FRED® Application Note

Photon ENGINEERING
Illuminating Ideas

FRED Thermal Imaging Application Note

Introduction

Thermal imaging is a key technology for defense and detection applications such as the classification and tracking of concealed weapons, personnel, vehicles, and objects. Recently, efforts have been aimed at expanding IR sensing to temperature measurement and mapping, forest fire sensing and suppression, surveillance, and multi-spectral earth imaging. Figure 1 shows an example of simple thermal imaging model in FRED: a teapot is imaged through a camera lens by an infrared detector.

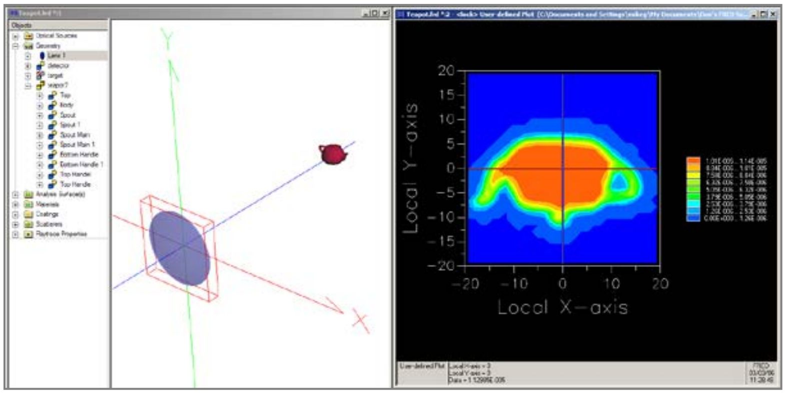
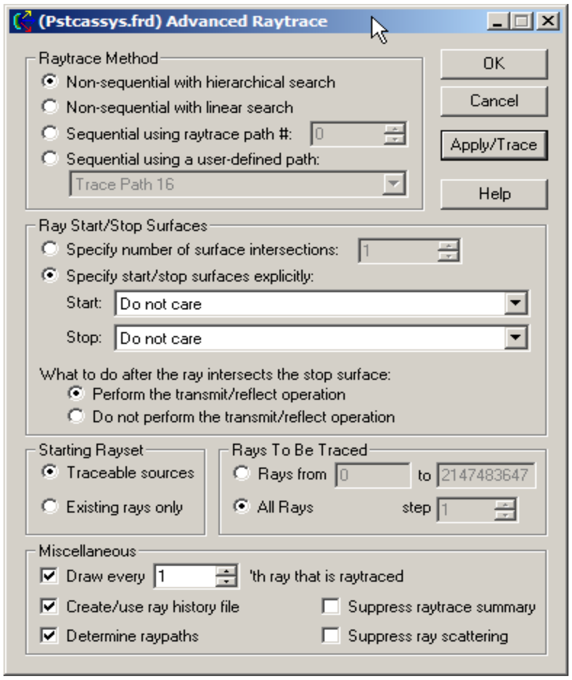


Figure 1. A warm teapot with different emissivities and temperature distribution across its surface is imaged through a singlet into a detector.

A key challenge in thermal imaging is noise. To combat this, systems typically subtract nominal background radiation to enhance contrast in the infrared scene. If the background is not uniform, however, a stray signal can be produced. Two sources that cause this variation are thermal emission and narcissus. Thermal emission is energy emitted from the environment or optical instrument that causes an *increased* signal in the detector. Narcissus, on the other hand, is a ghost image produced by a cooled detector array which reflects off of lens surfaces and re-enters the detector as a *reduced* signal: a dark, circular region.

Keeping track of thermal emission paths

FRED has the capability to do an advanced raytrace that keeps track of all ray paths in a system. This is accomplished by selecting [Raytrace→Advanced Raytrace…] from the main menu and checking "create/use ray history" and "determine raypaths" options (Figure 2).



(Pstcassys.frd) Advanced Raytrace

Raytrace Method
● Non-sequential with hierarchical search
○ Non-sequential with linear search
○ Sequential using raytrace path #: 0
○ Sequential using a user-defined path: Trace Path 16

Ray Start/Stop Surfaces
○ Specify number of surface intersections: 1
● Specify start/stop surfaces explicitly:
Start: Do not care
Stop: Do not care
What to do after the ray intersects the stop surface:
● Perform the transmit/reflect operation
○ Do not perform the transmit/reflect operation

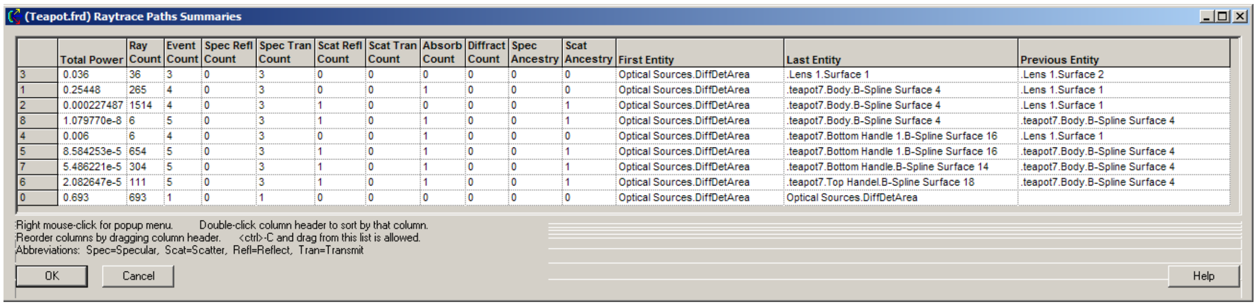
Starting Rayset
● Traceable sources
○ Existing rays only

Rays To Be Traced
○ Rays from 0 to 2147483647
● All Rays step 1

Miscellaneous
☑ Draw every 1 'th ray that is raytraced
☑ Create/use ray history file
☑ Determine raypaths
☐ Suppress raytrace summary
☐ Suppress ray scattering

Figure 2. Advanced Raytrace dialogue with create/use ray history file option and determine ray path options checked

After performing a raytrace, select [Tools→Reports…→Raytrace Paths…] from the main menu to produce report detailing how each ray paths reaches each surface (Figure 3). By using this method, it is possible to see how much power each of the ghosting, straight shot, single or multiple scatter paths contribute compared to the signal path.



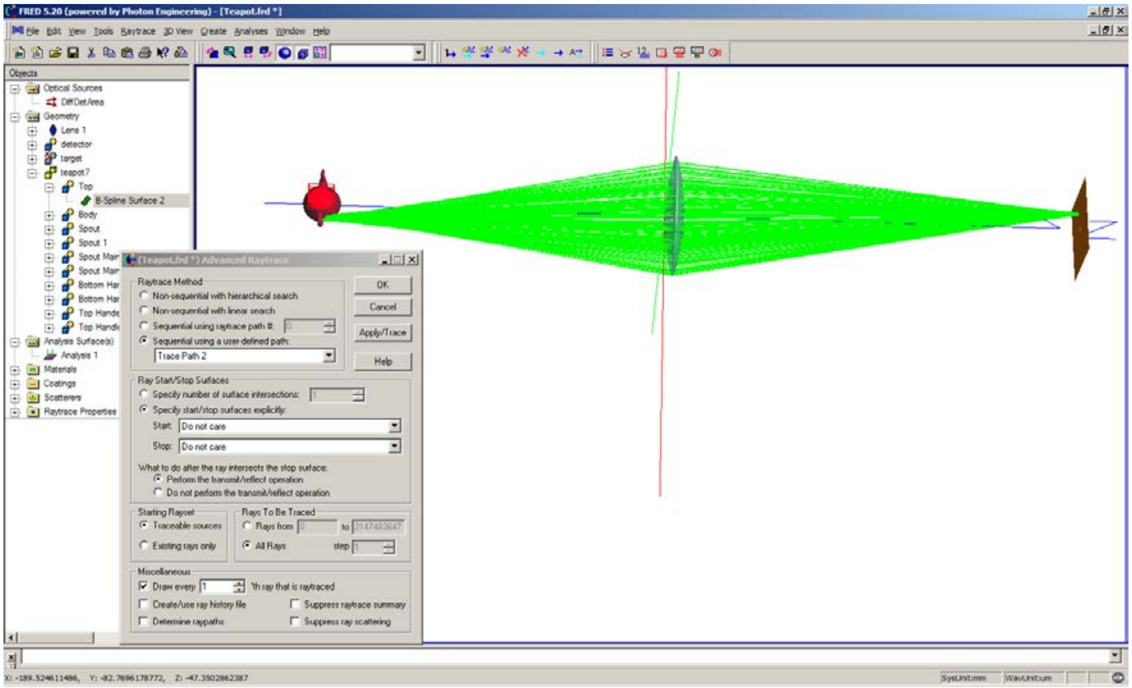
(Teapot.frd) Raytrace Paths Summaries

	Total Power	Ray Count	Event Count	Spec Refl Count	Spec Tran Count	Scat Refl Count	Scat Tran Count	Absorb Count	Diffract Count	Spec Ancestry	Scat Ancestry	First Entity	Last Entity	Previous Entity
3	0.036	36	3	0	3	0	0	0	0	0	0	Optical Sources.DiffDetArea	.Lens 1.Surface 1	.Lens 1.Surface 2
1	0.25448	265	4	0	3	0	0	1	0	0	0	Optical Sources.DiffDetArea	.teapot7.Body.B-Spline Surface 4	.Lens 1.Surface 1
2	0.000227487	1514	4	0	3	1	0	0	0	0	1	Optical Sources.DiffDetArea	.teapot7.Body.B-Spline Surface 4	.Lens 1.Surface 1
8	1.079770e-8	6	5	0	3	1	0	1	0	0	1	Optical Sources.DiffDetArea	.teapot7.Body.B-Spline Surface 4	.teapot7.Body.B-Spline Surface 4
4	0.006	6	4	0	3	0	0	1	0	0	0	Optical Sources.DiffDetArea	.teapot7.Bottom Handle 1.B-Spline Surface 16	.Lens 1.Surface 1
5	8.584253e-5	654	5	0	3	1	0	1	0	0	1	Optical Sources.DiffDetArea	.teapot7.Bottom Handle 1.B-Spline Surface 16	.teapot7.Body.B-Spline Surface 4
7	5.486221e-5	304	5	0	3	1	0	1	0	0	1	Optical Sources.DiffDetArea	.teapot7.Bottom Handle.B-Spline Surface 14	.teapot7.Body.B-Spline Surface 4
6	2.082647e-5	111	5	0	3	1	0	1	0	0	1	Optical Sources.DiffDetArea	.teapot7.Top Handel.B-Spline Surface 18	.teapot7.Body.B-Spline Surface 4
0	0.693	693	1	0	1	0	0	0	0	0	0	Optical Sources.DiffDetArea	Optical Sources.DiffDetArea	

Right mouse-click for popup menu. Double-click column header to sort by that column.
Reorder columns by dragging column header. <ctrl>-C and drag from this list is allowed.
Abbreviations: Spec=Specular, Scat=Scatter, Refl=Reflect, Tran=Transmit

Figure 3. Ray Paths for the Teapot Example shown in Figure 1. Path #1 is the direct thermal contribution from the teapot.

It is also possible to take a specific ray trace path and copy it to a user defined path list. Simply select the path, right mouse click and select the option to copy it to the user-defined path list. This path will now show up one of the ray methods to use in the advanced raytrace (Figure 4). Using this capability, spot diagrams and irradiance spread functions can be created for a single path.



Raytrace Method
○ Non-sequential with hierarchical search
○ Non-sequential with linear search
○ Sequential using raytrace path # 0
● Sequential using a user-defined path: Trace Path 2

Ray Start/Stop Surfaces
○ Specify number of surface intersections: 1
● Specify start/stop surfaces explicitly:
Start: Do not care
Stop: Do not care
What to do after the ray intersects the stop surface:
● Perform the transmit/reflect operation
○ Do not perform the transmit/reflect operation

Starting Rayset
● Traceable sources
○ Existing rays only

Rays To Be Traced
○ Rays from 0 to 2147483647
● All Rays step 1

Miscellaneous
☑ Draw every 1 'th ray that is raytraced
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☐ Suppress raytrace summary
☐ Determine raypaths
☐ Suppress ray scattering

Figure 4. Path #2 from the ray path report in Figure 3 is selected for an advanced raytrace. The raytrace of this path is shown for the teapot example.

Efficient thermal imaging simulation

Reverse ray tracing

There are several methods to simulate thermal emission in FRED. One technique is to create a source and raytrace it though the optical system. Another approach is to raytrace backwards from the detector through the system. Reverse ray tracing requires fewer rays, and is therefore a much more efficient. Faster ray tracing can allow one to assess the effect of incremental changes on the design in "real time". A comparison of forward and reverse ray tracing detector images is shown in Figure 5:

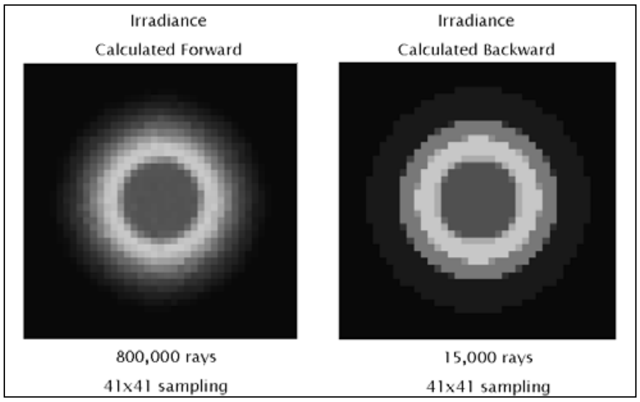


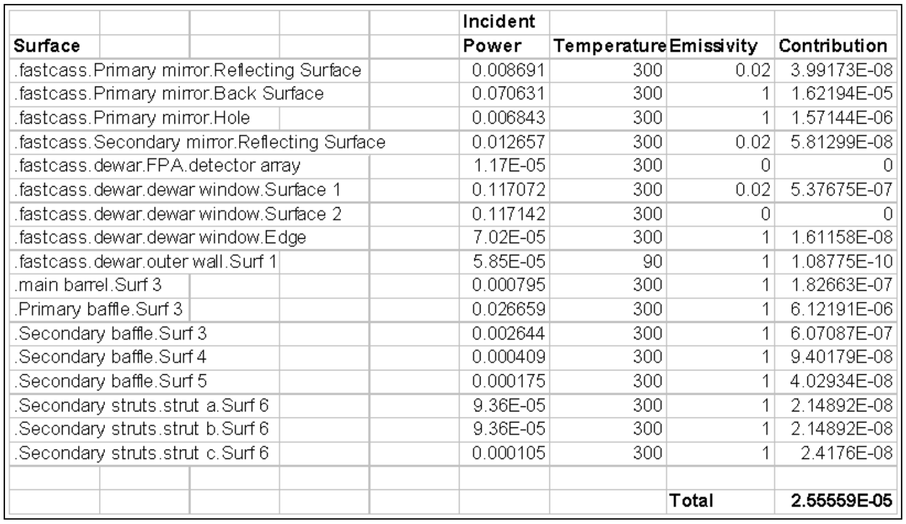
Figure 5. Comparison of two irradiance calculations: one performed using forward ray tracing and the other using backward ray tracing. The latter required 53x fewer rays to reach the same level of accuracy.

Quantifying thermal self-emission contributions

Thermal self-emission is the radiation of energy from structures within the system. If this energy is collected by the detector, it will contribute to a stray light signal. Each object in the system radiates as a function of temperature and emissivity. One way to quantify self-emission is to model each contributing surface as a Lambertian light source with appropriate energy and spectrum. However, this approach is incredibly inefficient! The detector fills a very small solid angle relative to the emission angle of these sources. A better approach is to perform a reverse raytrace from the detector and apply some radiometric concepts. The equation for thermal self-emission of a system is given by:

$$TSE = \sum_{all\ objects} \varepsilon\, f\, \sigma T^4 A_{detector} \left(\frac{\Omega_{object}}{\pi} \right) \qquad (1)$$

where ε = emissivity, f = fractional blackbody integral, σ = Stefan-Boltzmann constant, T = temperature (deg K), $A_{detector}$ is detector area and (Ω_{object}/π) is projected solid angle of an object with respect to the detector. It can be shown that power received by each object is numerically equal to its projected solid angle[1]. Therefore, to determine TSE, one can perform a reverse raytrace in FRED. After the raytrace is complete, incident power on each object can be obtained. This value may be substituted for (Ω/π) in equation 1. TSE contribution from each object can be calculated, given values of T and ε (Figure 6).



Surface	Incident Power	Temperature	Emissivity	Contribution
.fastcass.Primary mirror.Reflecting Surface	0.008691	300	0.02	3.99173E-08
.fastcass.Primary mirror.Back Surface	0.070631	300	1	1.62194E-05
.fastcass.Primary mirror.Hole	0.006843	300	1	1.57144E-06
.fastcass.Secondary mirror.Reflecting Surface	0.012657	300	0.02	5.81299E-08
.fastcass.dewar.FPA.detector array	1.17E-05	300	0	0
.fastcass.dewar.dewar window.Surface 1	0.117072	300	0.02	5.37675E-07
.fastcass.dewar.dewar window.Surface 2	0.117142	300	0	0
.fastcass.dewar.dewar window.Edge	7.02E-05	300	1	1.61158E-08
.fastcass.dewar.outer wall.Surf 1	5.85E-05	90	1	1.08775E-10
.main barrel.Surf 3	0.000795	300	1	1.82663E-07
.Primary baffle.Surf 3	0.026659	300	1	6.12191E-06
.Secondary baffle.Surf 3	0.002644	300	1	6.07087E-07
.Secondary baffle.Surf 4	0.000409	300	1	9.40179E-08
.Secondary baffle.Surf 5	0.000175	300	1	4.02934E-08
.Secondary struts.strut a.Surf 6	9.36E-05	300	1	2.14892E-08
.Secondary struts.strut b.Surf 6	9.36E-05	300	1	2.14892E-08
.Secondary struts.strut c.Surf 6	0.000105	300	1	2.4176E-08
			Total	**2.55559E-05**

Figure 6. Calculating thermal self-emission from a Cassegrain telescope using a spreadsheet such as Excel. The column "Incident Power" is actually projected solid angle of the object. The column "Contribution" implements eq. 5.

Conclusions

Using advanced raytracing capabilities in FRED, along with techniques derived from radiometry, it is possible to perform thermal imaging, narcissus, stray light, thermal illumination uniformity, and thermal self-emission calculations in a small fraction of the time it would take to trace the requisite number of rays in a brute force manner. FRED can also track each path traced through the system. The Raytrace Paths Report provides the contribution of each path to power reaching the detector. With these tools, one can quantify the effect of spurious signals in the detector and add features to the system to reduce these effects.

References:

1. R. Pfisterer, “Clever Tricks in Optical Engineering” (invited paper), Proceedings SPIE, Vol. 5524, October 2004.

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