Lightning-Induced Voltage of a Wire in an Airplane

Introduction

Civil aircraft are struck by lightning at least once a year. Lightning can cause direct and indirect effects. One indirect effect is the lightning electromagnetic pulse (LEMP) that can induce surge voltages in distant electrical and electronic devices and systems. Early aircraft were mostly constructed of aluminum and usually have great inherent immunity to LEMP. Aircraft windows are also manufactured with special materials, or by applying transparent conductive coatings.

In modern aircraft, structures are increasingly made of composite materials, especially carbon fiber composites. Aircraft control systems are also increasingly reliant on electronic systems. Both of these factors have resulted in increased emphasis on lightning protection. However, a real lightning strike is not possible to reproduce in laboratory. Current laboratory tests are therefore not able to capture the lightning effects completely.

Numerical simulation, on the other hand, can help aircraft design engineers predict and evaluate lightning effects during the design stage. Moreover, simulations provide more accurate results as a realistic lightning strike can be modeled numerically.

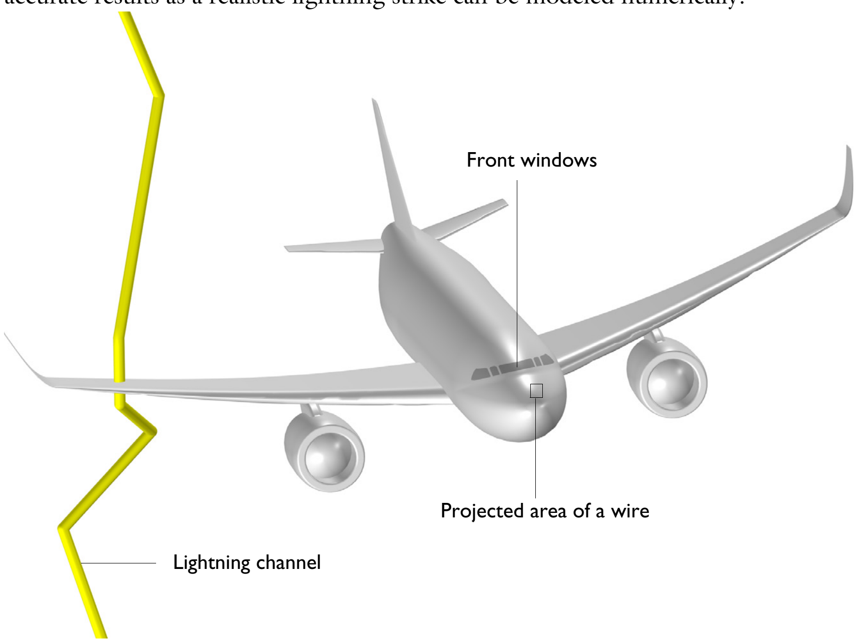


Figure 1: Schematic diagram of an aircraft being struck by lightning.

Model Definition

Lightning current is very nonlinear and requires a transient 3D study. The **RF Module** provides the physics interface **Electromagnetic Waves, Transient**, which is dedicated to this purpose. The **Electromagnetic Waves, Transient** interface provides predefined lightning current. The current can easily be visualized by clicking the **Plot Pulse Shape** button in the **Settings** window, as shown in Figure 2.

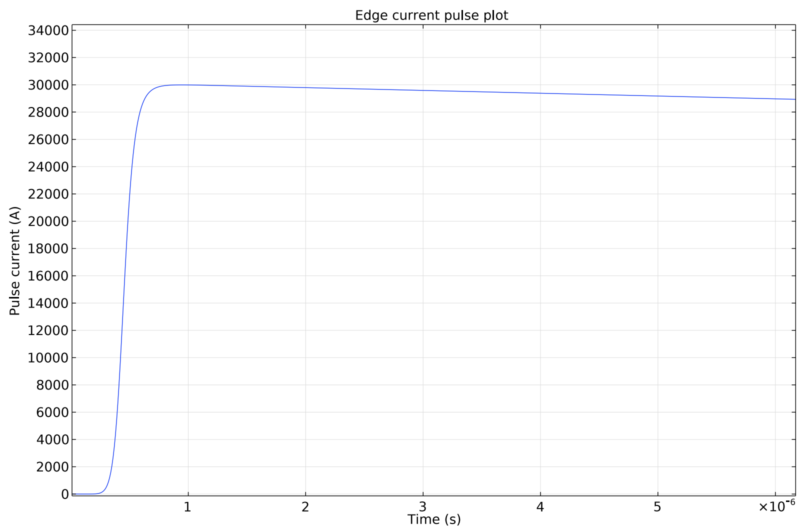


Figure 2: The lightning current used in the model.

The example computes the induced voltage of a wire loop inside an airplane under three electromagnetic shielding conditions:

- Completely not shielded
- Only front windows not shielded
- Completely shielded

The radius of a lightning channel is usually a few millimeters and it is here modeled with the **Edge Current** feature. Lightning current typically travels at one-third the speed of light due to corona discharges around the channel. The **Edge Current** feature defines the waveform of the current as well as how it is propagating along the edge (the lightning path).

As the induced current on the wire is significantly smaller than that of the lightning current, the induced voltage on the wire is computed in the postprocessing by integrating the tangential electric field along the wire loop.

Results and Discussion

Figure 3 illustrates the computed induced voltage on the wire under three different electromagnetic shielding conditions. For the case when the airplane is completely not shielded (made with nonconducting materials), the induced voltage can be as high as 70 V, which can have significant impact on internal electrical systems that typically operate at hundreds of volts. For the case when airplane is not completely shielded (with ordinary windows), the amplitude of the induced voltage might be reduced. However, it is still high enough to disorder the internal electrical circuit. Figure 4 shows the induced electric-field distribution on the airplane when the induced voltage reaches its first peak around 2.5 μs. As the figure shows, the areas close to the front window and other corners generate induced electric field greater than 3 kV/cm, which may damage other facilitates such as antennas.

The third case simulates the airplane being covered with a perfectly conductive material. In the physics interface, it is done by applying the Perfect Electric Conductor condition everywhere on the surface of the airplane.

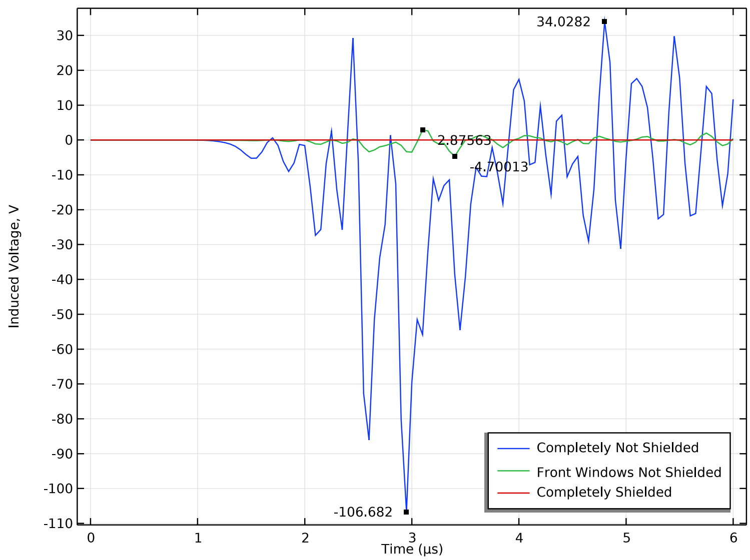


Figure 3: Lightning-induced voltage on the wire inside the airplane under different electromagnetic shielding conditions.

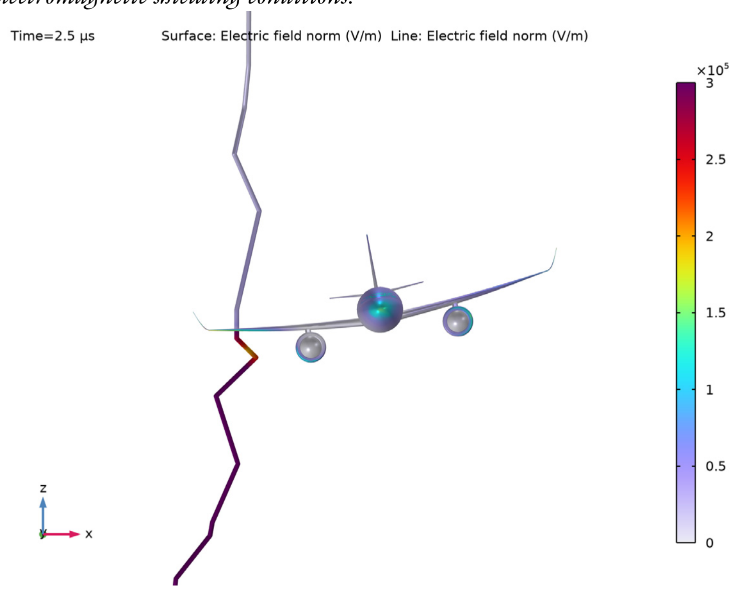


Figure 4: The induced electric field on the surface of the airplane at t = 2.5 µs when only the front windows are not shielded.

Application Library path: `RF_Module/ESD_and_Lightning_Surge/lightning_induced_voltage_airplane`

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 **Radio Frequency>Electromagnetic Waves, Transient (temw)**.
3. Click **Add**.
4. Click **Study**.
5. In the **Select Study** tree, select **General Studies>Time Dependent**.
6. Click **Done**.

GEOMETRY 1

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 `lightning_induced_voltage_airplane.mphbin`.
5. Click **Build Selected**.

Work Plane 1 (wp1)

1. In the **Geometry** toolbar, click **Work Plane**.
2. In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.
3. From the **Plane** list, choose **zx-plane**.
4. In the **y-coordinate** text field, type `-30[m]`.

Work Plane 1 (wp1)>Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Work Plane 1 (wp1)>Rectangle 1 (r1)

1 In the **Work Plane** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Object Type** section.

3 From the **Type** list, choose **Curve**.

4 Locate the **Position** section. In the **xw** text field, type 2.

Rotate 1 (rot1)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Transforms>Rotate**.

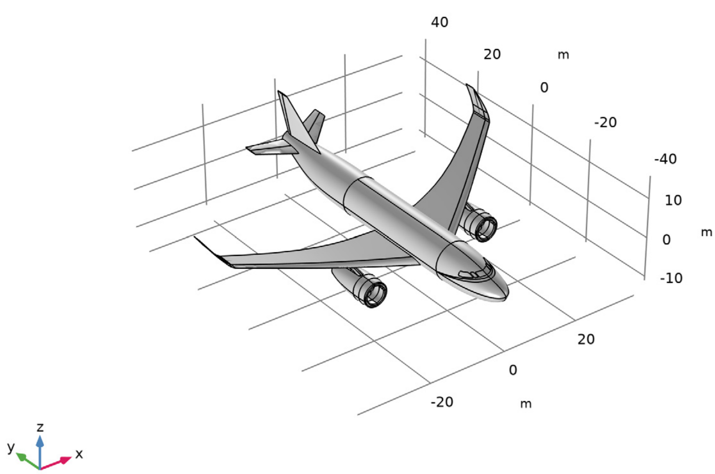
2 Click the **Select All** button in the **Graphics** toolbar.

3 In the **Settings** window for **Rotate**, locate the **Rotation** section.

4 From the **Axis type** list, choose **y-axis**.

5 In the **Angle** text field, type -10.

6 Click **Build Selected**.



Polygon 1 (pol1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

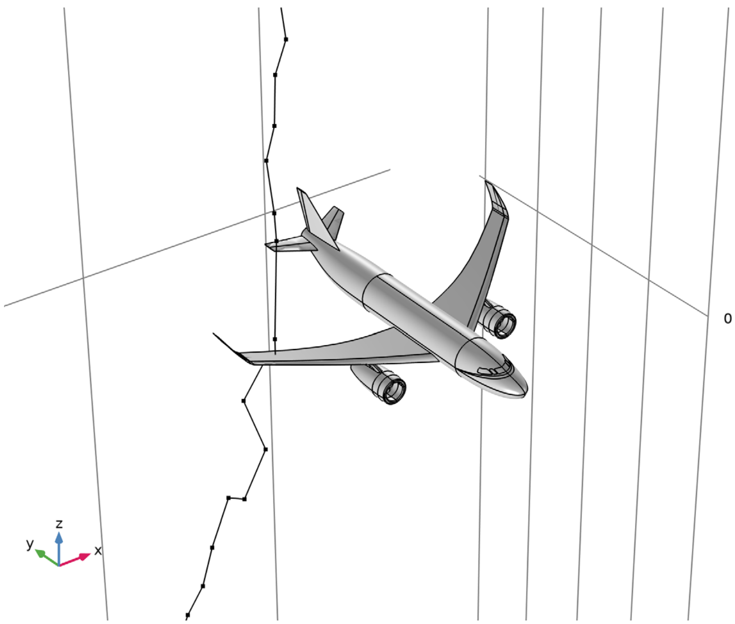
3 Click **Clear Table**.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `lightning_induced_voltage_airplane_table.txt`.

6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

7 Click **Build Selected**.



Sphere 1 (sph1)

1 In the **Geometry** toolbar, click **Sphere**.

2 In the **Settings** window for **Sphere**, locate the **Size** section.

3 In the **Radius** text field, type `1[km]`.

4 Click **Build All Objects**.

5 Click the **Go to Default View** button in the **Graphics** toolbar.

DEFINITIONS

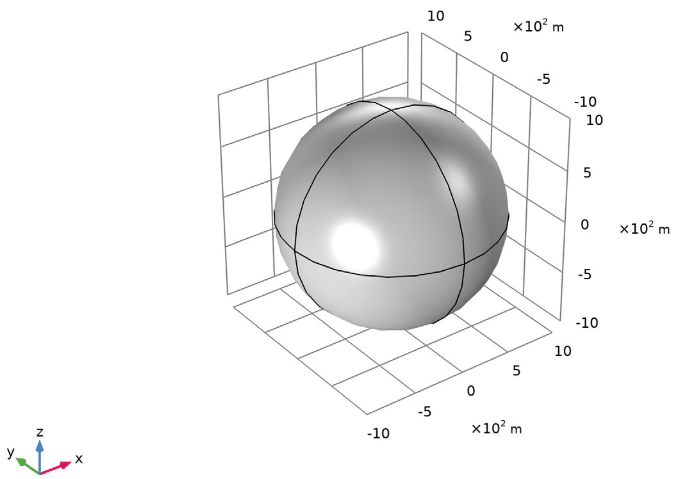
Hide for Geometry 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.

2 Right-click **View 1** and choose **Hide for Geometry**.

3 In the **Settings** window for **Hide for Geometry**, locate the **Selection** section.

4 From the **Geometric entity level** list, choose **Boundary**.



5 On the object **sph1**, select Boundaries 1, 2, 5, and 6 only.

6 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

Airplane Without Front Windows

1 In the **Definitions** toolbar, click **Explicit**.

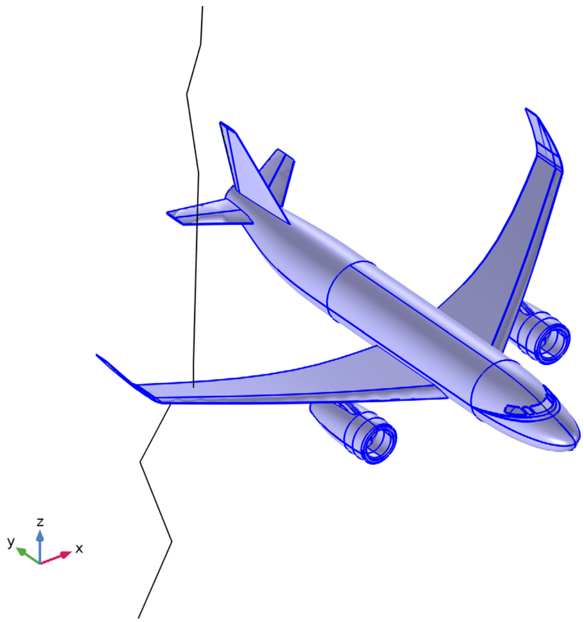
2 In the **Settings** window for **Explicit**, type `Airplane Without Front Windows` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `5-91, 93-98, 100, 101, 103-106, 108-110, 113, 116-118, 120, 121, 123-197` in the **Selection** text field.

6 Click **OK**.



7 Click the **Zoom to Selection** button in the **Graphics** toolbar.

Airplane All

1 In the **Definitions** toolbar, click **Explicit**.

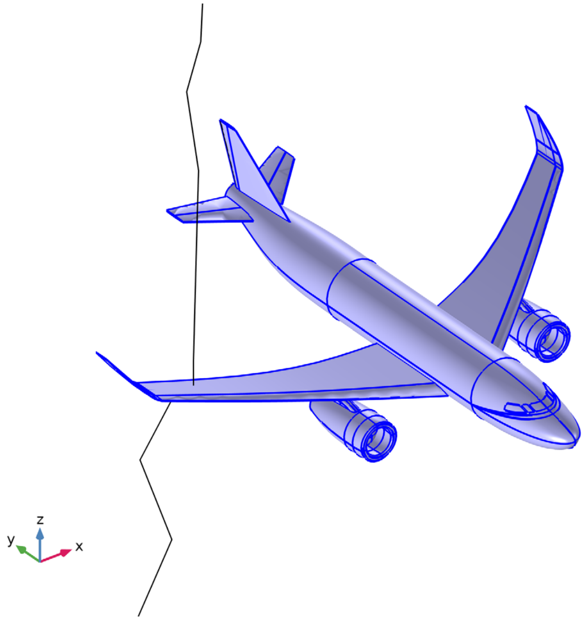
2 In the **Settings** window for **Explicit**, type `Airplane All` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `5-110, 113, 116-197` in the **Selection** text field.

6 Click **OK**.



Wire

1 In the **Definitions** toolbar, click **Explicit**.

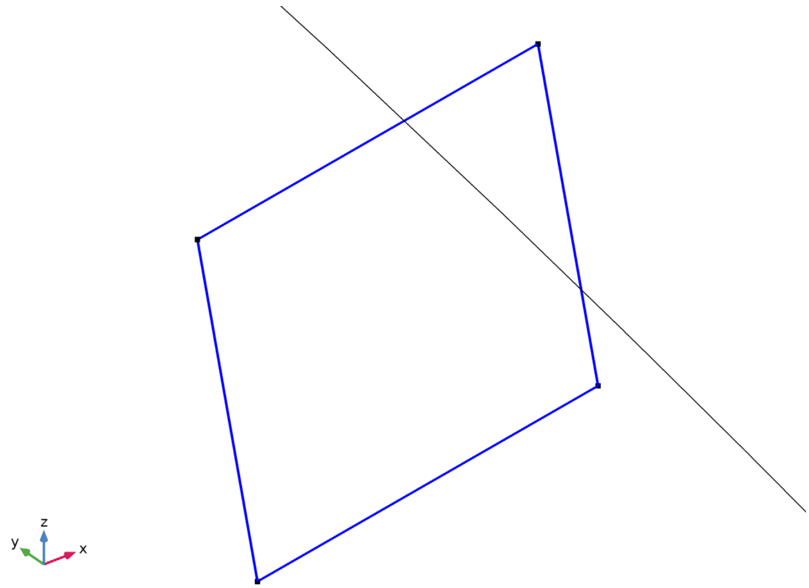
2 In the **Settings** window for **Explicit**, type `Wire` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Edge**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `290, 291, 300, 312` in the **Selection** text field.

6 Click **OK**.



7 Click the **Zoom to Selection** button in the **Graphics** toolbar.

MATERIALS

Air

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Air` in the **Label** text field.

3 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic

Property	Variable	Value	Unit	Property group
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

ELECTROMAGNETIC WAVES, TRANSIENT (TEMW)

Scattering Boundary Condition 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Electromagnetic Waves, Transient (temw)** and choose **Scattering Boundary Condition**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `1-4, 111, 112, 114, 115` in the **Selection** text field.

5 Click **OK**.

Edge Current 1

1 In the **Physics** toolbar, click **Edges** and choose **Edge Current**.

2 In the **Settings** window for **Edge Current**, locate the **Edge Current** section.

3 From the **Edge current type** list, choose **Lightning**.

4 Locate the **Edge Selection** section. From the **Selection** list, choose **Polygon 1**.

5 Locate the **Edge Current** section. In the v_p text field, type `c_const/3`.

6 Select the **Reverse direction** check box.

7 Click the **Zoom to Selection** button in the **Graphics** toolbar.

Perfect Electric Conductor 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Perfect Electric Conductor**.

2 In the **Settings** window for **Perfect Electric Conductor**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Airplane Without Front Windows**.

Perfect Electric Conductor 3

1 In the **Physics** toolbar, click **Boundaries** and choose **Perfect Electric Conductor**.

2 In the **Settings** window for **Perfect Electric Conductor**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Airplane All**.

4 Click the **Zoom to Selection** button in the **Graphics** toolbar.

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Electromagnetic Waves, Transient (temw)** section.

3 In the **Maximum element size in free space** text field, type `300[m]`.

4 In the **Model Builder** window, click **Mesh 1**.

5 Locate the **Sequence Type** section. From the list, choose **User-controlled mesh**.

Size

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

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 Click the **Predefined** button.

4 From the **Predefined** list, choose **Coarse**.

Size 1

1 In the **Model Builder** window, right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Edge**.

4 From the **Selection** list, choose **Wire**.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** check box. In the associated text field, type `0.3[m]`.

Size 2

1 Right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Edge**.

4 From the **Selection** list, choose **Polygon 1**.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** check box. In the associated text field, type `5[m]`.

8 Click the **Zoom to Selection** button in the **Graphics** toolbar.

Size 3

1 Right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

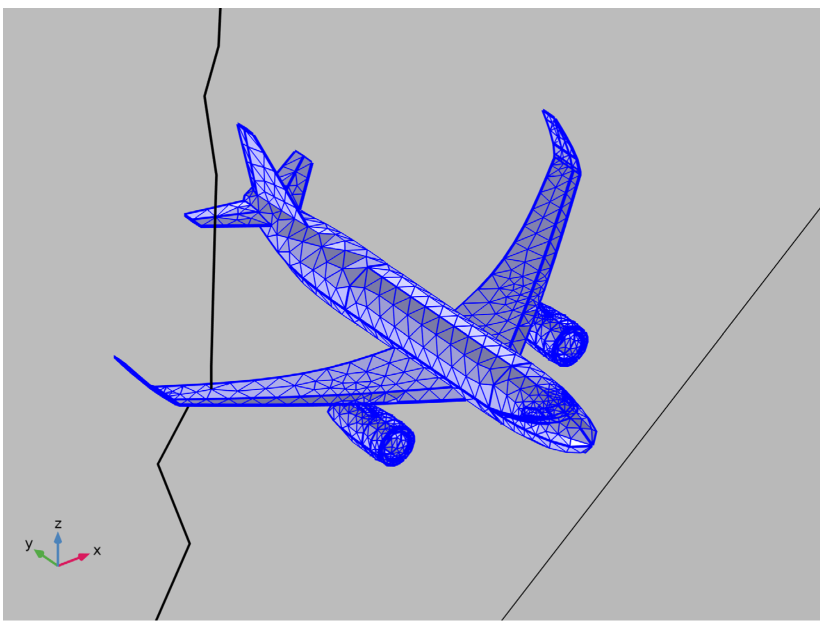
4 Select Domain 2 only.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** check box. In the associated text field, type `3.5[m]`.

8 Click **Build All**.



STUDY 1, COMPLETELY NOT SHIELDED

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, type `Study 1, Completely Not Shielded` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1, Completely Not Shielded** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **µs**.

4 In the **Output times** text field, type `range(0,0.05,6)`.

5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

6 In the **Model Builder** window, click **Step 1: Time Dependent**.

7 In the tree, select **Component 1 (comp1)>Electromagnetic Waves, Transient (temw)>Perfect Electric Conductor 2** and **Component 1 (comp1)>Electromagnetic Waves, Transient (temw)>Perfect Electric Conductor 3**.

8 Right-click and choose **Disable**.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.

3 In the **Model Builder** window, under **Study 1, Completely Not Shielded>Solver Configurations>Solution 1 (sol1)** click **Time-Dependent Solver 1**.

4 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

5 From the **Steps taken by solver** list, choose **Manual**.

6 In the **Time step** text field, type `0.05[us]`.

ADD STUDY

1 In the **Study** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Time Dependent**.

4 Right-click and choose **Add Study**.

STUDY 2, FRONT WINDOWS NOT SHIELDED

1 In the **Model Builder** window, click **Study 2**.
2 In the **Settings** window for **Study**, type `Study 2, Front Windows Not Shielded` in the **Label** text field.
3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 2, Front Windows Not Shielded** click **Step 1: Time Dependent**.
2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
3 From the **Time unit** list, choose **µs**.
4 In the **Output times** text field, type `range(0,0.05,6)`.
5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.
6 In the tree, select **Component 1 (comp1)>Electromagnetic Waves, Transient (temw)>Perfect Electric Conductor 3**.
7 Right-click and choose **Disable**.

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**.
2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node, then click **Time-Dependent Solver 1**.
3 In the **Settings** window for **Time-Dependent Solver**, locate the **Time Stepping** section.
4 From the **Steps taken by solver** list, choose **Manual**.
5 In the **Time step** text field, type `0.05[us]`.

ADD STUDY

1 Go to the **Add Study** window.
2 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Time Dependent**.
3 Right-click and choose **Add Study**.

STUDY 3, COMPLETELY SHIELDED

1 In the **Model Builder** window, click **Study 3**.
2 In the **Settings** window for **Study**, type `Study 3, Completely Shielded` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 3, Completely Shielded** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **µs**.

4 In the **Output times** text field, type `range(0,0.05,6)`.

5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

6 In the tree, select **Component 1 (comp1)>Electromagnetic Waves, Transient (temw)>Perfect Electric Conductor 2**.

7 Right-click and choose **Disable**.

8 In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

Solution 3 (sol3)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 3 (sol3)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, locate the **Time Stepping** section.

4 From the **Steps taken by solver** list, choose **Manual**.

5 In the **Time step** text field, type `0.05[us]`.

STUDY 1, COMPLETELY NOT SHIELDED

In the **Study** toolbar, click **Compute**.

STUDY 2, FRONT WINDOWS NOT SHIELDED

Click **Compute**.

STUDY 3, COMPLETELY SHIELDED

Click **Compute**.

RESULTS

Line Integration 1

1 In the **Model Builder** window, expand the **Results** node.

2 Right-click **Results>Derived Values** and choose **Integration>Line Integration**.

3 In the **Settings** window for **Line Integration**, locate the **Selection** section.

4 From the **Selection** list, choose **Wire**.

5 Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
`temw.Ex*t1x+temw.Ey*t1y+temw.Ez*t1z`	`V`	`Voltage`

6 Right-click **Line Integration 1** and choose **Duplicate**.

Line Integration 2

1 In the **Model Builder** window, click **Line Integration 2**.

2 In the **Settings** window for **Line Integration**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2, Front Windows Not Shielded/Solution 2 (sol2)**.

4 Right-click **Line Integration 2** and choose **Duplicate**.

Line Integration 3

1 In the **Model Builder** window, click **Line Integration 3**.

2 In the **Settings** window for **Line Integration**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3, Completely Shielded/Solution 3 (sol3)**.

4 In the **Results** toolbar, click **Evaluate** and choose **Clear and Evaluate All**.

Induced Voltage on Wire

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Induced Voltage on Wire` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **None**.

4 Locate the **Plot Settings** section.

5 Select the **y-axis label** check box. In the associated text field, type `Induced Voltage, V`.

6 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

Table Graph 1

Right-click **Induced Voltage on Wire** and choose **Table Graph**.

Table Graph 2

In the **Model Builder** window, right-click **Induced Voltage on Wire** and choose **Table Graph**.

Table Graph 1

1 In the **Settings** window for **Table Graph**, click to expand the **Legends** section.

2 Select the **Show legends** check box.

3 From the **Legends** list, choose **Manual**.

4 In the table, enter the following settings:

Legends
`Completely Not Shielded`

Graph Marker 1

1 Right-click **Table Graph 1** and choose **Graph Marker**.

2 In the **Settings** window for **Graph Marker**, click to expand the **Coloring and Style** section.

3 From the **Anchor point** list, choose **Middle right**.

Table Graph 2

1 In the **Model Builder** window, under **Results>Induced Voltage on Wire** click **Table Graph 2**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 From the **Table** list, choose **Table 2**.

4 Locate the **Legends** section. Select the **Show legends** check box.

5 From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends
`Front Windows Not Shielded`

Graph Marker 1

Right-click **Table Graph 2** and choose **Graph Marker**.

Table Graph 3

1 In the **Model Builder** window, right-click **Induced Voltage on Wire** and choose **Table Graph**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 From the **Table** list, choose **Table 3**.

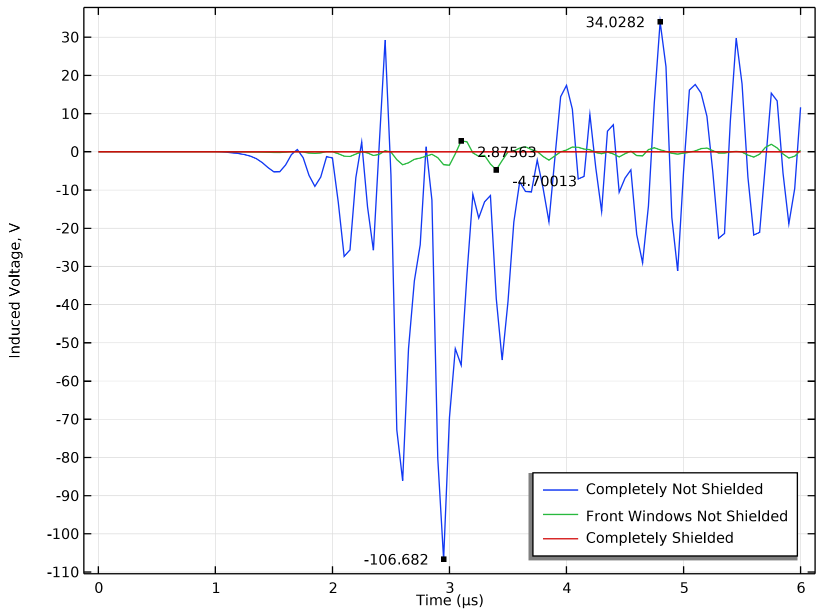
4 Locate the **Legends** section. Select the **Show legends** check box.

5 From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends
`Completely Shielded`

7 In the **Induced Voltage on Wire** toolbar, click **Plot**.



Surface Electric Field

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2, Front Windows Not Shielded/Solution 2 (sol2)**.

4 From the **Time (µs)** list, choose **2.5**.

5 In the **Label** text field, type `Surface Electric Field`.

6 Locate the **Plot Settings** section. Clear the **Plot dataset edges** check box.

Surface 1

1 Right-click **Surface Electric Field** and choose **Surface**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type `temw.normE`.

Selection 1

1 Right-click **Surface 1** and choose **Selection**.

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

3 From the **Selection** list, choose **Airplane All**.

4 Click the Go to XZ View button in the **Graphics** toolbar.

5 Click the **Zoom to Selection** button in the **Graphics** toolbar.

6 Click the **Zoom Out** button in the **Graphics** toolbar.

Surface 1

1 In the **Model Builder** window, click **Surface 1**.

2 In the **Settings** window for **Surface**, click to expand the **Range** section.

3 Select the **Manual color range** check box.

4 In the **Minimum** text field, type `0`.

5 In the **Maximum** text field, type `3e5`.

6 Click the **Show Grid** button in the **Graphics** toolbar.

7 Locate the **Coloring and Style** section. Click **Change Color Table**.

8 In the **Color Table** dialog box, select **Rainbow>Prism** in the tree.

9 Click **OK**.

Line 1

In the **Model Builder** window, right-click **Surface Electric Field** and choose **Line**.

Selection 1

1 In the **Model Builder** window, right-click **Line 1** and choose **Selection**.

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

3 From the **Selection** list, choose **Polygon 1**.

Line 1

1 In the **Model Builder** window, click **Line 1**.

2 In the **Settings** window for **Line**, click to expand the **Range** section.

3 Select the **Manual color range** check box.

4 Locate the **Coloring and Style** section. From the **Line type** list, choose **Tube**.

5 Select the **Radius scale factor** check box.

6 In the **Tube radius expression** text field, type `0.5`.

7 In the **Radius scale factor** text field, type `1`.

8 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

9 In the **Surface Electric Field** toolbar, click **Plot**.