Created in COMSOL Multiphysics 6.2

Vdara® Caustic Surface

Introduction

When the Vdara® hotel first opened in Las Vegas, visitors relaxing by the pool would experience intense periods of heat at certain times of the day and at certain times of the year. This intense heat was caused by the reflection of solar radiation from the curved, reflective surface on the South-facing side of the hotel. This model shows how a caustic surface is generated in the pool area around the time and date the problems were first reported.

Note: This application also requires the CAD Import Module.

Figure 1 below shows a small area of the CityCenter® complex which is the subject of this model. The concave surfaces of the Vdara® hotel are illuminated by sunlight, indicated by red arrows, at certain times of the day. The direction of the reflected rays depends on the direction of the incident solar radiation and the surface normal of the hotel.

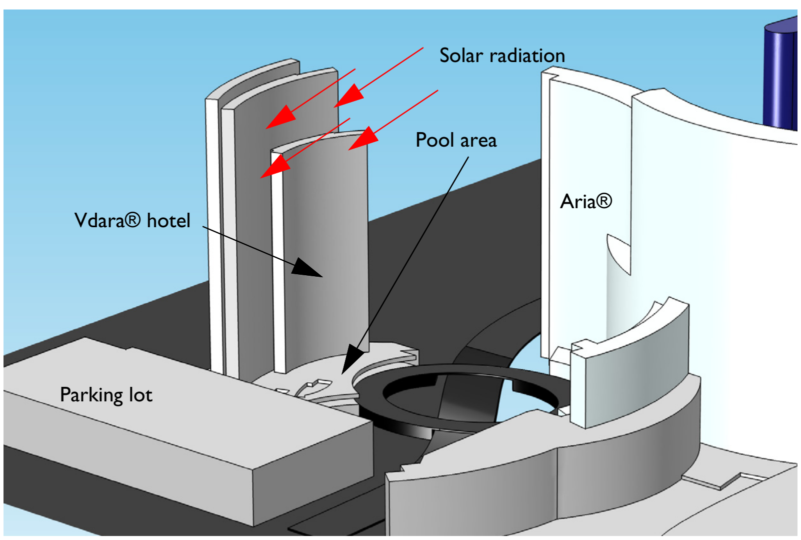

Figure 1: A solar flux incident on the concave surface of the Vdara® hotel is reflected down to the pool area beneath.

The Geometrical Optics interface can compute the intensity along individual ray paths by computing the principal radii of curvature of the associated wavefronts. When plane waves are reflected by the surface of the hotel, these principal radii of curvature are changed.

When the rays are reflected by a concave surface, the radius of curvature decreases in magnitude thereafter and eventually approaches zero. A continuous set of points at which either principal radius of curvature equals zero is called a caustic surface. In lens systems, the caustic surface often demarcates an envelope of rays. In the limit of geometrical optics, the ray intensity is infinite on a caustic surface. Practically, this corresponds to locations where the incident heat flux is extremely high, which can cause severe burns.

Model Definition

The model geometry includes the Vdara® hotel and several nearby buildings in the CityCenter® complex.

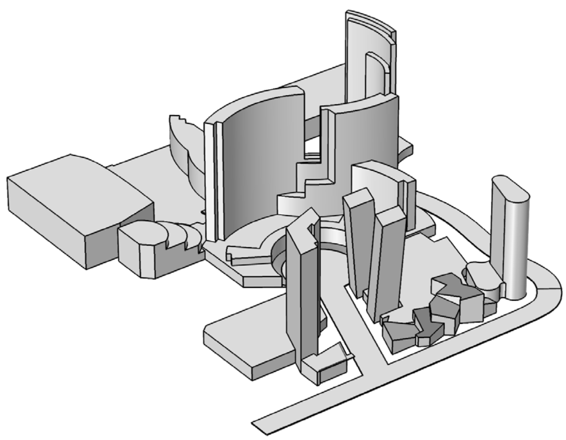

Figure 2: Imported CAD geometry of a section of the CityCenter® complex. The Vdara® hotel is shown at the top.

In order to avoid having to trace rays from the sun onto the surface of the hotel, a special boundary condition called the **Illuminated Surface** is employed. This boundary condition allows rays to be released from the surface of the hotel directly, significantly reducing the simulation time. The direction at which the rays are released from the surface of the hotel depends on the incoming ray direction vector $\mathbf{n}$ and the outward surface normal $\mathbf{n}_s$, according to the formula

$$\mathbf{n}_r = \mathbf{n}_i - 2(\mathbf{n}_i \cdot \mathbf{n}_s)\mathbf{n}_s$$

The principal radii of curvature of the released rays are also computed based on the radii of curvature of the incident wavefront and the curvature of the surface of the hotel. More details can be found in the *Ray Optics Module User's Guide*.

When the rays arrive at the swimming pool area, the intensity value of each ray is projected onto the surface mesh. This allows for more convenient visualization of the intersection of the caustic surface with the boundary. The **Accumulator** feature is used to accomplish this by implementing the following equation:

$$r_{\mathrm{b}} = \sum_{j=1}^{N_t} R_j \delta(\mathbf{r} - \mathbf{q}_j)$$

where R_j is the value of an arbitrary source term for the j^{th} incident ray, $\mathbf{q}_j$ is the position of the j^{th} ray when it strikes the pool area, and r_{b} is the value of the accumulated variable on a given boundary mesh element. Any expression for the source term R_j may be defined; for this example, $R_j = \log(I_j)$ is used, where I_j is the intensity of the j^{th} ray. The sum is taken over all rays that reach a given boundary element. The logarithm is used to better visualize changes in the order of magnitude of the ray intensity.

The selections for the boundary conditions are shown below. The curved, reflective surfaces of the hotel that face the sun are shown in orange. The other surfaces of the hotel are shown in gold. The pool and the surrounding area are shown in blue.

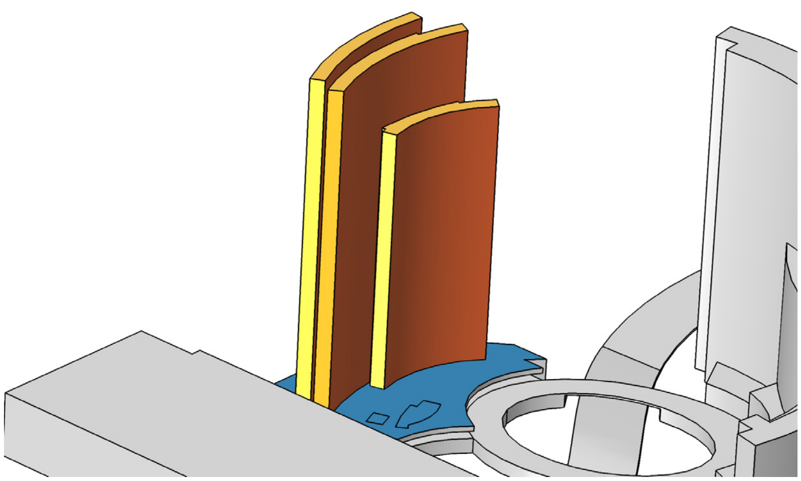

Figure 3: Close-up view of the Vdara® hotel.

Results and Discussion

The trajectories of the rays can be seen in Figure 4. The rays begin to cross each other after they reflect off the surface of the hotel. The color represents the intensity, which becomes very high at specific locations, indicated by the green and red coloring.

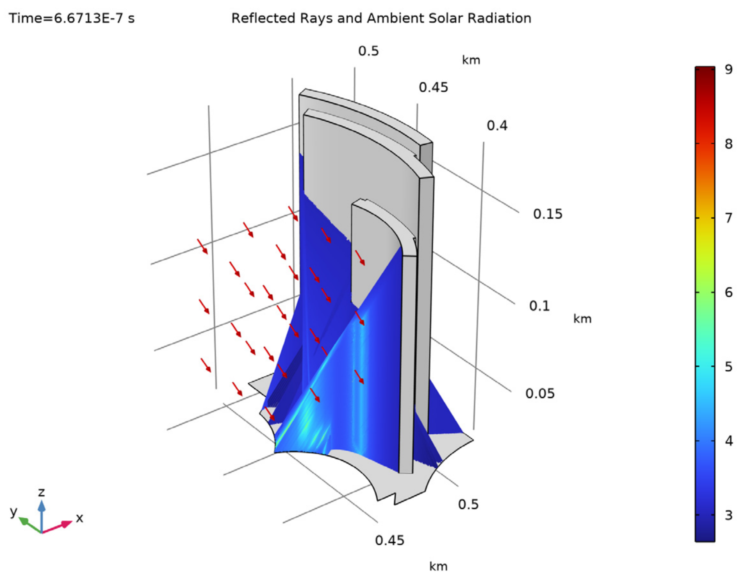

Figure 4: Ray trajectories reflecting off the Vdara® hotel in September at 11:45 am. The arrows indicate the direction vector of the solar radiation.

The projection of the high-intensity regions onto the swimming pool area is plotted in Figure 5. As expected, for this specific time of month and day, there is a clearly visible caustic surface cutting directly across the pool yard.

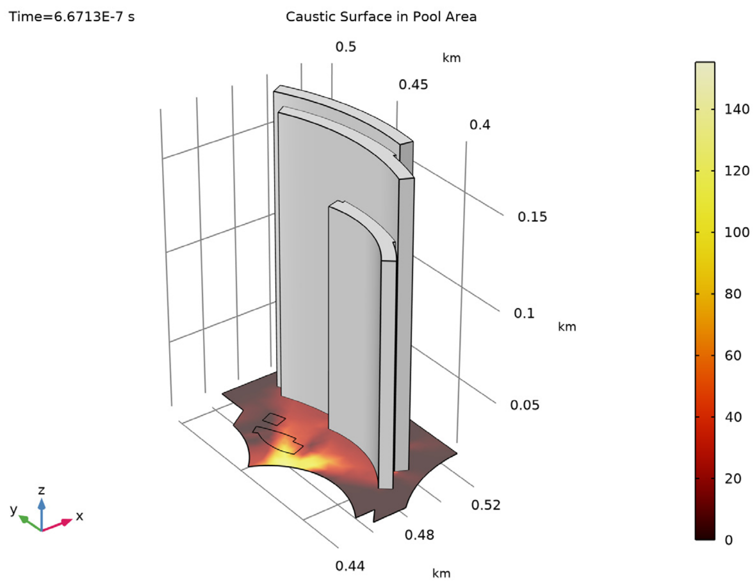

Figure 5: Plot of the log of the intensity projected onto the swimming pool area. There is a region of very high intensity right across the swimming pool.

Reference

1. M. Vollmer and K-P. Möllmann, "Caustic effects due to sunlight reflections from skyscrapers: simulations and experiments," *Eur. J. Phys.*, vol. 33, pp. 1429–1455, 2012.

Application Library path: `Ray_Optics_Module/Solar_Radiation/vdara_caustic_surface`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.
2 In the **Select Physics** tree, select **Optics>Ray Optics>Geometrical Optics (gop)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.
6 Click **Done**.

GEOMETRY 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
2 In the **Settings** window for **Geometry**, locate the **Units** section.
3 From the **Length unit** list, choose **km**.
4 This example uses an imported CAD geometry. Check that **CAD kernel** is selected from the **Geometry representation** list.

Import 1 (imp1)

1 In the **Home** toolbar, click **Import**.
2 In the **Settings** window for **Import**, locate the **Import** section.
3 Click **Browse**.
4 Browse to the model's Application Libraries folder and double-click the file `vdara_caustic_surface.x_b`.
5 Click **Import**.

   Compare the imported geometry to Figure 2.

DEFINITIONS

Create a **Box** selection that contains all of the surfaces of the hotel.

Hotel Surfaces

1 In the **Definitions** toolbar, click **Box**.
2 In the **Settings** window for **Box**, type `Hotel Surfaces` in the **Label** text field.
3 Locate the **Output Entities** section. From the **Include entity if** list, choose **Entity inside box**.
4 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.
5 Locate the **Box Limits** section. In the **x minimum** text field, type `0.475`.
6 In the **x maximum** text field, type `0.52`.

7 In the **y minimum** text field, type `0.38`.

8 In the **y maximum** text field, type `0.5`.

9 In the **z minimum** text field, type `0.01`.

10 In the **z maximum** text field, type `0.2`.

All of the surfaces of the hotel should be selected, including the orange and gold surfaces in Figure 3.

GEOMETRICAL OPTICS (GOP)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometrical Optics (gop)**.

2 In the **Settings** window for **Geometrical Optics**, locate the **Domain Selection** section.

3 Click **Clear Selection**.

4 Locate the **Ray Release and Propagation** section. In the **Maximum number of secondary rays** text field, type `0`.

5 Locate the **Intensity Computation** section. From the **Intensity computation** list, choose **Compute intensity**.

Selecting the **Store ray status data** check box causes a variable for the final ray status available for postprocessing; this will be used to filter rays so that only the rays that reach the pool are viewed.

6 Locate the **Additional Variables** section. Select the **Store ray status data** check box.

Illuminated Surface 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Illuminated Surface**.

2 Select boundaries 351, 356, and 359, the curved surfaces of the hotel that face the sun. These surfaces are colored orange in Figure 3.

3 In the **Settings** window for **Illuminated Surface**, locate the **Initial Position** section.

4 From the **Initial position** list, choose **Density**.

5 In the N text field, type `50000`.

6 Locate the **Ray Direction Vector** section. From the **Incident ray direction vector** list, choose **Solar radiation**.

7 From the **Location defined by** list, choose **City**.

8 In the table, enter the following settings:

Day	Month	Year
01	9	2014

9 In the table, enter the following settings:

Hour	**Minute**	**Second**
11	45	0

Wall 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 Select boundaries 321, 331, and 345, the pool and the surrounding area. These surfaces are colored blue in Figure 3.

Accumulator 1

1 In the **Physics** toolbar, click **Attributes** and choose **Accumulator**.

2 In the **Settings** window for **Accumulator**, locate the **Accumulator Settings** section.

3 From the **Accumulate over** list, choose **Rays in boundary elements**.

4 In the R text field, type `gop.logI`.

The **Source** text field will turn yellow and a tooltip warning will appear, indicating that the deduced unit does not match the expected unit. Fix this by specifying the dependent variable quantity.

5 Locate the **Units** section. Click **Custom Unit**.

6 In the **Dependent variable quantity** table, enter the following settings:

Dependent variable quantity	**Unit**
Custom unit	`m^-2`

Wall 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

The second **Wall** condition allows rays to be reflected multiple times at different surfaces of the building.

2 In the **Settings** window for **Wall**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Hotel Surfaces**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Specular reflection**.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Extremely fine**.

4 Click **Build All**.

STUDY 1

Step 1: Ray Tracing

1 In the **Model Builder** window, under **Study 1** click **Step 1: Ray Tracing**.

2 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.

3 From the **Time-step specification** list, choose **Specify maximum path length**.

4 Click **Range**.

5 In the **Range** dialog box, type `10` in the **Step** text field.

6 In the **Stop** text field, type `200`.

7 Click **Replace**.

8 In the **Home** toolbar, click **Compute**.

RESULTS

Ray Trajectories (gop)

1 In the **Settings** window for **3D Plot Group**, click to expand the **Title** section.

2 From the **Title type** list, choose **Manual**.

3 In the **Title** text area, type `Reflected Rays and Ambient Solar Radiation`.

Grid 3D 1

The default plot shows the paths of the reflected rays. The direction of the incident solar radiation is also shown as a vector field. First, adjust the **Grid 3D** dataset so that the vectors are closer together.

1 In the **Model Builder** window, expand the **Results>Datasets** node, then click **Grid 3D 1**.

2 In the **Settings** window for **Grid 3D**, locate the **Parameter Bounds** section.

3 Find the **First parameter** subsection. In the **Minimum** text field, type `0.4`.

4 In the **Maximum** text field, type `0.48`.

5 Find the **Second parameter** subsection. In the **Minimum** text field, type `0.4`.

6 In the **Maximum** text field, type `0.48`.

7 Find the **Third parameter** subsection. In the **Minimum** text field, type `0.05`.

8 In the **Maximum** text field, type `0.15`.

Ray Trajectories (gop)

Now resume editing the **Ray Trajectories** plot.

In the **Model Builder** window, expand the **Results>Ray Trajectories (gop)** node.

Color Expression 1

1. In the **Model Builder** window, expand the **Results>Ray Trajectories (gop)>** **Ray Trajectories 1** node, then click **Color Expression 1**.
2. In the **Settings** window for **Color Expression**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>** **Geometrical Optics>Intensity and polarization>gop.logI - Log of intensity - 1**.

Filter 1

Plot only the rays with final status `gop.fs==2`. This is true for all rays that have hit a **Wall** with the **Freeze** condition; that is, all rays that have reached the pool. Filtering the rays makes the solution easier to visualize.

1. In the **Model Builder** window, click **Filter 1**.
2. In the **Settings** window for **Filter**, locate the **Ray Selection** section.
3. From the **Rays to include** list, choose **Logical expression**.
4. In the **Logical expression for inclusion** text field, type `gop.fs==2`.

Ray Trajectories (gop)

Add a **Surface** plot to the building and poolside to make them appear solid.

Surface 1

1. In the **Model Builder** window, right-click **Ray Trajectories (gop)** and choose **Surface**.
2. In the **Settings** window for **Surface**, locate the **Coloring and Style** section.
3. From the **Coloring** list, choose **Uniform**.
4. From the **Color** list, choose **Gray**.
5. In the **Ray Trajectories (gop)** toolbar, click **Plot**.
6. Click the **Go to Default View** button in the **Graphics** toolbar. Compare the resulting plot to Figure 4.

Caustic Surface in Pool Area

1. In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.
2. In the **Settings** window for **3D Plot Group**, type `Caustic Surface in Pool Area` in the **Label** text field.
3. Locate the **Title** section. From the **Title type** list, choose **Manual**.
4. In the **Title** text area, type `Caustic Surface in Pool Area`.

Surface 1

1 Right-click **Caustic Surface in Pool Area** and choose **Surface**.
2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Geometrical Optics>Accumulated variables> Accumulated variable comp1.gop.wall1.bacc1.rpb>gop.wall1.bacc1.rpb - Accumulated variable rpb - 1/m²**.
3 Click to expand the **Quality** section. From the **Smoothing** list, choose **Everywhere**.
4 From the **Resolution** list, choose **No refinement**.
5 Locate the **Coloring and Style** section. Click **Change Color Table**.
6 In the **Color Table** dialog box, select **Thermal>ThermalDark** in the tree.
7 Click **OK**.

Create another **Surface** plot to display the surfaces of the hotel.

Caustic Surface in Pool Area

In the **Model Builder** window, click **Caustic Surface in Pool Area**.

Surface 2

1 In the **Caustic Surface in Pool Area** toolbar, click **Surface**.
2 In the **Settings** window for **Surface**, click to expand the **Title** section.
3 From the **Title type** list, choose **None**.
4 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.
5 From the **Color** list, choose **Gray**.

Selection 1

1 Right-click **Surface 2** and choose **Selection**.
2 In the **Settings** window for **Selection**, locate the **Selection** section.
3 From the **Selection** list, choose **Hotel Surfaces**.
4 In the **Caustic Surface in Pool Area** toolbar, click **Plot**.
5 Click the **Go to Default View** button in the **Graphics** toolbar. Compare the resulting plot to Figure 5.