Infrared ship signature prediction using measured BRDF data and global illumination rendering

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ABSTRACT

Current IR ship signature codes have some limitations in predicting ship IR signatures. They either model general BRDF while ignoring multi-reflections, or compute multi-reflections with simplified BRDF models. We propose a new Monte Carlo ray tracing method incorporating measured BRDF data, which can calculate multi-reflections with general BRDF data. Much works have been done in computer graphics to simulate light transport for global illumination. In order to apply the global illumination algorithm in infrared ship signature prediction, we have modified the global rendering algorithm to include some important features like validation of physically accuracy, capability of incorporating measured BRDF data into the rendering equation, environment modeling of sky and sea radiance distribution and modeling surface patch as both reflector and emitter. The validation of physical accuracy performed by comparing the analytically calculated value with global illumination based infrared simulation result. The measured BRDF data is interpolated and used in the recursive Monte Carlo ray tracing. The environment and surface emissivity modeling can benefit from the physically based sky and sea radiance simulation as well as the thermal simulation result.

Keywords: Ship Signature, Infrared, Global illumination, Bi-directional Reflectance Distribution Function (BRDF)

1. INTRODUCTION

Infrared (IR) seeker is widely used in the anti-ship missile guidance system. These IR guided anti-ship missiles pose a critical threat to the naval ships operating in littoral waters. There have been continuing efforts to accurately predict infrared ship signature and estimate the IR susceptibility under various environmental conditions. The predicted IR ship signature will further assist the design of infrared signature suppression system (IRSS) and Infrared threat countermeasure simulation. A typical IR signature simulation model consists of several sub models: thermal simulation model, radiative infrared light transfer model, 3D target geometric and reflectance model, background radiation model and other application dependant models. The thermal simulation model has been well studied and developed in the IR simulation packages e.g. WinTherm, SHIPIR and MuSES. However, the radiative infrared light transfer model, used in the current IR ship signature code and other military IR signature code, is based on *radiosity* method: an approach that simulates multiple light reflection using the simplified BRDF of the surface reflectance. The *radiosity* method has been proved to be less accurate in the lighting simulation of real world object whose reflectance is not pure diffuse or pure specular.

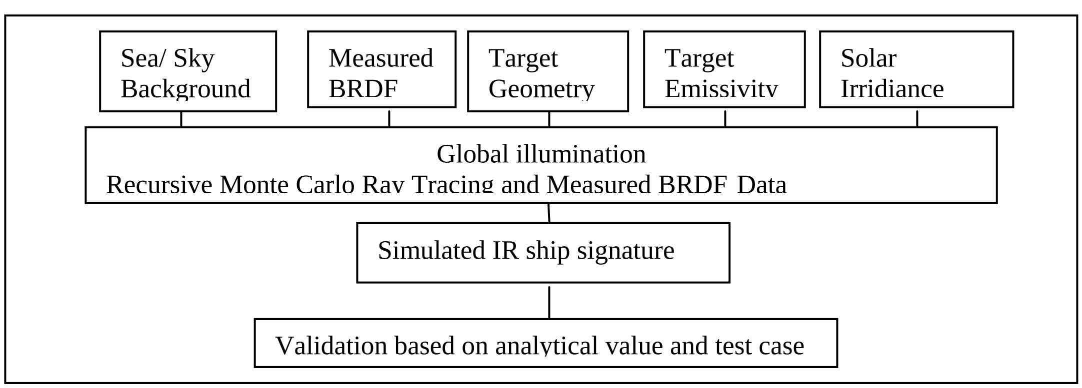
To solve the problem in current radiative infrared light transfer model, we propose a recursive Monte Carlo ray tracing based approach with measured BRDF data, by modifying the physically validated global illumination rendering package in computer graphics domain. Since the graphics rendering algorithm is optimized for the simulation of light transport in the visual frequency band, it needs some modification to meet the characteristics of infrared light transport. In the visual frequency band, a surface patch is either a light reflector or light emitter, while in the infrared frequency band a surface patch can be both light emitter and reflector. We have incorporated this feature to the global illumination rendering algorithm and modeled surface patch as both reflector and emitter. The 3D geometric model of target is converted from CAD data and the background radiation can be modeled analytically or from the simulated/observed radiance data.

In section 2, we will review the previous works on IR signature modeling and simulation, global illumination algorithms in computer graphics and sky radiance modeling methods. In section 3, we will provide the overview of the global illumination method and how to apply it to the IR simulation. The sea and sky background model, target geometric and reflectance model and IR scene rendering based on global illumination will be described in section 4, 5 and 6 respectively. We will present the experimental result in section 7 and discuss the limitation and future works in section 8.

2. PREVIOUS WORKS

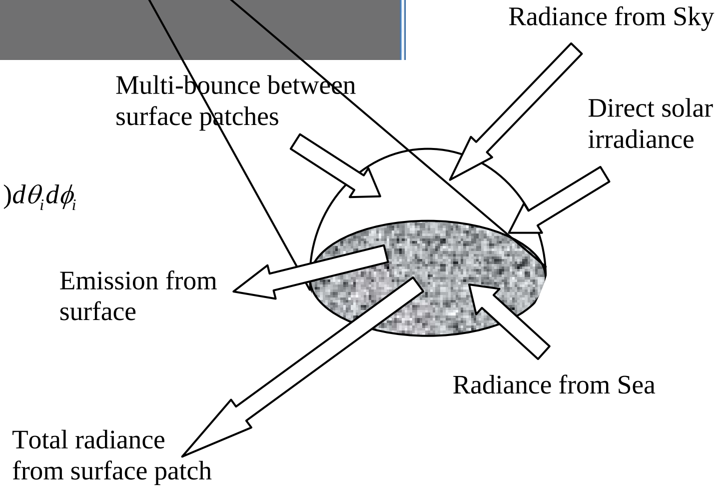
Johnson et al.(1995) have developed an IR simulator named WinTherm, in which the 3D thermal model is computed using finite difference nodal network solver and the diffuse radiant exchange is computed with *radiosity* method []. Later, Johnson et al.(1998) presented a new heat and signature design tool called MuSES (Multi-Service Electro-optics Signature). The MuSES provided a new modular thermally diffuse element solver that combined partially direct method and Net-Radiation method, and an anisotropic conductivity solver in its thermal simulation module. The MuSES also used *radiosity* approach for radiative IR energy transfer calculation, where the view factor computation accelerated by ray tracing 3D spatial subdivision volume []. Valitekunas et al. (1996) presented a naval ship signature countermeasure and threat engagement simulator (SHIPIR/NTCS). The SHIPIR/NTCS used finite differential method to compute the target thermal conduction. The thermal simulator can automatically generate solar heating, sea/air convection, sea sky radiation and inter-surface radiation. The *radiosity* approach is used to calculate multiple diffuse reflections in SHIPIR []. Valitekunas and Fraedrich (1998) validated SHIPIR for its use in Twenty-First Century Destroyer program, the validation performed by comparing SHIPIR prediction result with new panel test experiment []. Powell et al. (2000) introduced a way to use graphics animation software to simulate forward looking infrared scene. The animation capability, particle system, alpha-blending, 3D modeling and image-processing with gaussian noise features in MentalRay and SoftImage is used to develop a testing algorithm in airborne ATR (Automated Target Recognition) scenarios. Poglio et al. (2002) presented an outdoor scene simulation in thermal infrared range (OSIRIS). In OSIRIS, they assumed the surface reflectance as lambertian reflector and used *radiosity* method for global illumination.
In all these previous works, the radiative infrared energy transport between surface patches is simulated using *radiosity* approach. From the computer graphics point of view, the *radiosity* method has problem of modeling the surface BRDF as pure diffuse reflectance. Many following researches have been done to incorporate more complicated BRDF models with global illumination method. Wallace et al.(1987) extended radiosity method into two passes, with diffuse surfaces using radiosity method and with specular surfaces using ray-tracing method []. Two-pass radiosity and ray-tracing method generated realistic images in presence of mirrors and mirror-like objects. However, because it is a kind of ad hock approach, it is difficult to extend this method to more general BRDF models []. Because of the limitation in *radiosity* method, a new global illumination algorithm, recursive Monte Carlo Ray tracing method was introduced to synthesize realistic visual image. Ward (1994) developed RADIANCE software, which used deterministic and stochastic bi-directional ray tracing methods to simulates the complicated BRDF of the surface patch using Gaussian approximation of isotropic and an-isotropic diffuse and specular reflectance. iBRDF is an extension to the RADIANCE approach to incorporate general BRDF model. First, they subtract the smallest hemisphere that fits within the BRDF data. This removes the diffuse or uniformly varying portion of the BRDF and leaves only the highly directional specular part. Then, random number generation method is employed to create random variates from these remaining specular reflectances.

3. OVERVIEW OF GLOBAL ILLUMINATION IR PREDICTION



Our approach for the infrared ship signature prediction consists of Sea/Sky background modeling, measured BRDF modeling, Target geometric and emissivity modeling, global illumination based rendering, validation based on analytical value and test case.

All global illumination methods are theoretically based on the following rendering equation. This equation represents the radiance in a given direction $Lr(\lambda,\theta r,\phi r)$ as the sum of emitted radiation in that direction $Le(\lambda,\theta r,\phi r)$ and the convolution of all incoming radiation with the reflectance-transmittance function for all surface patches.



$$L_r(\lambda,\theta_r,\phi_r) = L_e(\lambda,\theta_r,\phi_r) + \int_0^{2\pi}\int_0^{\pi} L_i(\lambda,\theta_i,\phi_i)\rho_{BRDF}(\lambda,\theta_i,\phi_i,\theta_r,\phi_r)|\cos(\theta_i)|\sin(\theta_i)d\theta_i d\phi_i$$

θ is the polar angle from surface normal
ϕ is the azimuthal angle from surface normal
$Lr\ (\lambda, \theta r, \phi r)$ is the reflected radiance (w/s/m^2)
$Li\ (\lambda, \theta i, \phi i)$ is the incident radiance
$\rho\ (\lambda, \theta r, \phi r; \theta r, \phi i)$ is BRDF

4. BACKROUND MODEL

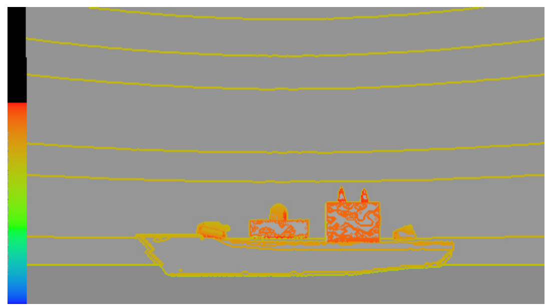
The sea and sky can be modeled using hemispherical and planar surface patches. However, polygon based sky and sea model have some problems to incorporate with RADIANCE global illumination algorithm. The first problem is the missing of horizontal radiance sample. Even the sea surface is modeled using enough large sized polygon, the horizontal rays still miss to sample radiance value when it hit the outside of surface patch. The second problem comes directly from the bounding size of the sea and sky model. The radiance ray tracing method uses octree structure to store the radiance value of 3D space. With the large bounding size of the sky and sea model, each cell in octree will occupy more space compared with cell size for the target model. So the accuracy of rendered result will decrease linearly with the growth of sky and sea model size. Based on the observation, the radiance from sky can be thought as coming from infinite distance. This feature can be used to model the hemispherical sky radiance using zodiacal and polar angles. There are several advantages using sampled sky data compared with analytical model. Using sampled data value can separate the sky radiance simulation and IR signature prediction works. MODTRAN is most commonly used in physically accurate IR simulation. By collecting radiance at certain IR wavelength, we can model the sky background radiance along vertical elevation.

We have modified the RADIANCE sky model to deal with the elevation based sky model. The modification of sky brightness function in Radiance enables us to use sampled radiance along the elevation angle.

```
{
    Sky brightness function based on elevation sample
    A1..A10 radiance sampled at increasing zenith angle
}
eta = Acos(Dy);                { angle from zenith to this point in sky }
wmean(a, x, b, y) : (a*x + b*y) / (a + b);
degree = 180*eta/PI;
index1 = floor(degree/10.0);
index2 = ceil(degree/10.0);
skybr = wmean((degree- index1*10)/10.0, arg(index1+1), (index2*10-degree)/10.0,
arg(index2+1));
```

The rendered results using elevation based sky radiance model are shown below. The left image indicates the radiance value and the right image shows the iso-radiance lines.

Sky radiance variation along elevation



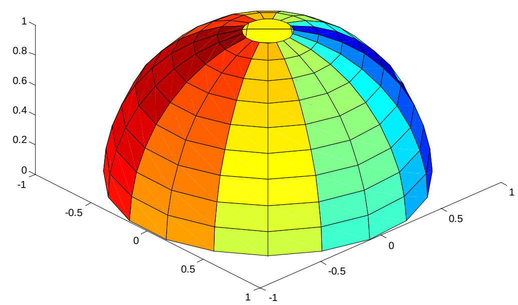
Iso-radiance lines along the elevation

However, the actual sky radiance distribution is not constant at every elevation angle. The sampled sky radiance data from SRRL (solar Radiation research Laboratory) shows that a more general sky model is required for accurate IR simulation. We have further extended our model to fully operate with general hemispherical sky model. The Radiance sky model is modified to take input of regularly sampled hemispherical radiance. We are now sampling the whole sky using 210 sample points. The sample points can be increased if the number of sample points is insufficient for the physical accuracy. The following code is actually used to model the hemisphereical sky radiance distribution. The radiance from certain point in the sky is linearly interpolated using four nearby radiance sample points.

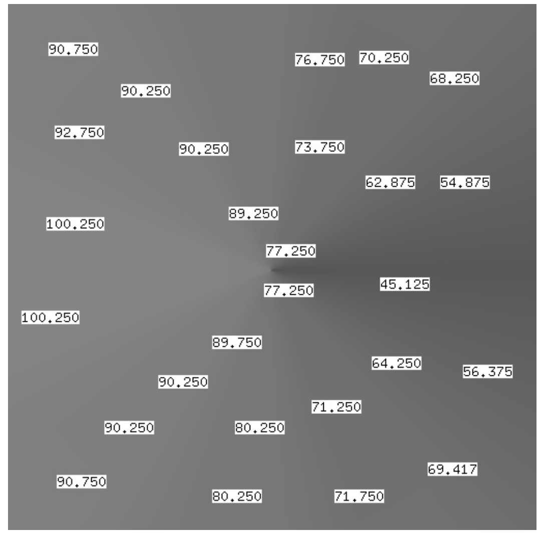
```
{A1..A210 Zenith to ground brightness }

eta = Acos(Dy);                      { angle from zenith to this point in sky }
wmean(a, x, b, y) : (a*x + b*y) / (a + b);
ydegree = 180*eta/PI;

theta = if(Dx*Dx, Atan2(Dz,Dx), 0);

rdegree = if(theta, 180*theta/PI, 360+180*theta/PI);

index_h1 = floor(ydegree/10.0);
index_h2 = ceil(ydegree/10.0);
index_r1 = floor(rdegree/18.0);
index_r2 = ceil(rdegree/18.0);

temp1 = wmean( (index_h2*10-ydegree)/10.0, arg(index_r1*10+index_h1+1), (ydegree-
index_h1*10)/10.0, arg(index_r1*10+index_h2+1));
temp2 = wmean( (index_h2*10-ydegree)/10.0, arg(index_r2*10+index_h1+1), (ydegree-
index_h1*10)/10.0, arg(index_r2*10+index_h2+1));

skybr = wmean((index_r2*18-rdegree)/18.0, temp1, (rdegree- index_r1*18)/18.0, temp2);
```

General Sky Radiance Representation

For the experimental purpose, we have randomly assigned sky radiance to 210 sample points in the sky. The radiance distribution is show at the hemispherical surface model. The rendered image shows the camera viewing directly up to the sky.



Radiance distribution in the experiment



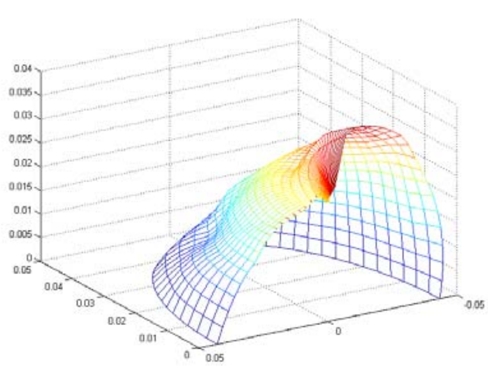
Camera Viewing upward to the sky

Our modification for the sky illumination model is flexible to be combined with various source of sky radiation model. The simulated sky model as well as scanned sky radiation data can be working with Radiance global illumination rendering algorithm.

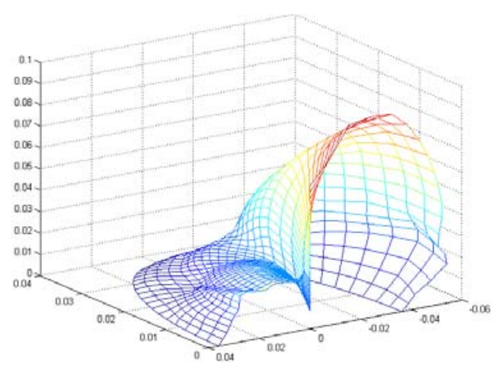
The sea model is similar to the sky model, the planar sea radiance sample is reprojected into the hemisphere and further modeled as sky model facing downward. For the IR target and sea surface inter-reflection, an appropriate sized surface patch is used to calculate the sea-ship inter-reflection.

5. MESASURED BRDF MODEL

We have obtained two sets of BRDF data from NRL, both of them isotropic. The BRDF data from NRL is irregularly sampled at incident polar angles of 20^o, 40^o and 60^o. The outgoing angles are regularly sampled polar angles from 0^o to 80^o and the corresponding azimuthal angles at 0^o, 90^o and 180^o. The BRDF samples are plotted over the hemisphere with their BRDF value.



BRDF Data at 20 degree



BRDF Data at 40 degree

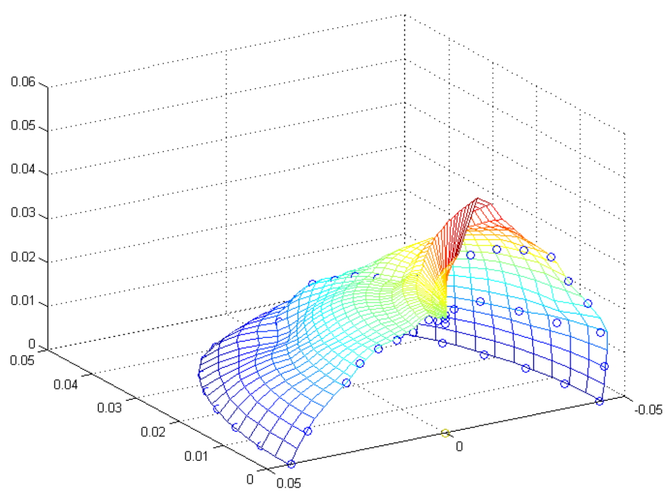
Thus, in order to render this kind of general BRDF, the Radiance rendering algorithm need to be modified to take the input from general BRDF data. We have extended iBRDF method to build a new shader "nrlbrdf". It is capable of uniformly sampling arbitrary isotropic BRDF in the Radiance Monte Carlo ray sampling. The reflected theta, reflected phi, and incident phi can be used as indexes to the sampled data array. Since the BRDF is isotropic we define the coordinate system so that incident theta= 0. For most of the BRDFs, uniform sampling was found to be sufficient. For each sampled BRDF surface patch, we added emissivity value to simulate self-emission in IR band.
For the Radiance scene description language, we need to specify the surface patch using "nrlbrdf" material type.

```
void nrlbrdf Surface_name
1 Nrlbrdf.brdf
0
8 0.33333 0.33333 0.33333 75 .2 18.675 18.675 18.675
```

The actual BRDF sampled data is stored in "Nrlbrdf.brdf" file. The data is interpolated and reconstructed regularly with 20 reflected phies and 40 reflected thetas.

```
# Nrlbrdf.brdf file
##########################################################
20        20        40
0.155000
0.054684  0.054927  0.055128  0.054534  0.054057  0.054635  0.054910  0.053474  0.052276
0.052028  0.051569  0.050476  0.050585  0.053500  0.055395  0.055395  0.055307  0.055089
0.055149  0.055550  0.055428  0.054784  0.054241  0.053779  0.054149  0.055072  0.054842
0.053992  0.053227  0.052498  0.054138  0.056567  0.060551  0.064923  0.071773
0.051468  0.052294  0.052697  0.052466  0.052607  0.053202  0.052787…………
```

Since the raw BRDF data is irregularly sampled data, we need to interpolate the data to generate regularly sampled reconstructed BRDF. The following figure shows the interpolated BRDF at degree 23.6. The stars indicate the original sample at degree 20.



Interpolated BRDF at degree 23.6
Compared with sampled data at 20 degree

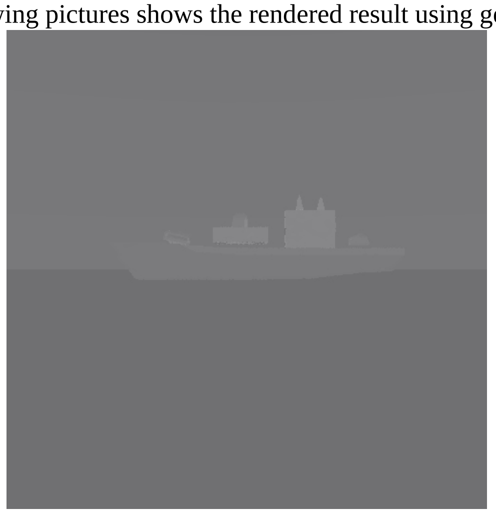
5. TARGET MODEL

we have modeled surface patch as both light source and reflector. Extended material method fully incorporated self-emission of surface patch to the rendering equation.

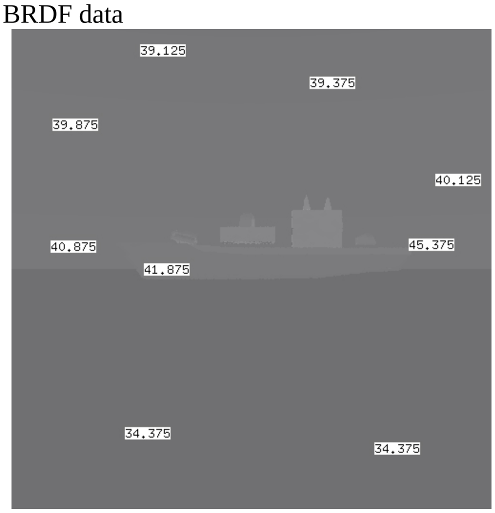
6. GLOBAL ILLUMINATION BASED RENDERING WITH TARGET AND BACKGROUND MODEL

7. EXPERIMENTAL RESULT

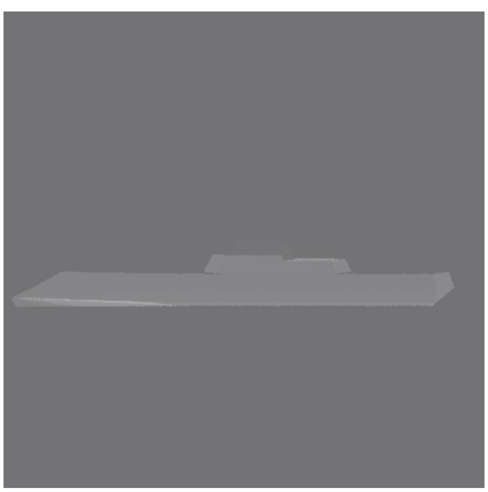
The following pictures shows the rendered result using general BRDF data



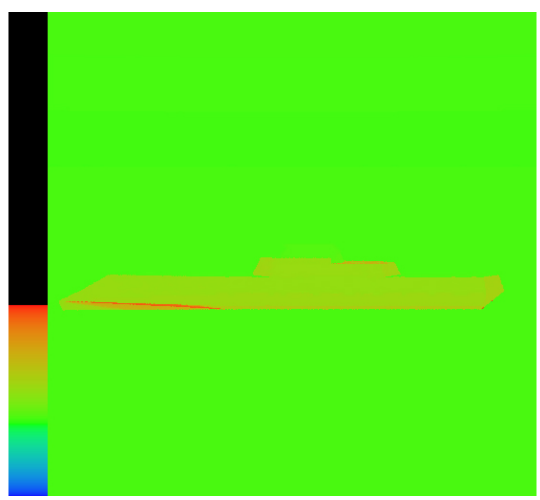
BRDF using data “FS480600”



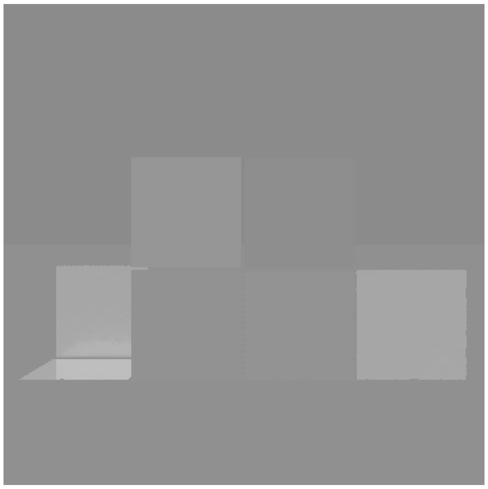
Corresponding analytical value



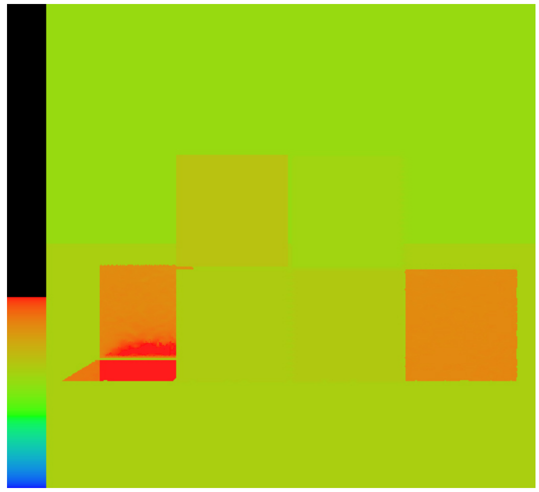
DD21 rendered using “FS480600”



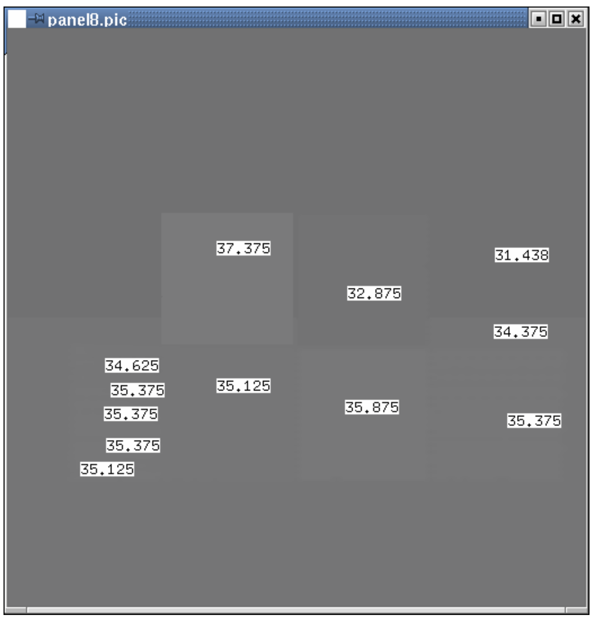
False colored result



Panel rendered using “FS480600”
And “aluminum” from iBRDF



False colored result



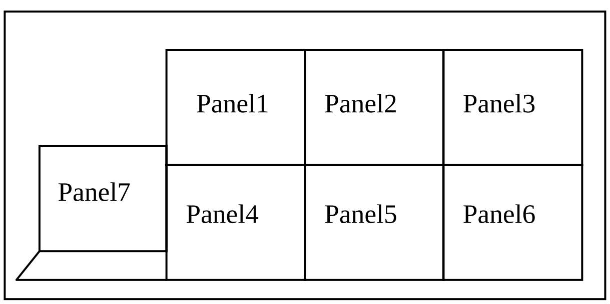
8.VALIDATION

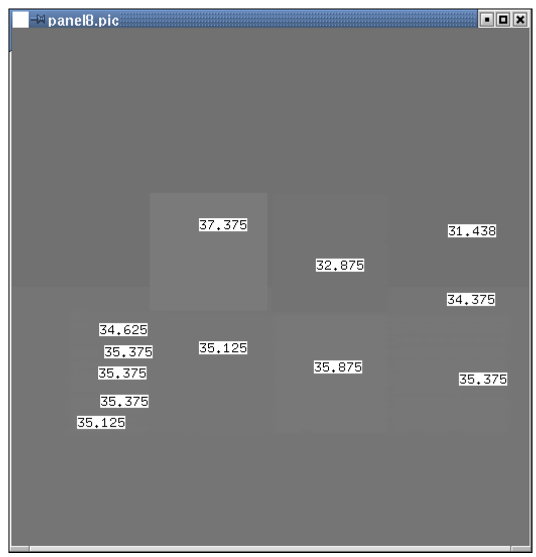
In order to apply the global illumination algorithm to the infrared ship signature prediction, we need to verify the physical accuracy of RADIANCE method. The following tables are the environment and reflectance parameters used in verification.

Object	*Temperature*	*Emissivity*	*Radiance*
Sky	*15^{o}C*	*1.0*	*31.48 W /m^2/Sr*
Sea	*20^{o}C*	*1.0*	*34.34 W/m^2/Sr*
Target	*25^{o}C*	*See Table below*	*Blackbody Radiance 37.35 W/m^2/Sr*

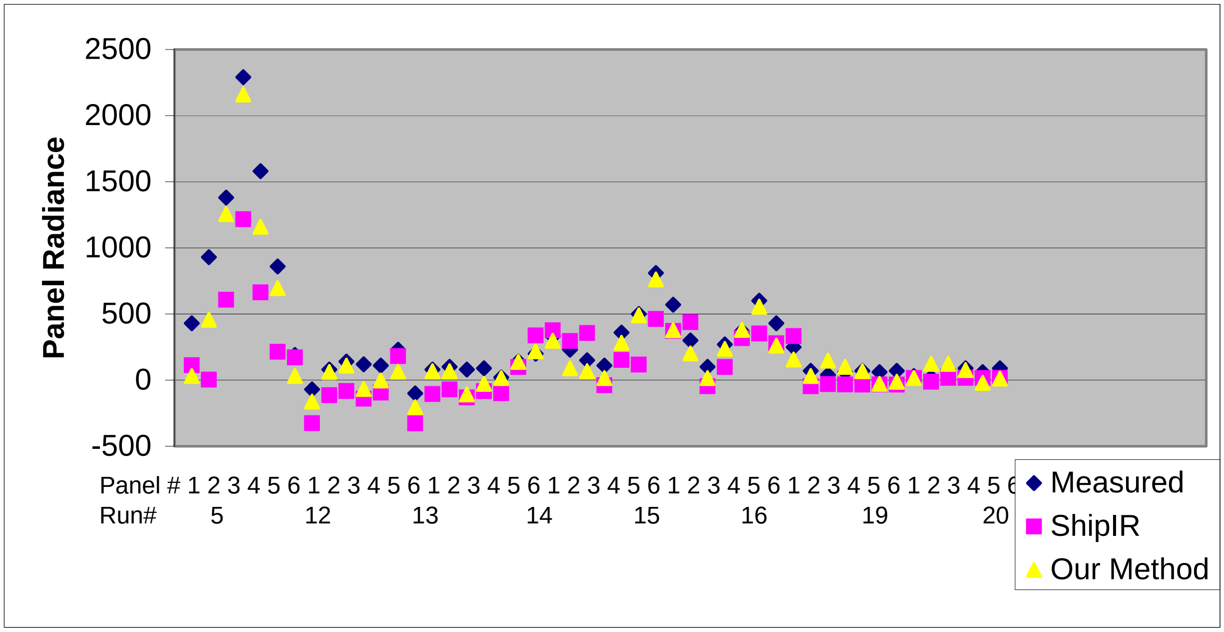
Optical Properties of the Test Panel			
Panel	*Emissivity*	*Diffuse*	*Specular*
1	*1.0*	*0.0*	*0.0*
2	*0.0*	*1.0*	*0.0*
3	*0.0*	*0.0*	*1.0*
4	*0.5*	*0.5*	*0.0*
5	*0.5*	*0.0*	*0.5*
6	*0.5*		
7	*0.5*	Complex BRDF	
		0.25	*0.1352*

We compared the result between analytic calculation and global rendering algorithm. The panel test verified that the global illumination algorithm based on importance sampling of the gaussian probe produces a physically correct simulation of energy transfer in certain wavelength.
The seven panels represent different material properties. Panel 1 has pure emissive energy source. The second panel is pure diffuse, third one is pure specular-like a mirror. Panel 4 to 5 has half emissivity and half diffuse and specular reflectance value. The panel 6 and 7 has more complex BRDF and the approximated reflectance is shown on the table.
The global illumination algorithm has correctly rendered 7 test panels and the maximum error does not exceed 0.3% of the analytically calculated value.





Panel Number	1	2	3	4	5	6	7
Analytic Value	37.35	32.91	31.48 / 34.34	35.13	35.845	35.5375	35.23
Rendered Value	37.375	32.875	31.438/ 34.375	35.125	35.875	35.375	35.125
Error	0.06%	0.1%	0.13% / 0.1%	0.01%	0.08%	0.105%	0.298%



9. FUTURE WORKS

We have extended the *global illumination algorithm* in the visible spectrum to predict infrared ship signatures. The research has resulted in a stable, open source (source code can be freely distributed) and well-documented code that satisfies a number of important requirements. These include realizing the physical accuracy required of the algorithm, incorporating surface self-emissivity in the model, incorporating sky and sea environment models, and incorporating general BRDF data representation in distributed ray tracing. The future works are simulation of participating media and environment such as clouds, plume, fog, mist and sub-surface scattering of the water. The accurate and efficient modeling and rendering of participating media is still a challenge for the simulation community. In the current implementation, the final rendering of the images assumed a perfect sensor. In order to accurately model the image seen by a particular real sensor, we need to take into consideration the physics of the sensors. These include the field of view, spectral response and sensitivity, jitter and noise. Such a model will be particularly important for real-time simulation in training. The general approach of the use of stochastic Monte Carlo techniques makes this type of modeling more amenable. Although, the global illumination algorithm can predict the infrared signature with high precision, one problem with this approach is its slow calculation speed. Recent advances in programmable graphics hardware made it possible to migrate distributed ray tracing computation to the graphics hardware, thus tremendously increasing the rendering speed. We will use a graphics hardware accelerated global illumination algorithm to speedup the IR simulation by incorporating our method presented in this paper.

REFERENCES