



Model created in COMSOL Multiphysics 6.4

Microstrip Patch Antenna Surrogate Model

Introduction

This example builds surrogate models with deep neural network (DNN) training to quickly estimate the performance of a microstrip patch antenna based on four design parameters: patch length, tuning stub length, dielectric constant of a substrate, and frequency. The model also simulates a full finite element (FEM) model using asymptotic waveform evaluation of the computed S-parameters to efficiently evaluate the frequency response with fine frequency resolution. This approach can be much faster than a conventional discrete frequency sweep, which may take a long time due to the large number of samples. The full model is used to verify the accuracy of the surrogate models.

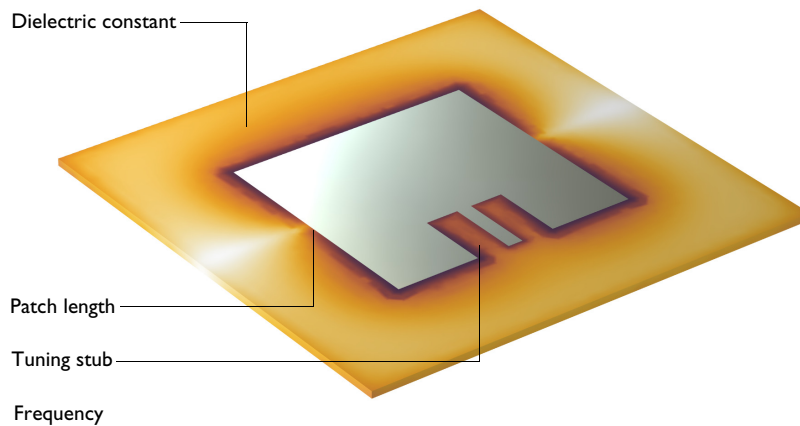


Figure 1: Base microstrip patch antenna model with four parameters, used for generating surrogate models.

Model Definition

The embedded model is based on the [Microstrip Patch Antenna](#) model from the RF Module Application Library. It includes:

- Surrogate model training data generation
- Deep neural network (DNN) training for fast antenna performance evaluation via the surrogate model
- Full finite element simulation using adaptive frequency sweep for reference comparison of antenna performance metrics, such as 2D and 3D far-field realized gain (dBi), the

norm of the electric field on the top surface of the antenna (in the logarithmic scale), and S-parameters (S_{11}) with given design parameters

STUDY FOR TRAINING DATA GENERATION

To efficiently generate the input parameter space and the output quantities of interest, two geometry sampling features are added separately under the Definitions. One is for the antenna’s realized gain configured based on the far-field calculation boundary feature selections. The other is for near field, sampling the norm of the electric field on the top surface of the antenna substrate.

TABLE 1: QUANTITIES OF INTEREST.

Expression	Note
compl.emw.S11dB	Set without geometry sampling, as the S-parameter is global variable and does not depend on the geometry configuration
compl.emw.normE	Geometry Sampling, Fa-Field Calculation
compl.emw.rGainDBefar	Geometry Sampling, Substrate

TABLE 2: INPUT PARAMETERS.

Parameter	Description	Distribution	Range
L_patch	Patch length	Uniform	from 50 to 54 mm
e_r	Dielectric constant	Uniform	from 3.13 to 3.63
L_stub	Tuning stub length	Uniform	from 12.5 to 18.5 mm
f0	Frequency	Uniform	from 1.525 to 1.625 GHz

The number of input point is set to 1000. The Surrogate Modeling study step is executed in combination with a Frequency Domain study step.

DEEP NEURAL NETWORK (DNN) TRAINING

DNN training for each quantity of interest is performed with separate layer configurations and training settings.

TABLE 3: DNN SETTINGS.

	S-parameter	Norm of E-field	Realized gain
Hidden layer number	6	5	4
Node configuration	{128, 128, 128, 64, 32, 16}	{64, 128, 128, 64, 32}	{32, 64, 64, 32}
Activation function, hidden layers	tanh	tanh, last layer Sigmoid	tanh, last layer Sigmoid

TABLE 3: DNN SETTINGS.

	S-parameter	Norm of E-field	Realized gain
Activation function, output	Linear	Linear	Linear
Learning rate	4e-4	5e-4	2e-4
Weight decay	2e-4	1e-6	2e-7
Batch size	512	512	1024
Loss function	Mean absolute error	Mean absolute error	Mean absolute error

Learning rate, weight decay, and batch size were tuned to minimize the validation loss with the given training data and preventing overfitting.

STUDY FOR FULL FEM MODEL

The output from the DNN-trained surrogate model can be visualized by comparing it to results from the full FEM model. Adaptive Frequency Sweep, based on asymptotic waveform evaluation with computed S-parameters, is used to achieve S-parameter and other quantities of interest with a finer frequency resolution, 0.5 MHz. To reduce the file size, only the solutions on the far-field calculation boundaries and the top surface of the substrate were saved.

Results and Discussion

The following analyses are addressed between the full model and DNN-trained surrogated models:

- S-parameter (S_{11}) in dB comparison.
- Norm of electric field comparison.
- 3D realized gain (dBi) comparison.

The DNN-trained surrogate models can predict quantities of interest such as S-parameters, near- and far-field intensities, almost instantly, while producing results that closely resembles those of full models. Minor discrepancies are anticipated to diminish with improved DNN configuration.

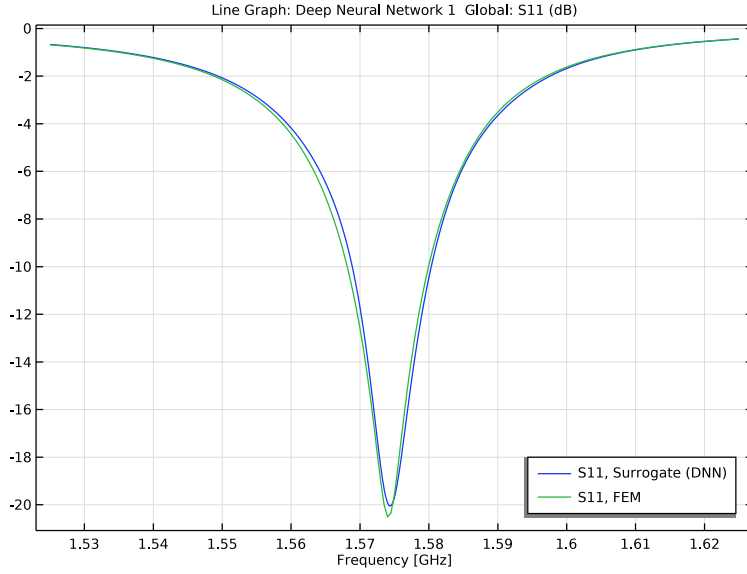


Figure 2: Comparison of S-parameters between the full model and the DNN-trained surrogate model.

Surface: 20*log10(dnn_normE(x,y,l_patch,l_stub,e_r,f0)+1e1) Surface: 20*log10(emw.normE+1e1)

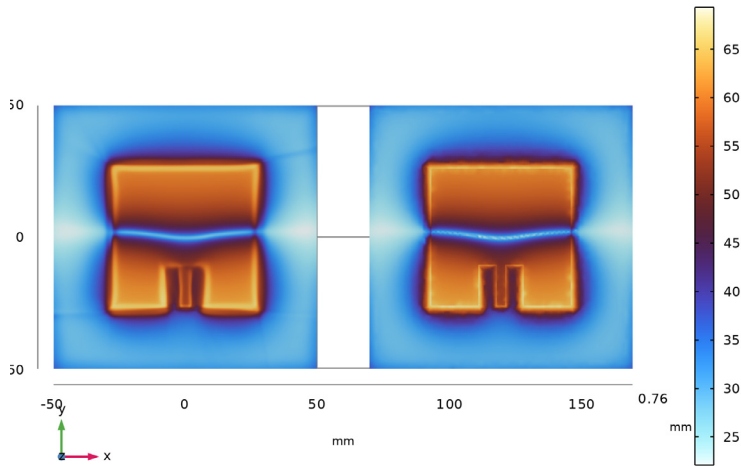


Figure 3: Norm of the electric field on the top surface of the antenna for the full model (right) and the DNN-trained surrogated model (left).

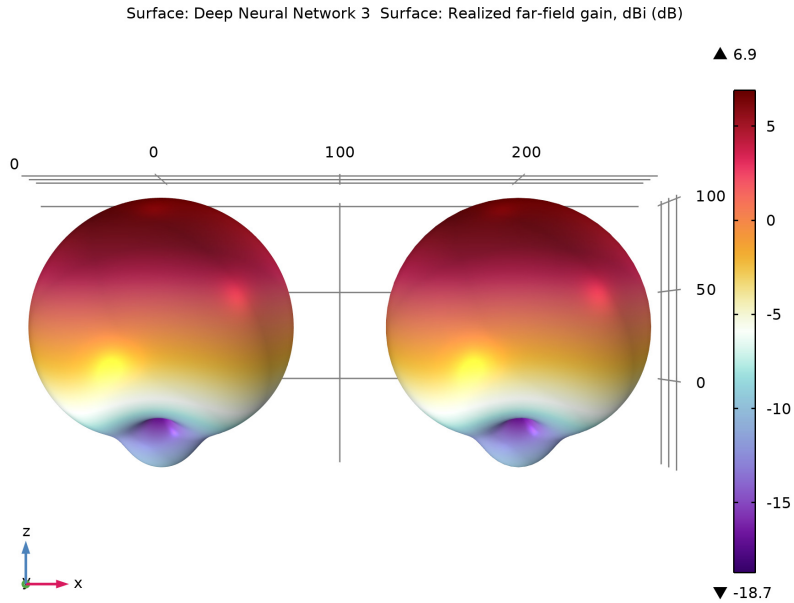



Figure 4: Realized far-field gain for the full model (right) and the DNN-trained surrogate model (left).

Notes About the Implementation

The size of the data generated for surrogate model training and the DNN configurations may be subjected to change in order to improve the regression models and enhance accuracy. The specific numbers used in this app are merely examples and maybe adjusted, which could affect the output of the surrogate models.

Application Library path: RF_Module/Antenna_Arrays/
microstrip_patch_antenna_surrogate

APPLICATION LIBRARIES

- 1 From the **File** menu, choose **Application Libraries**.
- 2 In the **Application Libraries** window, select **RF Module > Antenna Arrays > microstrip_patch_antenna_inset** in the tree.
- 3 Click  **Open**.

GLOBAL DEFINITIONS

Parameters 1

- 1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
- 2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
- 3 In the table, enter the following settings:

Name	Expression	Value	Description
freq_min	1.525[GHz]	1.525E9 Hz	Minimum frequency
freq_max	1.625[GHz]	1.625E9 Hz	Maximum frequency
e_r	3.38	3.38	Dielectric constant
f0	1.575[GHz]	1.575E9 Hz	Frequency

Several parameters have been introduced for deep neural network training. The parameters `l_patch`, `l_stub`, `e_r`, and `f0` will be used as input parameters for generating surrogate model training data.

COMPONENT 1 (COMP1)

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

MATERIALS

Substrate (mat2)

- 1 In the **Model Builder** window, expand the **Component 1 (comp1) > Materials** node, then click **Substrate (mat2)**.
- 2 In the **Settings** window for **Material**, locate the **Material Contents** section.


3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilon _{r_} iso ; epsilon _{r_} ii = epsilon _{r_} iso, epsilon _{r_} nij = 0	e_r		Basic

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

In the **Model Builder** window, expand the **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain (emw)** node.


Far-Field Calculation 1

- 1 In the **Model Builder** window, expand the **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain (emw) > Far-Field Domain 1** node, then click **Far-Field Calculation 1**.
- 2 In the **Settings** window for **Far-Field Calculation**, locate the **Boundary Selection** section.
- 3 Click  **Create Selection**.
- 4 In the **Create Selection** dialog, type Far-Field Calculation in the **Selection name** text field.
- 5 Click **OK**.

The explicit selection created directly from the **Far-Field Calculation** feature assists in configuring the geometry sampling area for generating training data.


DEFINITIONS

Geometry Sampling, Far-Field Calculation

- 1 In the **Definitions** toolbar, click  **Geometry Sampling**.
- 2 In the **Settings** window for **Geometry Sampling**, type Geometry Sampling, Far-Field Calculation in the **Label** text field.
- 3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Boundary**.
- 4 From the **Selection** list, choose **Far-Field Calculation**.

SURROGATE MODEL SAMPLING

Geometry Sampling, Substrate

- 1 In the **Definitions** toolbar, click  **Geometry Sampling**.

- 2 In the **Settings** window for **Geometry Sampling**, type Geometry Sampling, Substrate in the **Label** text field.
- 3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Boundary**.
- 4 Select Boundaries 16 and 21 only.

The surrogate model training data for deep neural network training is not generated across the entire simulation domain, but only within specific areas of interest. For example, the near-field data, specifically the electric field norm, is sampled and trained on the substrate surface, including the radiating patch area. Far-field values are collected at the boundaries where the near-field to far-field transformation is performed.

In the first study, surrogate model training data is generated for S-parameters, electric field norm, and realized far-field gain. For each variable of interest, data is generated by systematically varying the patch length, impedance-matching stub length, dielectric constant, and operating frequency.

STUDY 1



Solver Configurations

- 1 In the **Model Builder** window, expand the **Study 1** node.
- 2 Right-click **Study 1** > **Solver Configurations** and choose **Delete Configurations**.

Step 1: Frequency Domain

- 1 In the **Settings** window for **Frequency Domain**, locate the **Study Settings** section.
- 2 In the **Frequencies** text field, type f0.
- 3 In the **Model Builder** window, click **Study 1**.
- 4 In the **Settings** window for **Study**, type Study, Data Generation for Surrogate Model Training in the **Label** text field.

Surrogate Model Training

- 1 In the **Study** toolbar, click  **More Study Extensions** and choose **Surrogate Model Training**.
- 2 In the **Settings** window for **Surrogate Model Training**, locate the **Quantities of Interest** section.
- 3 Click  **Add**.

4 In the table, enter the following settings:

Expression	Include study-dependent input	Study-dependent input description
comp1.emw.S11dB	Configure study-dependent input	l Study-dependent input parameters

S-parameter S11dB is a global variable and geometry sampling is not required.

5 Click **+** **Add**.

6 In the table, enter the following settings:

Expression	Include study-dependent input	Study-dependent input description
comp1.emw.normE	Configure study-dependent input	l Study-dependent input parameters

7 From the **Geometry sampling** list, choose **Geometry Sampling, Substrate**.

8 Click **+** **Add**.

9 In the table, enter the following settings:

Expression	Include study-dependent input	Study-dependent input description
comp1.emw.rGainDBefar	Configure study-dependent input	l Study-dependent input parameters

10 From the **Geometry sampling** list, choose **Geometry Sampling, Far-Field Calculation**.

11 Locate the **Input Parameters** section. Click **+** **Add**.

12 In the table, enter the following settings:

Parameter	Source type	Source description
l_patch (Patch length)	Analytic	Uniform

13 In the **Lower bound** text field, type 50[mm].

14 In the **Upper bound** text field, type 54[mm].

15 Click **+** **Add**.

16 In the table, enter the following settings:

Parameter	Source type	Source description
l_stub (Tuning stub length)	Analytic	Uniform

17 In the table, click to select the cell at row number 2 and column number 3.

18 In the **Lower bound** text field, type 12.5[mm].

19 In the **Upper bound** text field, type 18.5[mm].

20 Click  **Add**.

21 In the table, enter the following settings:

Parameter	Source type	Source description
e_r (Dielectric constant)	Analytic	Uniform

22 In the **Lower bound** text field, type 3.13.

23 In the **Upper bound** text field, type 3.63.

24 Click  **Add**.

25 In the table, enter the following settings:

Parameter	Source type	Source description
f0 (Frequency)	Analytic	Uniform

26 In the **Lower bound** text field, type freq_min.

27 In the **Upper bound** text field, type freq_max.

28 In the **Unit** text field, type Hz.

29 Find the **Sampling settings** subsection. In the **Number of input points** text field, type 1000.

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

31 Click  **Clear Solutions**.

The necessary data for training is generated in the form of tables, and there is no need to retain the solution. By removing the solution, the model file size can be reduced.

RESULTS

2D Far Field (emw), 3D Far Field, Gain (emw), Electric Field (emw), Electric Field, Logarithmic (emw)

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Electric Field (emw)**, **Electric Field, Logarithmic (emw)**, **2D Far Field (emw)**, and **3D Far Field, Gain (emw)**.

- 2 Right-click and choose **Delete**.

Train each quantity of interest using a deep neural network. Each hidden layer uses the \tanh activation function, except for the last hidden layer for the field quantities, which uses the Sigmoid function to prevent over-truncation of maximum values. The output layer uses a linear activation function to leave the output unmodified.

GLOBAL DEFINITIONS

Deep Neural Network 1

- 1 In the **Home** toolbar, click $f(\infty)$ **Functions** and choose **Global > Deep Neural Network**.
- 2 In the **Settings** window for **Deep Neural Network**, locate the **Data** section.
- 3 From the **Data source** list, choose **Result table**.
- 4 Locate the **Data Column Settings** section. In the table, enter the following settings:

Columns	Type	Settings
f0 (Hz)	Ignored column	

- 5 In the table, click to select the cell at row number 6 and column number 3.
- 6 In the **Name** text field, type dnn_S11dB.
- 7 Locate the **Layers** section. Click $+$ **Add Hidden Layer**.
- 8 In the **Output features** text field, type 256.
- 9 Click $+$ **Add Hidden Layer**.
- 10 In the **Output features** text field, type 256.
- 11 Click $+$ **Add Hidden Layer**.
- 12 In the **Output features** text field, type 256.
- 13 Click $+$ **Add Hidden Layer**.
- 14 In the **Output features** text field, type 128.
- 15 Click $+$ **Add Hidden Layer**.
- 16 In the **Output features** text field, type 64.
- 17 Click $+$ **Add Hidden Layer**.
- 18 In the **Output features** text field, type 32.
- 19 In the table, click to select the cell at row number 8 and column number 2.
- 20 From the **Activation** list, choose **Linear (none)**.
- 21 Locate the **Training, Validation, and Test** section. In the **Learning rate** text field, type $3e-4$.

- 22 In the **Weight decay** text field, type $2e-4$.
- 23 In the **Batch size** text field, type 1024.
- 24 From the **Loss function** list, choose **Mean absolute error**.
- 25 Find the **Stop condition** subsection. In the **Number of epochs** text field, type 20000.
- 26 Find the **Validation/test seed settings** subsection. In the **Random seed** text field, type $1e-6$.

Tuning parameter values for **Learning rate**, **Weight decay**, **Batch size**, **Loss function**, **Number of epochs**, and **Random seed** is application-specific and can vary depending on the quantity of interest and the layer configuration. Minor modifications may reduce the risk of overfitting or lead to undesired results. Therefore, tuning should be done gradually and in small increments.

Deep Neural Network 2

- 1 In the **Home** toolbar, click **f(∞) Functions** and choose **Global > Deep Neural Network**.
- 2 In the **Settings** window for **Deep Neural Network**, locate the **Data** section.
- 3 From the **Data source** list, choose **Result table**.
- 4 From the **Result table** list, choose **Design Data (QoI2)**.
- 5 Locate the **Data Column Settings** section. In the table, enter the following settings:

Columns	Type	Settings
Z (mm)	Ignored column	
e_r	Argument	Name=x6, Scaling=Normalization
f0 (Hz)	Ignored column	
freq (GHz)	Argument	Name=x8, Scaling=Normalization

Since only the flat surface of the substrate is evaluated and there is no height variation, the spatial coordinate z is not included.

- 6 In the table, click to select the cell at row number 9 and column number 3.
- 7 In the **Name** text field, type `dnn_normE`.
- 8 Locate the **Layers** section. Click **+ Add Hidden Layer**.
- 9 In the **Output features** text field, type 64.
- 10 Click **+ Add Hidden Layer**.
- 11 In the **Output features** text field, type 128.
- 12 Click **+ Add Hidden Layer**.
- 13 In the **Output features** text field, type 128.

- 14 Click **+ Add Hidden Layer**.
- 15 In the **Output features** text field, type 64.
- 16 Click **+ Add Hidden Layer**.
- 17 In the **Output features** text field, type 32.
- 18 From the **Activation** list, choose **Sigmoid**.
- 19 In the table, click to select the cell at row number 7 and column number 2.
- 20 From the **Activation** list, choose **Linear (none)**.
- 21 Locate the **Training, Validation, and Test** section. In the **Learning rate** text field, type 5e-4.
- 22 In the **Weight decay** text field, type 1e-6.
- 23 From the **Loss function** list, choose **Mean absolute error**.
- 24 Find the **Stop condition** subsection. In the **Number of epochs** text field, type 500.

Deep Neural Network 3


- 1 In the **Home** toolbar, click **f(x) Functions** and choose **Global > Deep Neural Network**.
- 2 In the **Settings** window for **Deep Neural Network**, locate the **Data** section.
- 3 From the **Data source** list, choose **Result table**.
- 4 From the **Result table** list, choose **Design Data (QoI3)**.
- 5 Locate the **Data Column Settings** section. In the table, enter the following settings:

Columns	Type	Settings
e_r	Argument	Name=x6, Scaling=Normalization
f0 (Hz)	Ignored column	
freq (GHz)	Argument	Name=x8, Scaling=Normalization

- 6 In the table, click to select the cell at row number 9 and column number 3.
- 7 In the **Name** text field, type dnn_rGaindBefar.
- 8 Locate the **Layers** section. Click **+ Add Hidden Layer**.
- 9 In the **Output features** text field, type 32.
- 10 Click **+ Add Hidden Layer**.
- 11 In the **Output features** text field, type 64.
- 12 Click **+ Add Hidden Layer**.
- 13 In the **Output features** text field, type 64.
- 14 Click **+ Add Hidden Layer**.


- 15 In the **Output features** text field, type 32.
- 16 From the **Activation** list, choose **Sigmoid**.
- 17 In the table, click to select the cell at row number 6 and column number 2.
- 18 From the **Activation** list, choose **Linear (none)**.
- 19 Locate the **Training, Validation, and Test** section. In the **Learning rate** text field, type $2e-4$.
- 20 In the **Weight decay** text field, type $2e-7$.
- 21 In the **Batch size** text field, type 1024.
- 22 From the **Loss function** list, choose **Mean absolute error**.
- 23 Find the **Stop condition** subsection. In the **Number of epochs** text field, type 3000.

Deep Neural Network 1 (dnn_S1IdB)


- 1 In the **Model Builder** window, click **Deep Neural Network 1 (dnn_S1IdB)**.
- 2 In the **Settings** window for **Deep Neural Network**, click  **Train Model**.

While performing deep neural network training, the validation and training losses can be monitored to determine whether the loss values have converged to a desirable level. Once training is complete, the plotted values are volatile and will be overwritten by subsequent training sessions. To preserve the data, activate the **Progress** window and click the first toolbar button, **Copy Convergence Data to Model**. This will generate a table containing up to the last 20,000 epochs. When the **Deep neural network training** Table window is active, click the **Table Graph** toolbar button to generate the loss plot.

Deep Neural Network 2 (dnn_normE)

- 1 In the **Model Builder** window, click **Deep Neural Network 2 (dnn_normE)**.
- 2 In the **Settings** window for **Deep Neural Network**, click  **Train Model**.
- 3 In the **Convergence Plot 1** window, click the **x-Axis Log Scale** button in the window toolbar.

Deep Neural Network 3 (dnn_rGaindBefar)



- 1 In the **Model Builder** window, click **Deep Neural Network 3 (dnn_rGaindBefar)**.
- 2 In the **Settings** window for **Deep Neural Network**, click  **Train Model**.
- 3 In the **Convergence Plot 1** window, click the **x-Axis Log Scale** button in the window toolbar.

The results from the surrogate models will be verified using a full finite element method (FEM) simulation with an adaptive frequency sweep study. This study uses a very fine

frequency resolution, which leads to a large model file. Therefore, only the solution on the boundary selection of interest is stored by using the **Store in Output** option.

DEFINITIONS



FEM Data Storage

- 1 In the **Definitions** toolbar, click  **Explicit**.
- 2 In the **Settings** window for **Explicit**, type FEM Data Storage 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, type 9-12, 16, 21, 26, 32, 33, 37, 40 in the **Selection** text field.
- 6 Click **OK**.

STUDY, FULL MODEL


- 1 In the **Model Builder** window, click **Study 2**.
- 2 In the **Settings** window for **Study**, type Study, Full Model in the **Label** text field.

Step 1: Adaptive Frequency Sweep

- 1 In the **Model Builder** window, under **Study, Full Model** click **Step 1: Adaptive Frequency Sweep**.
- 2 In the **Settings** window for **Adaptive Frequency Sweep**, locate the **Study Settings** section.
- 3 In the **Frequencies** text field, type `range(freq_min,500[kHz],freq_max)`.
- 4 Click to expand the **Store in Output** section. In the table, click to select the cell at row number 1 and column number 3.
- 5 In the **Selections** list box, select **Lumped Port**.
- 6 Under **Selections**, click  **Delete**.
- 7 Under **Selections**, click  **Add**.
- 8 In the **Add** dialog, select **FEM Data Storage** in the **Selections** list.
- 9 Click **OK**.

Solver Configurations


- 1 In the **Model Builder** window, under **Study, Full Model** right-click **Solver Configurations** and choose **Delete Configurations**.

- 2 In the **Home** toolbar, click  **Compute**.


Functions, including the output of a deep neural network, can be mapped to a **Grid** dataset for visualization. Use a **Grid ID** dataset to plot the regression model of the S-parameters. For field quantities, use a **Parametric Surface** based on a **Grid 3D** dataset.

RESULTS

Grid ID for DNN S-parameter Plot

- 1 In the **Results** toolbar, click  **More Datasets** and choose **Grid > Grid ID**.
- 2 In the **Settings** window for **Grid ID**, type Grid ID for DNN S-parameter Plot in the **Label** text field.
- 3 Locate the **Parameter Bounds** section. In the **Minimum** text field, type 1.525.
- 4 In the **Maximum** text field, type 1.625.
- 5 Locate the **Data** section. From the **Source** list, choose **Function**.
- 6 From the **Function** list, choose **Deep Neural Network 1 (dnn_S11dB)**.
- 7 Click to expand the **Grid** section. Click to expand the **Advanced** section. Locate the **Grid** section. In the **Resolution** text field, type 401.


Grid 3D for DNN Near Field on Substrate

- 1 In the **Results** toolbar, click  **More Datasets** and choose **Grid > Grid 3D**.
- 2 In the **Settings** window for **Grid 3D**, type Grid 3D for DNN Near Field on Substrate in the **Label** text field.
- 3 Locate the **Data** section. From the **Source** list, choose **Function**.
- 4 From the **Function** list, choose **Deep Neural Network 2 (dnn_normE)**.
- 5 Locate the **Parameter Bounds** section. Find the **First parameter** subsection. In the **Minimum** text field, type -0.8×10^{-3} .
- 6 In the **Maximum** text field, type 0.8×10^{-3} .
- 7 Find the **Second parameter** subsection. In the **Minimum** text field, type -0.8×10^{-3} .
- 8 In the **Maximum** text field, type 0.8×10^{-3} .
- 9 Find the **Third parameter** subsection. In the **Minimum** text field, type -0.8×10^{-3} .
- 10 In the **Maximum** text field, type 0.8×10^{-3} .
- 11 Click to expand the **Grid** section. In the **x resolution** text field, type 201.
- 12 In the **y resolution** text field, type 201.

13 In the **z resolution** text field, type 2.

The factor $1e-3$ is for scaling based on the geometry unit of millimeters (mm) used in the model.


Parametric Surface for DNN Near Field on Substrate

- 1** In the **Results** toolbar, click  **More Datasets** and choose **Parametric Surface**.
- 2** In the **Settings** window for **Parametric Surface**, type Parametric Surface for DNN Near Field on Substrate in the **Label** text field.
- 3** Locate the **Data** section. From the **Dataset** list, choose **Grid 3D for DNN Near Field on Substrate**.
- 4** Locate the **Parameters** section. Find the **First parameter** subsection. In the **Minimum** text field, type -1.
- 5** Find the **Second parameter** subsection. In the **Minimum** text field, type -1.
- 6** Locate the **Expressions** section. In the **x** text field, type $s1*w_{sub}/2/1e-3$.
- 7** In the **y** text field, type $s2*1_{sub}/2/1e-3$.
- 8** In the **z** text field, type $d/2/1e-3$.

Grid 3D for DNN Far Field


- 1** In the **Model Builder** window, right-click **Grid 3D for DNN Near Field on Substrate** and choose **Duplicate**.
- 2** In the **Settings** window for **Grid 3D**, type Grid 3D for DNN Far Field in the **Label** text field.
- 3** Locate the **Data** section. From the **Function** list, choose **Deep Neural Network 3 (dnn_rGainBEfar)**.
- 4** Locate the **Grid** section. In the **x resolution** text field, type 71.
- 5** In the **y resolution** text field, type 71.
- 6** In the **z resolution** text field, type 71.

Parametric Surface for Far Field

- 1** In the **Results** toolbar, click  **More Datasets** and choose **Parametric Surface**.
- 2** In the **Settings** window for **Parametric Surface**, type Parametric Surface for Far Field in the **Label** text field.
- 3** Locate the **Data** section. From the **Dataset** list, choose **Grid 3D for DNN Far Field**.
- 4** Locate the **Parameters** section. Find the **First parameter** subsection. In the **Maximum** text field, type $\pi*2$.
- 5** Find the **Second parameter** subsection. In the **Maximum** text field, type π .

- 6 Locate the **Expressions** section. In the **x** text field, type $0.8 \cdot l_{\text{sub}} \cdot \cos(s1) \cdot \sin(s2) / 1e-3$.
- 7 In the **y** text field, type $0.8 \cdot l_{\text{sub}} \cdot \sin(s1) \cdot \sin(s2) / 1e-3$.
- 8 In the **z** text field, type $0.8 \cdot l_{\text{sub}} \cdot \cos(s2) / 1e-3$.

S-parameters, Surrogate (DNN) vs. FEM

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **S-parameters, Surrogate (DNN) vs. FEM** in the **Label** text field.
- 3 Locate the **Plot Settings** section.
- 4 Select the **x-axis label** checkbox. In the associated text field, type **Frequency [GHz]**.
- 5 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

Line Graph 1

- 1 Right-click **S-parameters, Surrogate (DNN) vs. FEM** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Grid ID for DNN S-parameter Plot**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type $\text{dnn_S11dB}(l_{\text{patch}}, l_{\text{stub}}, e_r, x[\text{GHz}])$.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type $(x/1[\text{m}])[\text{GHz}]$.
- 7 From the **Unit** list, choose **GHz**.

The expression for the **x-Axis Data** is modified to plot the surrogate model output alongside the results of the FEM simulation.

- 8 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 9 From the **Legends** list, choose **Manual**.
- 10 In the table, enter the following settings:

Legends
S11, Surrogate (DNN)

Global 1

- 1 In the **Model Builder** window, right-click **S-parameters, Surrogate (DNN) vs. FEM** and choose **Global**.
- 2 In the **Settings** window for **Global**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study, Full Model/Solution 6 (sol6)**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

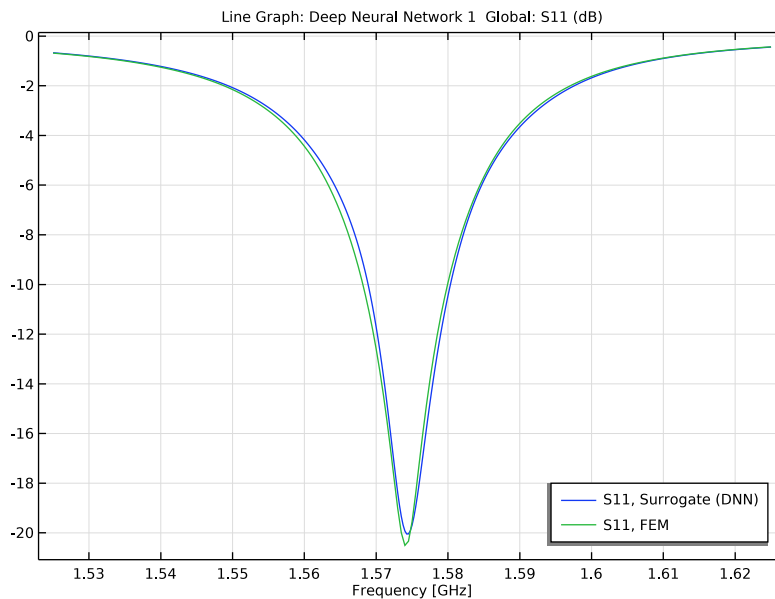
Expression	Unit	Description
emw.S11dB	dB	S11

5 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.


6 In the table, enter the following settings:

Legends
S11, FEM

7 In the **S-parameters, Surrogate (DNN) vs. FEM** toolbar, click  **Plot**.



normE, Surrogate (DNN) vs. FEM

1 In the **Results** toolbar, click  **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type *normE, Surrogate (DNN) vs. FEM* in the **Label** text field.

3 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

Surface 1

1 Right-click **normE, Surrogate (DNN) vs. FEM** and choose **Surface**.

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

- 3 From the **Dataset** list, choose **Parametric Surface for DNN Near Field on Substrate**.
- 4 Locate the **Expression** section. In the **Expression** text field, type $20 * \log_{10}(\text{dnn_normE}(x, y, l_patch, l_stub, e_r, f0) + 1e1)$.
Adding $1e1$ helps produce a more vivid color distribution when plotting on a logarithmic scale.
- 5 Locate the **Coloring and Style** section. From the **Color table** list, choose **ThermalWave**.


Surface 2


- 1 In the **Model Builder** window, right-click **normE, Surrogate (DNN) vs. FEM** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study, Full Model/Solution 6 (sol6)**.
- 4 From the **Parameter value (freq (GHz))** list, choose **1.575**.
- 5 Locate the **Expression** section. In the **Expression** text field, type $20 * \log_{10}(\text{emw.normE} + 1e1)$.
- 6 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Selection 1

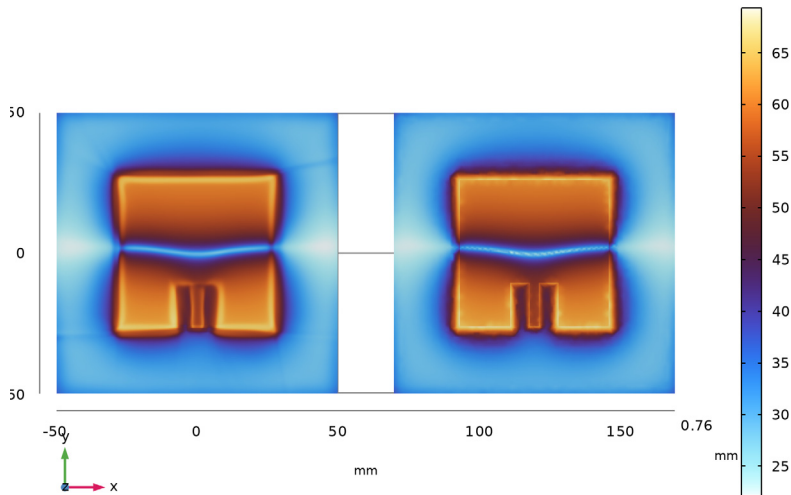
- 1 Right-click **Surface 2** and choose **Selection**.
- 2 Select Boundaries 16 and 21 only.

Transformation 1

- 1 In the **Model Builder** window, right-click **Surface 2** and choose **Transformation**.
- 2 In the **Settings** window for **Transformation**, locate the **Transformation** section.
- 3 In the **X** text field, type 120.
- 4 Click the  **Go to XY View** button in the **Graphics** toolbar.


- Click the  **Zoom Extends** button in the **Graphics** toolbar.

Surface: $20 \cdot \log_{10}(\text{dnn_normE}(x,y,l_patch,l_stub,e_r,f_0)+1e1)$ Surface: $20 \cdot \log_{10}(\text{emw.normE}+1e1)$



The output of the function mapped to the **Parametric Surface** is not compatible with the conventional Radiation Pattern plot. Therefore, a surface plot is used and deformed to create a volumetric 3D radiation pattern shape.

rGai_{nd}BE_{far}, Surrogate (DNN) vs. FEM

- In the **Results** toolbar, click  **3D Plot Group**.
- In the **Settings** window for **3D Plot Group**, type *rGai_{nd}BE_{far}, Surrogate (DNN) vs. FEM* in the **Label** text field.
- Locate the **Data** section. From the **Dataset** list, choose **None**.
- Locate the **Color Legend** section. Select the **Show maximum and minimum values** checkbox.

Surface 1

- Right-click *rGai_{nd}BE_{far}, Surrogate (DNN) vs. FEM* and choose **Surface**.
- In the **Settings** window for **Surface**, locate the **Data** section.
- From the **Dataset** list, choose **Parametric Surface for Far Field**.
- Locate the **Expression** section. In the **Expression** text field, type $\text{dnn_rGai}_{nd}BE_{far}(x, y, z, l_patch, l_stub, e_r, f_0)$.

5 Locate the **Coloring and Style** section. From the **Color table** list, choose **Ctenophora**.

Deformation 1

- 1 Right-click **Surface 1** and choose **Deformation**.
- 2 In the **Settings** window for **Deformation**, locate the **Expression** section.
- 3 In the **x-component** text field, type $x*(dnn_rGaindBefar(x,y,z,l_patch,l_stub,e_r,f0))/25$.
- 4 In the **y-component** text field, type $y*(dnn_rGaindBefar(x,y,z,l_patch,l_stub,e_r,f0))/25$.
- 5 In the **z-component** text field, type $z*(dnn_rGaindBefar(x,y,z,l_patch,l_stub,e_r,f0))/25$.
- 6 Locate the **Scale** section.
- 7 Select the **Scale factor** checkbox. In the associated text field, type 1.

Surface 2

- 1 In the **Model Builder** window, right-click **rGaindBefar, Surrogate (DNN) vs. FEM** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study, Full Model/Solution 6 (sol6)**.
- 4 From the **Parameter value (freq (GHz))** list, choose **1.575**.
- 5 Locate the **Expression** section. In the **Expression** text field, type `emw.rGaindBefar`.
- 6 Locate the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.
- 7 Clear the **Deform scale factor** checkbox.

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 **Far-Field Calculation**.

Transformation 1


- 1 In the **Model Builder** window, right-click **Surface 2** and choose **Transformation**.
- 2 In the **Settings** window for **Transformation**, locate the **Transformation** section.
- 3 In the **X** text field, type 200.

Deformation 1



- 1 Right-click **Surface 2** and choose **Deformation**.
- 2 In the **Settings** window for **Deformation**, locate the **Expression** section.

- 3 In the **X-component** text field, type $x \cdot \text{emw.rGaindBefar}/25$.
- 4 In the **Y-component** text field, type $y \cdot \text{emw.rGaindBefar}/25$.
- 5 In the **Z-component** text field, type $z \cdot \text{emw.rGaindBefar}/25$.
- 6 Locate the **Scale** section.
- 7 Select the **Scale factor** checkbox. In the associated text field, type 1.
- 8 In the **rGaindBefar, Surrogate (DNN) vs. FEM** toolbar, click  **Plot**.
- 9 In the **Model Builder** window, expand the **Results > Views** node.

Camera

- 1 In the **Model Builder** window, expand the **Results > Views > View 3D 7** node, then click **Camera**.
- 2 In the **Settings** window for **Camera**, locate the **Camera** section.
- 3 From the **View scale** list, choose **None**.
- 4 Click  **Update**.

rGaindBefar, Surrogate (DNN) vs. FEM

- 1 Click the  **Go to XZ View** button in the **Graphics** toolbar.
- 2 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 3 In the **Model Builder** window, under **Results** click **rGaindBefar, Surrogate (DNN) vs. FEM**.

