful means of assigning material properties to objects in the scene. The goal is to allow DIRSIG to access the NEF materials database so that users may easily choose materials for their scenes. To verify that the DIRSIG implementation is correct, the NEFDS model was first implemented in Matlab and compared against the NEFDS values.

NEFDS Calculations and Parameters

The Beard-Maxwell BRDF model is based on the microfacet model. The model assumes that a rough surface consists of a collection of tiny microfacets. The slopes of the microfacets are assumed to be randomly oriented according to a probability distribution. Each microfacet acts as a specular reflector that obeys the law of reflection so that reflection occurs in the plane of incidence and the reflected angle equals the incident angle. The reflectance of the microfacet is calculated from the Fresnel equations.

The modified Beard-Maxwell model used in the NEFDS is of the form,

\[
\rho_{BM}' = \frac{\text{BRDF}_I\left(\theta_N\right) \cos^2(\theta_N)}{R(\beta = 0; n, k) \cos(\theta_i) \cos(\theta_r)} \cdot \text{SO}(\beta, \theta_N; \tau, \Omega) + \frac{2 \rho_v}{\cos(\theta_i) + \cos(\theta_r)}
\]  

(2.1)

where \(\theta_i\) is the incident polar angle and \(\theta_r\) is the reflected polar angle. \(\rho_D\) and \(\rho_v\) are the diffuse and volumetric BRDF parameters, respectively. The angle between the surface normal and the microfacet normal is \(\theta_N\) while the local angle of incidence/reflectance with respect to the microfacet is \(\beta\). These angles can be derived from the incident and reflected ray geometries through the following equations.

\[
\beta = \frac{1}{2} \cos^{-1}\left[\cos \theta_i \cos \theta_r + \sin \theta_i \sin \theta_r \cos(\phi_r - \phi_i)\right]
\]  

(2.2)

\[
\theta_N = \cos^{-1}\left[\frac{\cos \theta_i + \cos \theta_r}{2 \cos \beta}\right]
\]  

(2.3)

The incident and reflected ray azimuth angles are \(\phi_i\) and \(\phi_r\), respectively. The geometry of the BRDF model is illustrated in Figure 2-1.

Figure 2-1: Geometry of the NEFDS Beard-Maxwell BRDF model.

The Fresnel reflectance is given by \(R(\beta; n, k)\) and is dependent on the complex index of refraction for the material, \(\tilde{n} = n + ik\).
\[ R(\beta; n, k) = \frac{1}{2} \left( |r_s|^2 + |r_p|^2 \right) \]  

(2.4)

where the perpendicular and parallel polarization reflectance coefficients are,

\[ r_s = \frac{\cos \beta - \sqrt{n^2 - \sin^2 \beta}}{\cos \beta + \sqrt{n^2 - \sin^2 \beta}} \]

\[ r_p = \frac{n^2 \cos \beta - \sqrt{n^2 - \sin^2 \beta}}{n^2 \cos \beta + \sqrt{n^2 - \sin^2 \beta}} \]  

(2.5)

The facet-normal distribution function is a Cauchy distribution and takes on the form,

\[ \text{BRDF}_{FS}(\theta_N) = \frac{R(\beta = 0; n, k) \cdot B}{4 \cos^3(\theta_N) \left[ \sigma^2 + \tan^2(\theta_N) \right]} \]  

(2.6)

where \( \sigma \) is the mean square value of the facet slope and \( B \) is a scaling parameter describing the overall magnitude of the function. The shadowing and obscuration function, \( \text{SO} \), takes into account the shadowing of facets by adjacent facets and takes on the form,

\[ \text{SO}(\beta, \theta_N; \tau, \Omega) = \frac{1 + \frac{\theta_N}{\Omega} e^{-2\beta \tau}}{1 + \frac{\theta_N}{\Omega}} \]  

(2.7)

where \( \tau \) and \( \Omega \) are fit parameters.

The Beard-Maxwell fit parameters listed in the NEF material database are \( n, k, \rho_X \), \( \rho_{\rho}, \sigma, \tau, \omega, \beta \) and the measured directional hemispherical reflectance (DHR). These parameters are measured at up to five reference wavelengths of 0.325, 0.6328, 1.06, 3.39, and 10.6 microns. For desired wavelengths that are not one of the reference wavelengths, a spectral interpolation must be performed. In addition, the NEF material database may provide a spectral DHR curve, \( \rho_{\text{DHR}}(\lambda) \), covering the wavelength range of 0.3 to 15.0 microns. The full DHR curve is present for most, but not all, materials in the database. The spectral interpolation scheme modifies the calculated BRDF at the nearest reference wavelengths by the value of the DHR curve at the desired wavelength. The interpolation is given by,

\[ \rho'(\Theta, \lambda) = \rho_{\text{DHR}}(\lambda) \left[ \frac{\lambda_j - \lambda}{\lambda_j - \lambda_k} \cdot \rho'(\Theta, \lambda_j) + \frac{\lambda - \lambda_k}{\lambda_j - \lambda_k} \cdot \rho'(\Theta, \lambda_k) \right] \]  

(2.8)

where \( \lambda_j \) and \( \lambda_k \) represent the two reference wavelengths that bound the desired wavelength, \( \lambda \). The BRDF value at the given geometry, \( \Theta \), for wavelength \( \lambda \) is \( \rho'(\Theta, \lambda) \). The BRDF values at \( \Theta \) for wavelengths \( \lambda_j \) and \( \lambda_k \) calculated from equation (1) are \( \rho'(\Theta, \lambda_j) \) and \( \rho'(\Theta, \lambda_k) \). The DHR value at \( \lambda \) from the DHR curve is \( \rho_{\text{DHR}}(\lambda) \). The DHR parameters from the material file at the
reference wavelengths are $\rho_{DHR}(\lambda_j)$ and $\rho_{DHR}(\lambda_k)$. If the desired wavelength is one of the reference wavelengths ($\lambda = \lambda_j$), then equation (2.8) reduces to,

$$\rho'(\Theta, \lambda = \lambda_j) = \rho_{DHR}(\lambda = \lambda_j) \frac{\rho'(\Theta, \lambda_j)}{\rho_{DHR}(\lambda_j)}$$  \hspace{1cm} (2.9)

Note that even at a reference wavelength, the BRDF is scaled by the measured DHR values. This is necessary to match the modeled BRDF with measured values. For NEF materials without a DHR curve value at the desired wavelength or materials without reference wavelength parameters, this interpolation is not possible.

Finally, certain NEF parameters must be modified in order for the calculated BRDF values from equation (2.1) to match the BRDF values generated from the BRDF program provided with the NEFDS. The following corrections must be performed:

- The bias parameter, $B$, incorporates the “4” in the BRDF$_{FS}$ function from equation (2.6).
  - correction: $B \rightarrow 4 \cdot B$

- The SO parameters, $\tau$ and $\Omega$, are in terms of degrees and must be converted to radians.
  - correction: $\tau \rightarrow \tau \cdot \left(\frac{\pi}{180^\circ}\right)$ and $\Omega \rightarrow \Omega \cdot \left(\frac{\pi}{180^\circ}\right)$

- A spectral interpolation is always performed even at a reference wavelength (see equations (2.8) and (2.9)).

These corrections are courtesy of Michael Metzler at ISciences, LLC through phone and email correspondence 21 May 2007 and 14-15 June 2007 [3] with the help of Doug Ratay at Cortana Corporation through phone and email correspondence 8 June 2007 [4].

**NEFDS Implementation**

The NEFDS equations and corrections described above were implemented in Matlab. The BRDF for two materials are shown in the following figures. The incident polar angle is 40 degrees and the incident azimuth angle is 0 degrees. The BRDF was calculated for reflected polar angles of 0 to 80 degrees in 1 degree increments and reflected azimuth angles of 0 to 359 degrees in 1 degree increments. The resulting surface plot is a three-dimensional representation of the BRDF in which the distance between the origin and a point on the surface is the value of the BRDF in that direction.

The materials used in this example are white weathered paint on aluminum (NEF material number 0886UUUPNT) and weathered bare construction lumber pine wood (NEF material number 0404UUUWOD). The tau, omega, and bias parameters have been corrected as described in the previous section.

Figures 2-2 and 2-3 are the three dimensional BRDF plots for the two materials. A BRDF plot was generated for wavelengths of 1.0 microns and 10.0 microns for each material. The incident zenith and azimuth angle is 40 degrees and 0 degrees. For wavelengths outside the range of the reference wavelengths (i.e. – less than 0.325 microns or greater than 10.6 microns) the DHR parameter in equation (2.8), $\rho_{DHR}(\lambda_j)$, was fixed at the nearest reference wavelength (either for 0.325 microns or 10.6 microns).
Figure 2-2: BRDF of 0886UUUPNT for incident zenith angle of 40° at 1.0 μm (left) and 10 μm (right). The calculated DHR values from the BRDF are approximately 0.75 at 1.0 μm and 0.07 at 10.0 μm.

Figure 2-3: BRDF of 0404UUWOD for incident zenith angle of 40° at 1.0 μm (left) and 10 μm (right). The calculated DHR values from the BRDF are approximately 0.84 at 1.0 μm and 0.06 at 10.0 μm.
The Matlab implementation was compared with the NEFDS calculated BRDF values. The provided BRDF program was used to calculate the BRDF for the 0886UUUPNT material at a given geometry. A typical syntax for the BRDF program is:

```
./BRDF -M ../dbmF_05-1/materials/Single_Materials/0886UUUPNT.nmf -w 10.6 10.6 -e 180 45 -i 0 45 -n 0 90 -v
```

The above command calculates the BRDF for the 0886UUUPNT material at incident azimuth/elevation angles of (0, 45) and reflected angles of (180, 45) at a wavelength of 10.6 microns.

The BRDF value was calculated for several geometries and then compared to the NEFDS results. Table 2A summarizes these comparisons.

<table>
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<th>$(\theta, \phi)_i$</th>
<th>$(\theta, \phi)_r$</th>
<th>$\lambda$</th>
<th>Matlab</th>
<th>NEFDS</th>
<th>% diff</th>
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<td>0.35039</td>
<td>0.086578</td>
</tr>
<tr>
<td>40, 0</td>
<td>40, 180</td>
<td>10.0</td>
<td>0.282534</td>
<td>0.287614</td>
<td>0.065876</td>
</tr>
<tr>
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</tr>
<tr>
<td>40, 0</td>
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<td>0.010403</td>
<td>0.019050</td>
</tr>
<tr>
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<td>0.022100</td>
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</tr>
</tbody>
</table>

Table 2A: Comparison of NEFDS and Matlab values for 0886UUUPNT. Angles are in degrees, wavelength in microns, and BRDF in inverse steradians.

The Matlab values do not agree 100% with the NEFDS values. The main reason involves the scaling done in the spectral interpolation in equation (2.8). The NEFDS v9.5 calculates the DHR in the denominator, $DHR_{\lambda,k}$, by integrating the BRDF for an incident zenith angle of 10 degrees. In the Matlab implementation, the DHR value at the reference wavelength from the material file is used instead. This is essentially the integrated BRDF as before except at an incident zenith angle of 20 degrees. The NEF material file provides this value for each reference wavelength. Early NEF measurements used a DHR calculated at 10 degrees while later measurements used a DHR calculated at 20 degrees. New versions of the NEFDS will use the DHR calculated at 20 degrees. For this reason, the DHR in the parameter list at the reference wavelength was used for $DHR_{\lambda,k}$ in the Matlab implementation.

References

Section 3
Spectral Measurements of MDCT materials
Tech Report # RIT-30571-0011

Summary
Spectral reflectance measurements were taken of several MDCT construction materials. The material samples were obtained from the Johnston Equipment Company in Rochester, New York. The visual, near- and short-wave infrared (VIS-NIR-SWIR) measurements were obtained from the Cary-500 instrument. The short-wave, mid-wave, and longwave infrared (SWIR-MWIR-LWIR) measurements were obtained from the SOC-400 instrument. In total, reflectance data was obtained for a spectral range of 0.35 microns to 25.0 microns. The full spectra plots are shown along with a photograph of the material.

All of the materials measured have a reflectance of less than 0.30 at longwave infrared wavelengths. Most of the materials have reflectances around 0.10 or less at these wavelengths. In other words, these materials have relatively high emissivities in the longwave infrared.
Metal Plate 1

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Metal Plate 2

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Plastic Disc

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Sprinkler Head

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Wood Support 1

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Wood Support 2

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Drift Eliminator 1

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Drift Eliminator 2

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Drift Eliminator 3

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Drift Eliminator 4

- Image (top), VIS-NIR-SWIR spectra (center), SWIR-MWIR-LWIR spectra (bottom)
Section 4
DIRSIG Model of the Apparent Temperature / Effective Emissivity for Multiple Internal Reflections for Closed and Open Cavities

Tech Report # RIT-30571-0012

Summary
Several three-dimensional cavities were modeled in the DIRSIG software to investigate the apparent temperature and effective emissivity for multiple internal reflections. DIRSIG is a first-principles physics-based synthetic image generation application developed by the Digital Imaging and Remote Sensing (DIRS) Laboratory at the Rochester Institute of Technology (RIT).

The DIRSIG simulation consisted of two scenarios. For the first case, a longwave infrared sensor was placed into a sealed six-sided box. The box facets were assigned a temperature of 306 K. The facets of the box were also assigned various reflection/emissivity properties. The apparent temperature recorded by the sensor was observed as the number of reflections was incremented. Theoretically, the apparent temperature should increase and approach the actual assigned blackbody temperature of the box as the number of reflections increases.

For the second case, a longwave infrared sensor was targeted at a deep well. The well is assigned a temperature of 306 K and it is open to a 240 K sky. As before, the facets of the well were assigned various reflective/emissivity properties and the apparent temperature was recorded as the number of internal reflections were incremented. The apparent temperature was expected to increase and approach a certain temperature. That temperature would be a combination of the well temperature and the sky temperature depending on the reflective/emissivity properties of the well.
The apparent temperature of a cavity recorded by a sensor will be affected by the reflective/emissivity properties of the cavity walls and also by the number of reflections taking place within the cavity.

The reflective/emissivity properties are summarized by the bidirectional reflectance distribution function (BRDF) of the material. The BRDF describes the distribution of reflected radiance into the hemisphere above a material surface from a given source illumination geometry. It can be thought of as a probability distribution function for the reflected radiance in any direction. The integral of the BRDF over the hemisphere results in the Directional Hemispherical Reflectance (DHR). The DHR, \( \rho(\theta, \lambda) \), is related to the emissivity, \( \varepsilon(\theta, \lambda) \), of the material through Kirchhoff's law,

\[
\varepsilon(\theta, \lambda) = 1 - \rho(\theta, \lambda)
\]  

The BRDF is dependent on the incident ray angles, the reflected ray angles, and the wavelength. Bidirectional reflectance functions are very difficult to measure directly since spectral measurements must be taken over all incident and reflected angles. In practice semi-empirical models are used to approximate the BRDF based on several measured or estimated parameters. The BRDF model described by Ward is a mathematical model designed to approximate a true physical BRDF. The model's input parameters are \( \rho_d \), the diffuse component, \( \rho_s \), the specular component, and \( \sigma \), the surface roughness. The \( \sigma \) parameter essentially controls the width of the specular lobe. Figure 4-1 illustrates the two Ward BRDF shapes used for the DIRSIG simulations.

![Figure 4-1: Ward BRDF shapes used in the DIRSIG simulations. A diffuse (no specular component) BRDF (left) and a specular (no diffuse component) BRDF (right).](image)

Two different scenarios were performed in DIRSIG. The first case consisted of a sealed six-facet box. A broadband 8-14\( \mu \)m sensor with a unit spectral response was placed inside the box and targeted at a facet at a 45° angle. See Figure 4-2 for the simulation layout. The total number of reflections that a photon is allowed to make before being recorded by the sensor can be set manually in DIRSIG. Several runs were performed with a diffuse (no specular component) Ward BRDF and then with a specular (no diffuse component) Ward BRDF. The model parameters were carefully chosen so that that DHR values were 0.05, 0.15, and 0.25 for the diffuse and specular models. These DHR values correspond to emissivity values of 0.95, 0.85, and 0.75, respectively, through equation (1). The box facets were also assigned a temperature of 306 K. The radiance recorded by the sensor is an integrated radiance between 8 and 14\( \mu \)m. This radiance is then converted into an apparent temperature. For both the diffuse and specular BRDF models and for each DHR value, trends in the apparent temperature as a function of the number of internal bounces were investigated.
The second scenario consisted of an open, deep well. A broadband 8-14μm sensor with a unit spectral response was placed outside the well and targeted at an interior facet at a 45° angle. See Figure 4-2 for the simulation layout. Several runs were performed with a diffuse Ward BRDF and then with a specular Ward BRDF. As before, DHR values of 0.05, 0.15, and 0.25 were chosen for the diffuse and specular models. The well facets were assigned a temperature of 306 K while the atmosphere was a spectrally flat 240 K source with a transmission of unity. Again, the integrated radiance recorded by the sensor was converted into an apparent temperature. For both the diffuse and specular BRDF models and for each DHR value, trends in the apparent temperature as a function of the number of internal bounces were investigated.

The results of scenario 1 (sealed box) are shown in Figure 4-3 while the results from scenario 2 (open well) are shown in Figure 4-4.

Figure 4-2: Diagram of the DIRSIG simulation layout for the sealed box scenario (left) and the deep well scenario (right).

Figure 4-3: Results of Scenario 1 (sealed box) simulation. Diffuse Ward BRDF (left) and specular Ward BRDF (right). Actual temperature is 306 K (indicated by arrow)
Theoretically, the apparent temperature should increase and approach a final apparent temperature as the number of bounces increases. The radiance reaching a sensor is the self-emitted radiance of the target facet, modified by its emissivity, plus the reflected background radiances.

\[ L_{\text{sensor}} = \varepsilon L_{\text{target}} + \rho L_{\text{bgd}} \]  

(4.2)

The BRDF of the target facet will affect what direction in the hemisphere has the largest contribution to the reflected background radiance. For example, for a diffuse BRDF, every direction is equally weighted so the background radiance from the entire hemisphere has equal importance. For a specular BRDF, radiances in the specular direction will contribute more to the sensor reaching radiance than radiances in off-specular directions. For the sealed box, since the background radiances are always just the other facets of the box (at the same temperature) the shape of the BRDF should not matter so the apparent temperature should approach the actual assigned blackbody temperature of 306 K. This can be seen in Figure 4-3. However, in the open well case, the background consists both of the other well facets and also the much colder sky. A specular BRDF would cause the sensor to see more of the well than the sky, so the apparent temperature should still approach the actual blackbody temperature of 306 K as it does in Figure 4.4 (right). On the other hand, a diffuse BRDF would cause the sensor to see both the other well facets and the sky. The apparent temperature in this last case will therefore be some average of the cold sky temperature and the warm well temperature as seen in Figure 4.4 (left).

In addition, the DHR of the BRDF will affect how quickly the apparent temperature approaches its asymptote. A lower DHR value will result in a higher emissivity by equation (4.1). A higher emissivity will cause the apparent temperature to approach its asymptote more quickly since a higher emissivity indicates an object has a higher efficiency as a radiator. In other words, a high-emissivity object is more like a blackbody. This trend is seen in all plots of Figures 4-3 and 4-4.

The results of this DIRSIG study confirm that a cavity will behave as a blackbody radiator if there have been a sufficient number of internal reflections. The sealed box scenario demonstrated that the apparent temperature approaches the actual blackbody temperature after approximately one, two, and three reflections for DHR values of 0.05, 0.15, and 0.25, respectively. This scenario also confirmed that the shape of the facet BRDF does not matter since the sensor will always see one of the box facets.
The open well scenario demonstrated that the shape of the facet BRDF is important when there is more than one background source. A diffuse BRDF will cause more of a blend between the warm well radiance and the cold sky radiance. The resulting apparent temperature is lower than the blackbody temperature of the well. A specular BRDF on the other hand will cause more of the warm well radiance to reach the sensor. The resulting apparent temperature is the blackbody temperature of the well. Again, the DHR will determine how quickly the apparent temperature approaches its asymptotic temperature.

For the Mechanical Draft Cooling Tower (MDCT) project, the open well, diffuse case represents the worse-case scenario in terms of the internal geometry and material properties of the tower materials. If the internal tower materials are perfectly diffuse and have sufficiently high emissivities in the longwave infrared, then the apparent temperature will be within one or two Kelvin of the actual blackbody temperature if there has been approximately three internal reflections.
Section 5
MDCT DIRSIG rendering with BRDF Materials

Summary
The DIRSIG modeling tool was used to investigate the apparent temperature of a mechanical draft cooling tower (MDCT) model. The DIRSIG rendering was generated by assigning basic thermal properties to a geometric model of a tower. The geometrically detailed three-dimensional CAD drawing was intended to mimic a counter-flow tower similar to the H-area units at the Savannah River Site (SRS). The geometry of the drawing was based on measurements taken at SRS and on schematics made available by the manufacturer. A high fidelity geometric model is necessary to reproduce the geometry for multiple reflections within the cooling tower.

Each facet of the CAD drawing was assigned a temperature of 306 K. Each facet was also assigned a Ward BRDF reflectance. Two scenarios were conducted. In the first case, the Ward BRDF model parameters were set to a perfectly diffuse reflectance with a Directional Hemispherical Reflectance (DHR) of 0.15. In the second case, a specular Ward model was used with a DHR of 0.15. For both cases the maximum number of internal reflections was set to three. A broadband 8 – 14 μm sensor was positioned approximately 120 m above the tower. The simulated tower was placed in an environment designed to approximate the environment of the Savannah River Site.

The output of the DIRSIG simulation is an integrated radiance image of the tower in the 8 – 14 μm band. This radiance is then converted to an apparent temperature for subsequent analysis. Temperature profiles across the tower throat were taken for analysis.
As suggested by Figures 5-1 and 5-2, a sensor targeted at the tower throat will probably not be able to see past the drift eliminator layer. Therefore, the geometry above the drift eliminators was carefully reproduced, as it would have the greatest influence on the observed radiance. Structures located below the drift eliminators were only approximated or deleted altogether. Post analysis may reveal that these structures are indeed needed.

**Figure 5-1:** Schematic of the interior layout of a counter-flow tower.

Tower schematics were obtained from SPX Cooling Technologies (http://www.marleyct.com) and Johnston Equipment Company (http://www.jecoroc.com). Various views of a counter-flow tower structure are shown in figure 3.

**Figure 5-2:** Counter-flow tower structural views.
The drift eliminators are shown in the lower right portion of Figure 5-2. As mentioned earlier, the drift eliminators are the final surfaces visible to an overhead sensor. This structure also represents one of the most geometrically complex aspects of the cooling tower. Therefore, much attention was given to reproduce the detailed geometry of the drift eliminators.

![Image of drift eliminators](image)

**Figure 5-3:** H-area counter-flow towers at SRS.

The H-area towers at SRS are grouped in a set of four cells. For our purposes, we concentrated on constructing only one cell. In addition, the water collection basin shown in Figure 5-1 was not reproduced at this time.

Figures 5-1 to 5-3 were used as a reference to produce a three-dimensional CAD drawing of a counter-flow tower. Detailed views of the CAD drawing are shown in Figure 5-4.

![CAD drawing of counter-flow tower](image)

**Figure 5-4:** CAD drawing of a counter-flow tower exterior view (left) and interior view (right).
For the DIRSIG model, each facet of the CAD drawing was assigned a temperature of 306 K. In the first scenario, a diffuse Ward BRDF (no specular component) was assigned to every facet. The model parameters were adjusted to produce a DHR of 0.15. In the second scenario, a specular Ward BRDF (no diffuse component) was assigned to every facet. The approximate shapes of the Ward models used are shown in Figure 5-5.

The total number of reflections that a photon is allowed to make before being recorded by the sensor can be set manually in DIRSIG. This parameter was held fixed at three bounces since it has been shown that for a relatively low DHR value, the apparent temperature would reach the blackbody temperature after approximately three internal reflections (See Section 4 – Tech Report # RIT-30571-0012).

In the DIRSIG environment, the time was set to 23.00 local time in mid-June in the south-eastern United States. A broadband 8 – 14 μm sensor was positioned 25 degrees from zenith at a distance of 120 m from the tower throat. A standard mid-latitude summer atmosphere was generated. These parameters were chosen to approximate the conditions at the Savannah River Site where actual infrared images of such towers were obtained.

DIRSIG outputs a radiance image of the scene visible by the sensor. Bright pixels indicate higher radiances while dark pixels indicate lower radiance values. The DIRSIG renderings for both scenarios are shown in Figure 5-6.
A quick look at the DIRSIG image indicates that the general output is as expected. The brightest pixels, representing the highest temperatures, are deep within the tower. The exterior of the tower is cooler than the interior because it partially reflects the colder sky. The ground plane was assigned a temperature of 288 K and makes up the darkest pixels in the image, as expected.

The differences in the two Ward models are apparent in the images. In the right hand image, the warm pixels on the deck and on the ground plane are the result of specular reflections from the hot tower surfaces due to the specular Ward BRDF. A quantitative analysis of the DIRSIG images was performed by taking profiles across the tower throats. The radiances were converted into apparent temperatures. These profiles are shown in Figure 5-7.

Figure 5-6: DIRSIG radiance image with diffuse Ward BRDF (left) and specular Ward BRDF (right).

Figure 5-7: Apparent temperature profiles across the tower throat for the Diffuse Ward BRDF image (left) and the Specular Ward BRDF image (right).
The profiles indicate that for both BRDF models, the maximum apparent temperature detected is the blackbody temperature of the tower, 306 K.

The highest values in the plots are pixels located deep within the tower. The central depression indicates the fan hub while the low values at the left and right extremes of the plots indicate the tower decking. The apparent temperatures at these points are lower than the interior of the tower due to the reflected sky temperature. The specular material contains more pixels at 306 K because it reflects the warm interior directly into the sensor. The diffuse material, on the other hand, reflects the warm interior and the cooler sky into the sensor, resulting in a lower apparent temperature.

The results of the DIRSIG simulation show that a detailed geometric model along with basic thermal properties can produce a good approximation of the apparent temperatures of a mechanical draft cooling tower. For both a diffuse and specular material with a low DHR of 0.15, the apparent temperature of the MDCT approaches the blackbody temperature of the tower if there are at least three internal reflections. These conditions are consistent with the results of Sections 3 and 4.
Section 6
Future Work

A paper was submitted to the SPIE Defense & Security 2007 conference last March entitled “Radiometric modeling of cavernous targets to assist in the determination of absolute temperature for input to process models”. The paper focuses on the initial DIRSIG rendering of a MDCT and comparison to actual thermal MDCT imagery.

The plume study summarized in Section 1 will be expanded to include up-welled radiance effects along with transmission effects on the apparent temperature. An atmospheric correction scheme will be developed to compensate for the exhaust plume.

A scientific journal paper is currently in work explaining how the DIRSIG software tool is useful in performing apparent temperature studies. Results from Section 4 on the simple cavity demonstration and results from Section 5 on a practical application of DIRSIG modeling will be included in this paper.

An abstract has been submitted for the SPIE Defense & Security 2008 conference in Orlando Florida. The subject of the paper will be the MDCT plume study described above.