Ansys High Frequency Structure Simulator (HFSS) Tutorial

MARK JONES
PACIFIC NORTHWEST NATIONAL LABORATORY

1/10/17

Agenda

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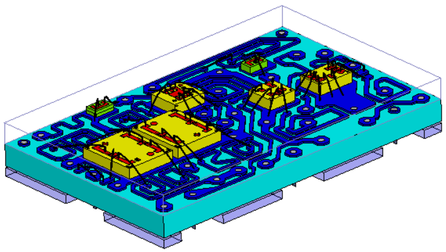
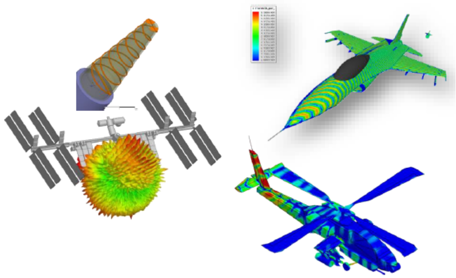
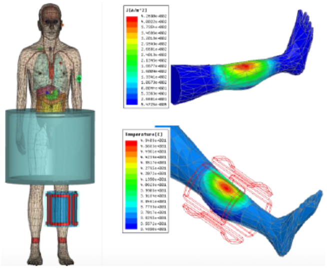
- Overview of HFSS
  - Capabilities and key features
  - Example measurement comparisons
- Cylindrical cavity tutorial
  - Eigenmode solver
  - Parametric geometry
  - Curvilinear elements
  - Modal frequencies, Q-factors, and fields
  - Field calculator
- Dipole antenna tutorial
  - Driven excitation solver
  - Radiation boundaries
  - Frequency sweep
  - S-parameters, near and far fields

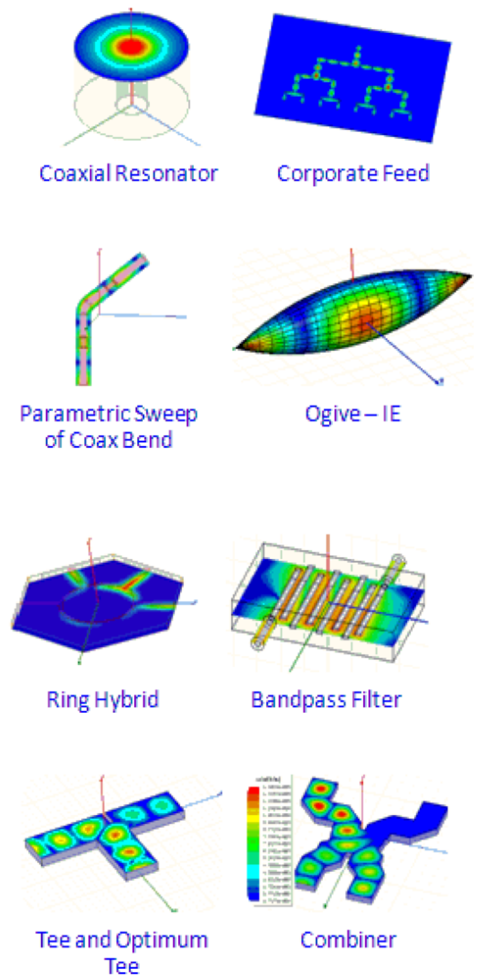






Introduction to HFSS

- Full-wave frequency-domain 3-D field solver based upon finite element method
  - Industry-standard accuracy
  - Adaptive meshing of arbitrary geometry
  - Fully parametric modeling
  - Optimization and HPC
  - Multi-physics via Ansys Workbench
- Widely used for RF/microwave design
  - Antenna design and platform integration
  - Filters and waveguide structures
  - Electronic packages and PCBs
  - Connectors and transitions
  - EMC/EMI
  - Radar cross-section
- Integrated into Ansys Electronics Desktop
  - Part of Ansys Electromagnetics Suite



HFSS User Interface

Toolbars

Project Manager

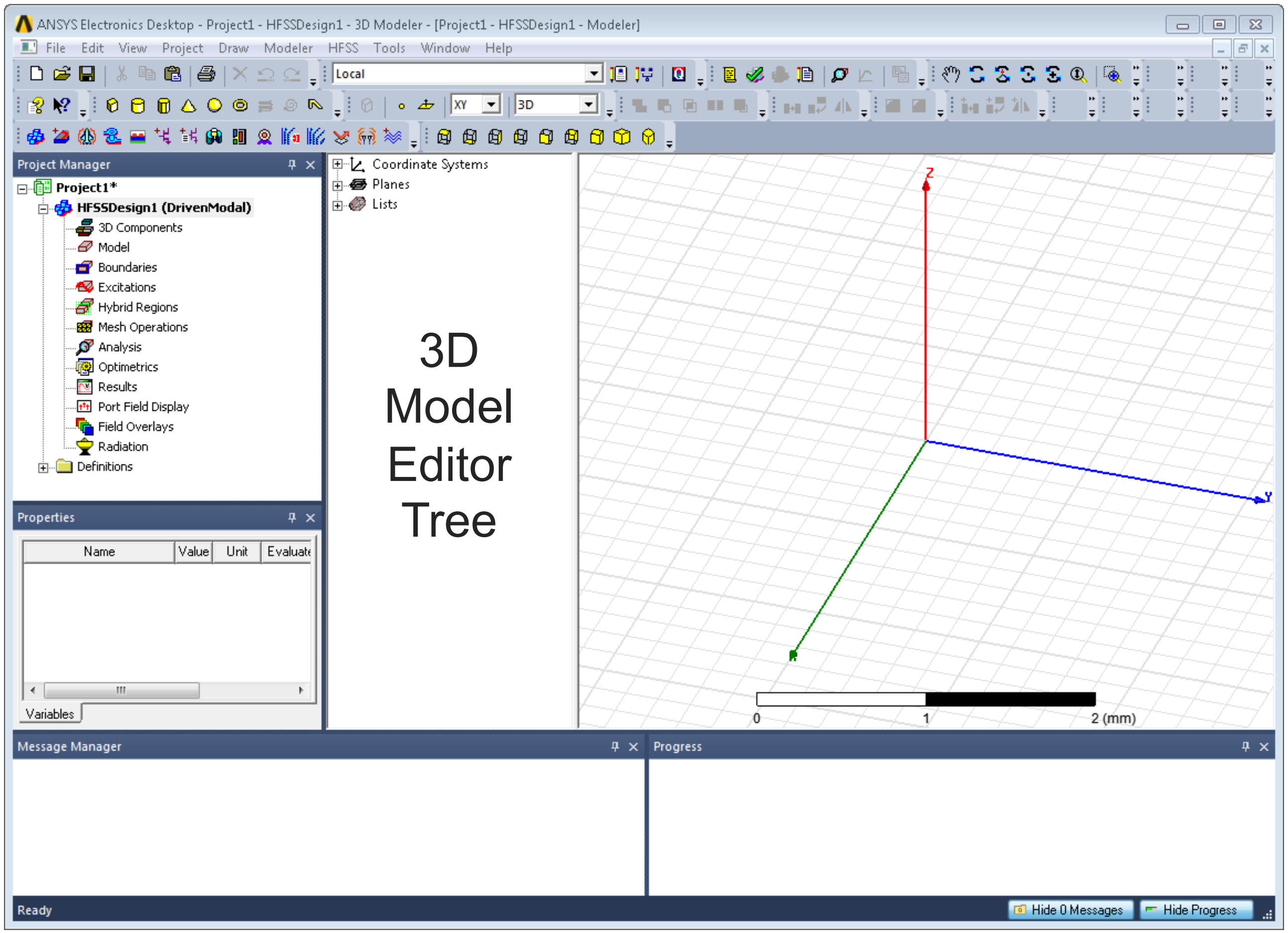
3D Model Editor Tree

3D Model Editor Graphics

Properties

Message Manager

Progress Window



Solution Types

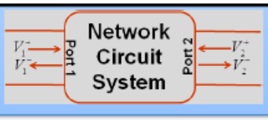
- Eigenmode solution
  - Solves for natural resonances of structure based on geometry, materials, and boundaries
  - Provides modal frequencies, unloaded Q-factors, and fields
- Driven solution
  - Port or incident field used to excite the structure
  - *Driven modal* method commonly used for RF/microwave designs
  - *Driven terminal* method commonly used for multi-conductor transmission lines
  - Provides S-parameters and fields

Driven Modal

- Fields based transmission line interpretation
- Port's signal decomposed into incident and reflected waves
- Excitation's magnitude described as an incident power

Modal Propagation

- Energy propagates in a set of orthogonal modes
- Modes can be TE, TM and TEM w.r.t. the port's normal
- Mode's field pattern determined from entire port geometry
- Each Mode has its own column and row in the S, Y, and Z parameters

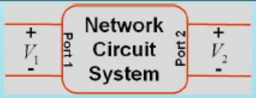


Driven Terminal

- Circuit Based transmission line interpretation
- Port's signal interpreted as a total voltage (Vtotal = Vinc + Vref)
- Excitation's magnitude described as either a total voltage or an incident voltage
- Supports Differential S-Parameters

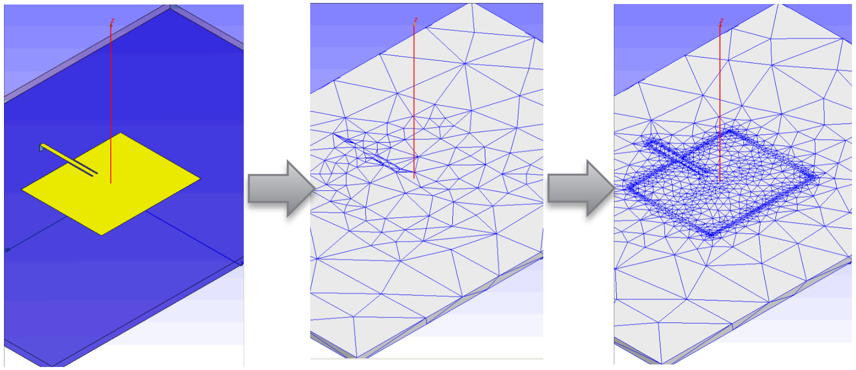
Terminal Propagation

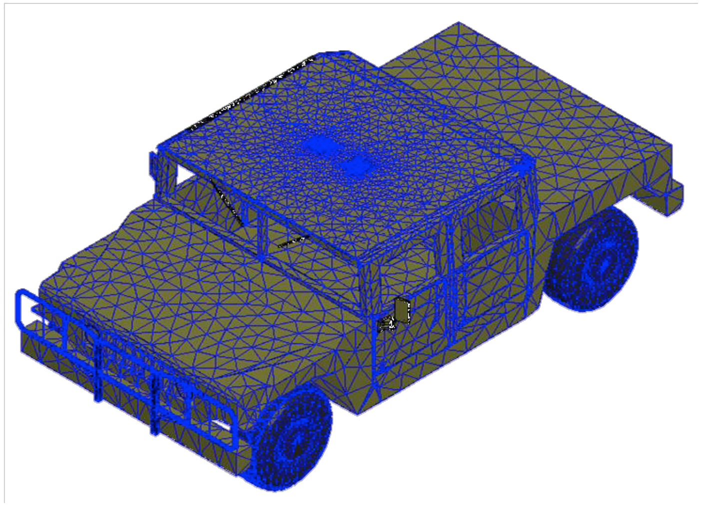
- Each conductor touching the port is considered a terminal or a ground
- Energy propagates along each terminal in a single TEM mode
- Each Terminal has its own column and row in the S, Y and Z parameters
- Does not support symmetry boundaries or Floquet Ports



Adaptive Mesh Algorithm

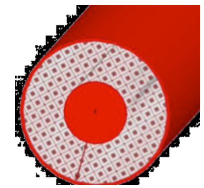
- Tetrahedral mesh automatically generated and refined below user-defined electrical length
  - Tetrahedral element shape conforms to arbitrary geometries
- Iterative algorithm solves fields and refines mesh until user-defined convergence threshold value is reached
  - Driven modal: S-parameter convergence
  - Eigenmode: Frequency convergence
- Produces graded mesh with fine discretization only where needed to accurately represent field behavior
  - Efficient use of computational resources
  - Tunes mesh to capture EM performance

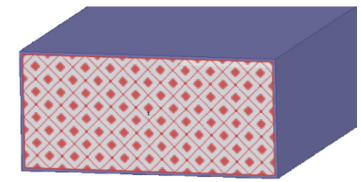


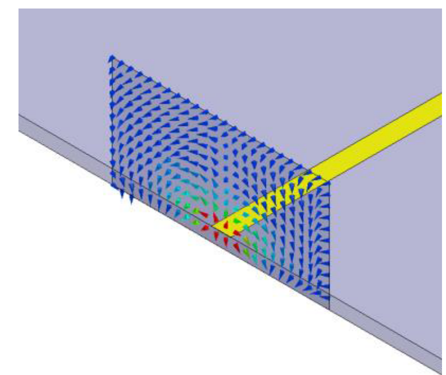


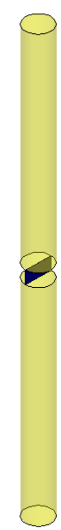
Port Excitations

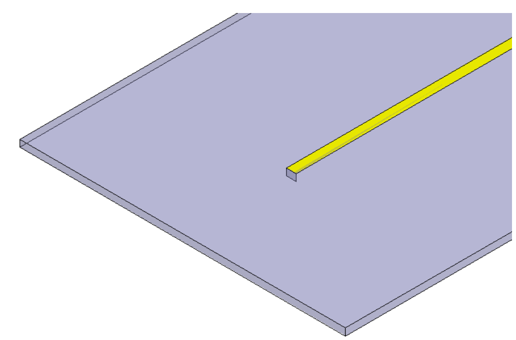
- Wave ports
  - 2D FEM solver calculates requested number of modes (treated as t-line cross-section)
  - Solves for impedances and propagation constants
  - Supports multiple modes and de-embedding
  - Simple for closed t-lines
  - Must allow room for fields of open t-lines
  - Must touch external boundary or backed by conducting object
- Lumped ports
  - User-assigned constant impedance
  - Uniform electric field on surface
  - Single TEM mode with no de-embedding
  - Can be internal to model





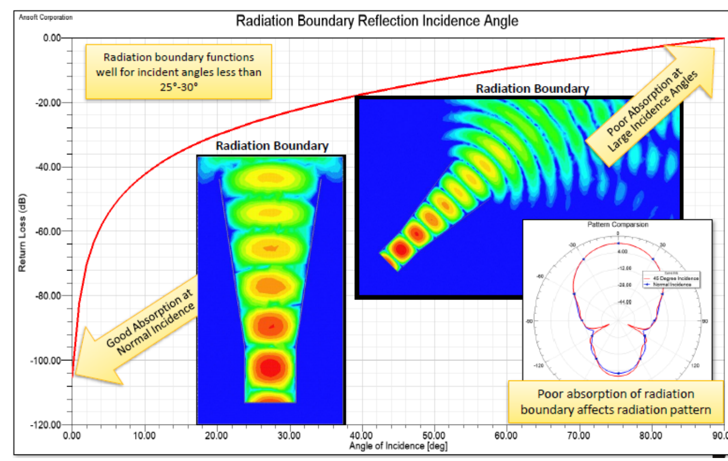






Boundary Conditions

- Used to simplify geometry or make meshing more efficient
- Material properties for surfaces
  - Finite conductivity (imperfect conductor)
  - Perfect electric or magnetic conductor
- Surface approximations for components
  - Lumped RLC
  - Layered impedance
- Radiation
  - Absorbing boundary condition
  - Perfectly matched layers (PML)
- Any object surface that touches the background is automatically defined as Perfect E boundary



Frequency Sweeps

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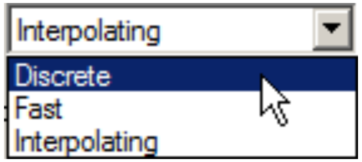
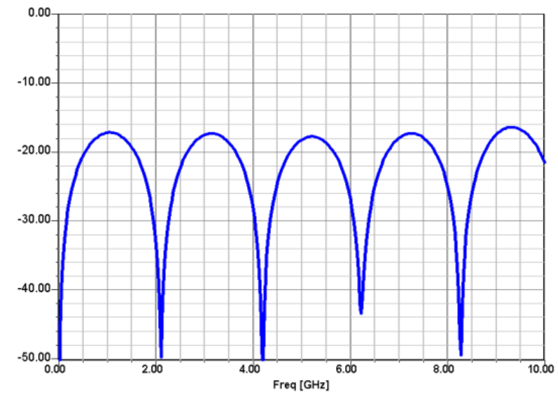
- Discrete sweep
  - Solves adapted mesh at every frequency
  - Matrix data and fields at every frequency
- Fast sweep
  - Extrapolates rational polynomial function for electric field over specified range
  - Usually valid over less than 10:1 BW
  - Matrix data and fields at every frequency
- Interpolating sweep
  - Solves minimum number of frequencies to create polynomial fit for S-parameters
  - Useful for very broadband S-parameters
  - Matrix data at every frequency

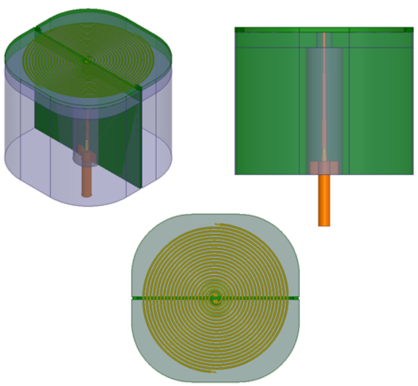


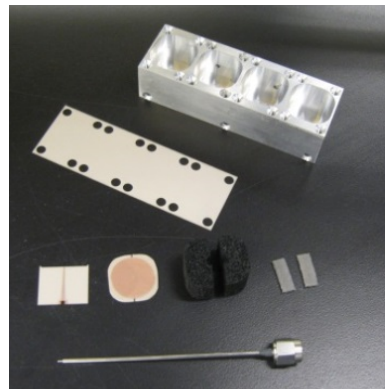
$$S = \frac{\beta_q (s - z_q)(s - z_{q-1})\ldots(s - z_1)}{\alpha_q (s - p_q)(s - p_{q-1})\ldots(s - p_1)}$$

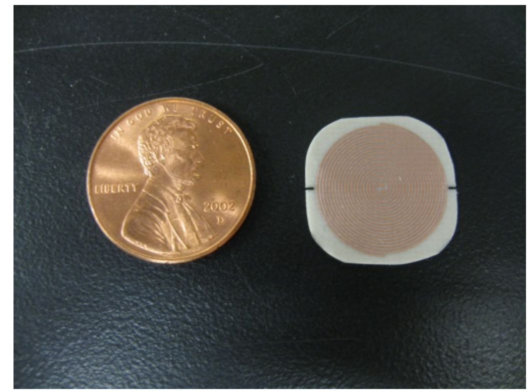


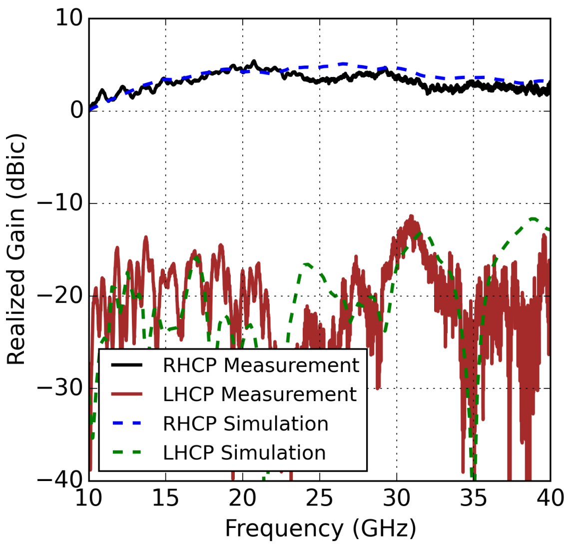
Example Comparison with Measurement

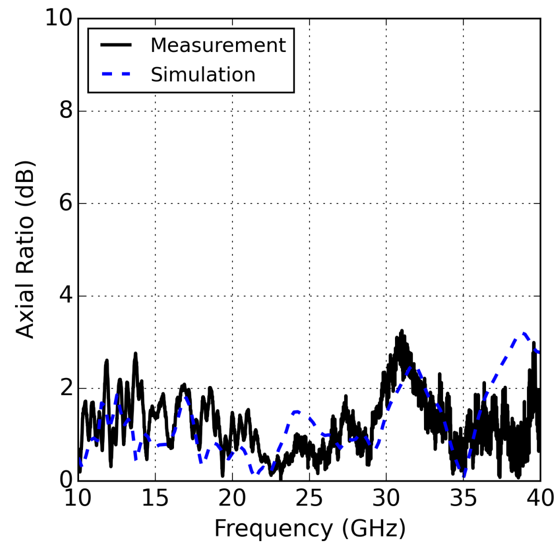
- Cavity-backed Archimedean spiral antenna with tapered line balun











Example Comparisons with Measurement

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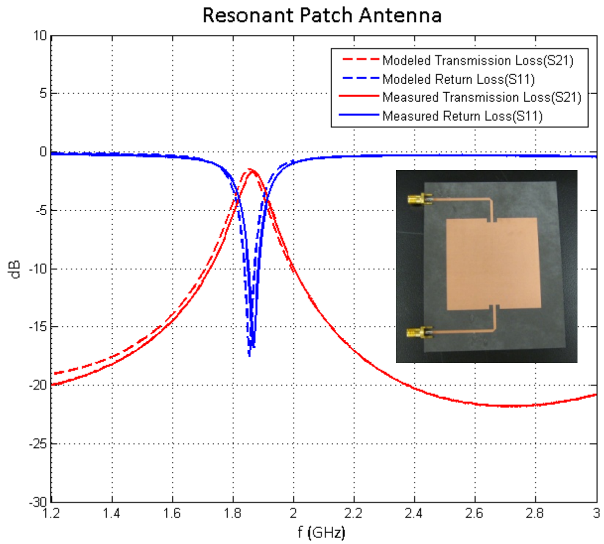
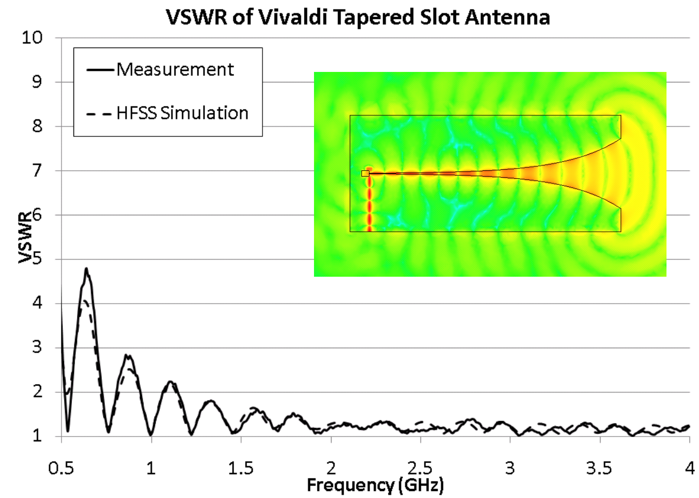
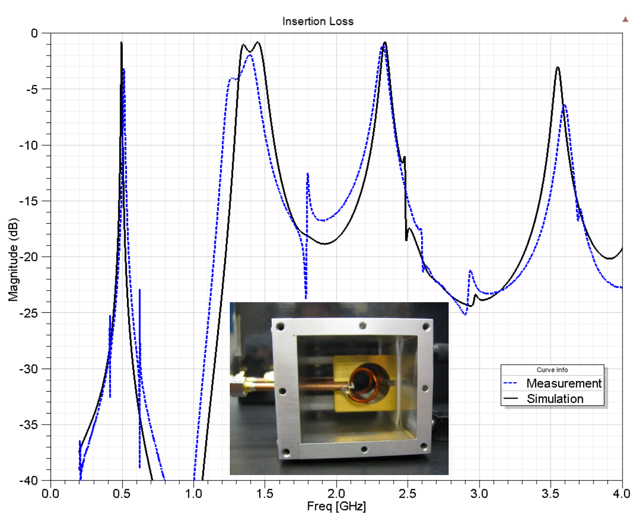
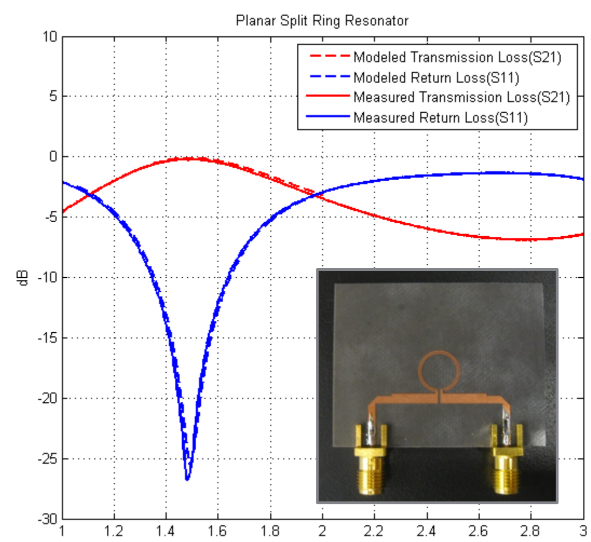


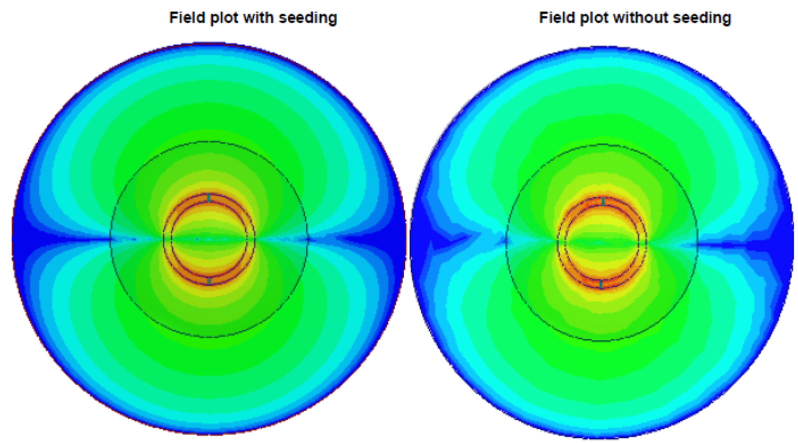


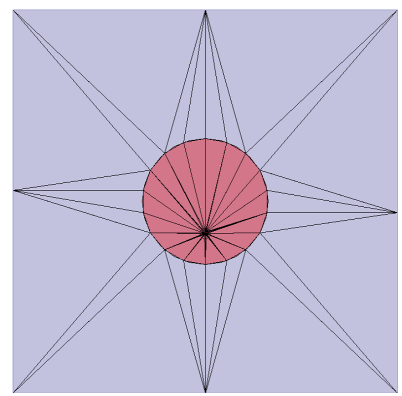


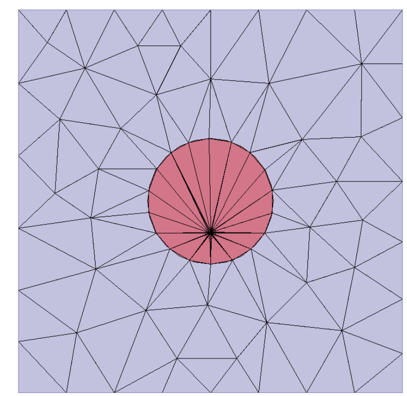


Mesh Controls

- Mesh seeding allows user to directly influence initial mesh
  - Reduce number of adaptive passes
  - Focus mesh elements in critical areas
  - Not required for accurate results
  - Can create better-looking field plots
  - Seeding radiation boundary can improve far-field data
- Lambda refinement
  - Ensures that initial mesh is refined to fraction of electrical wavelength
  - Electrical size depends on solver basis order
    - Zero: λ/10, First: λ/3, Second: 2λ/3, Mixed: 2λ/3




Initial geometric mesh


Electrical mesh after lambda refinement

Curvilinear Mesh Elements

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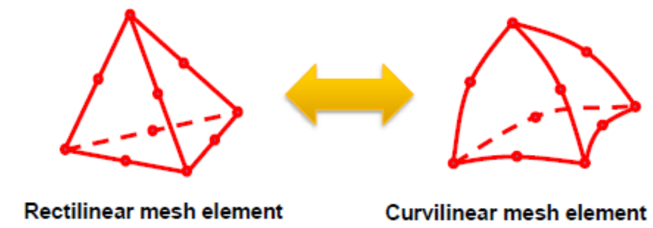
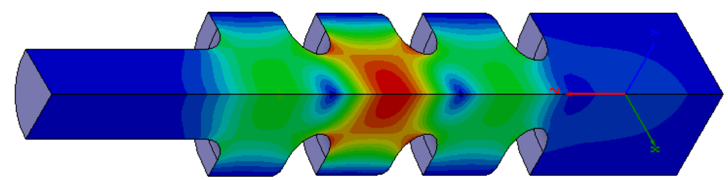
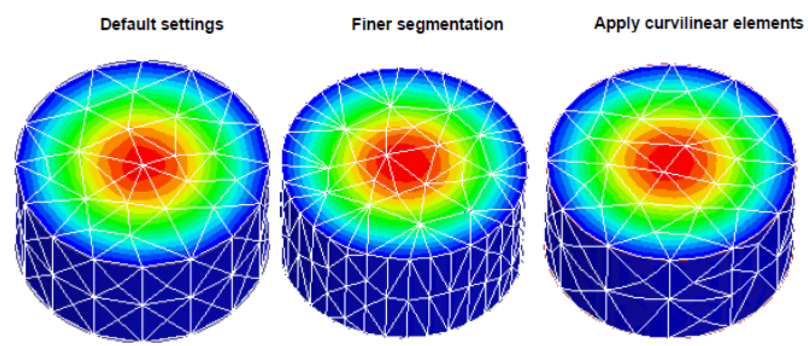
- Global mesh approximation setting for all true surfaces in model
- Higher order (curvilinear) elements used to represent the geometry
  - Pulls midpoints of tetrahedra surfaces to true surface
- Pillbox resonator with analytical f_R = 22.950 GHz for TM_{010} mode
  - Default setting: 23.269 GHz
  - Finer segmentation: 23.012 GHz
  - Curvilinear elements: 22.950 GHz







6024 DOF	6140 DOF	4966 DOF
1.38% error	0.03% error	0.00% error

FEM Solver

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- Direct matrix solver is default technique
  - Exactly solves matrix equation Ax = b
  - Multi-frontal sparse matrix solver to find inverse of A (LU decomposition)
  - Solves for all excitations b simultaneously
- Iterative matrix solver is optional technique for driven solutions
  - Reduces RAM usage and often runtime
  - Solves matrix equation Max = Mb where M is preconditioner
  - Begins with initial solution and recursively updates solution until tolerance is reached
  - Iterates for each excitation b
  - More sensitive to mesh quality, reverts to direct solver if it fails to converge

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

$$\nabla \cdot D = \rho$$

$$\nabla \cdot B = 0$$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ 0 & a_{22} & a_{23} & a_{24} \\ 0 & 0 & a_{33} & a_{34} \\ 0 & 0 & 0 & a_{44} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$$

FEM Basis Functions

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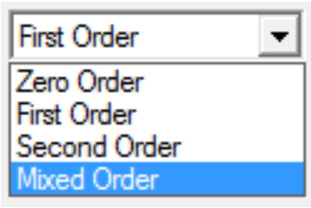
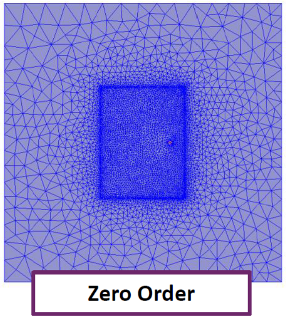
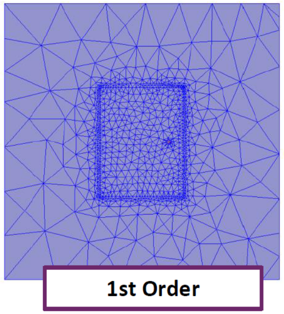
- Basis functions are n-order polynomials that describe how E-field varies along mesh elements edge, face, or volume
- Hierarchical basis functions
  - Zero ***or*** first ***or*** second order basis functions
  - Higher-order elements have increased accuracy but more unknowns (6, 20, 45)
- Mixed order basis functions
  - Zero ***and*** first ***and*** second order basis functions
  - hp-FEM method refines element order p and element size h
  - Automatically distributes element order based on element size to optimize use of resources
- Choice of ideal basis function is problem dependent
  - Mixed order efficiency is comparable to or better than best of single order basis functions



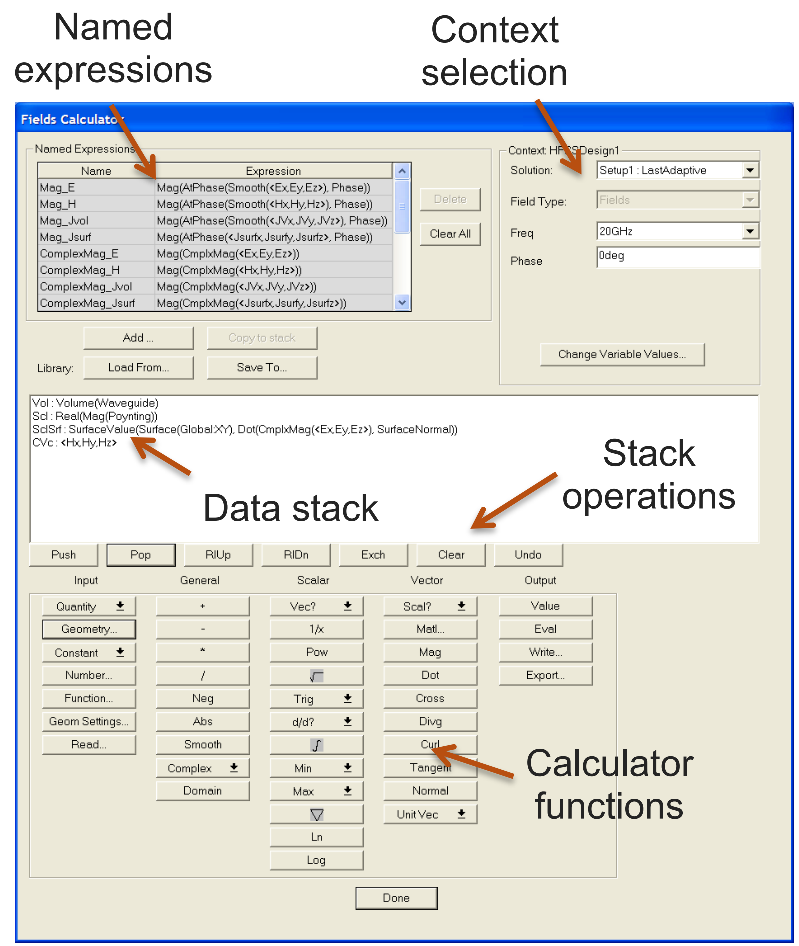




Order	Tetrahedra	RAM	Solution Time	Adaptive Passes
0	449,445	2.9 GB	21 min	16
1^{st}	28,559	681 MB	2.5 min	11
2^{nd}	20,782	1.8 GB	9.5 min	9
Mixed	**17,385**	**355MB**	**1.3 min**	**11**

Fields Calculator

- Tool for performing math operations on saved fields
  - E, H, J, and Poynting data available
  - Geometric, complex, vector, and scalar data
  - Perform operations using model or non-model geometry
  - Generate numerical, graphical, geometrical, or exportable data
- Reverse Polish notation
- Frequently used expressions can be included in user library and loaded into any project
  - Eliminates need to re-create expressions used across projects



$$\frac{1}{2}\iint_{s} \mathrm{Re}\{\vec{E}\times\vec{H}^*\}\bullet\vec{ds}$$

$$\frac{1}{2}\sigma\iiint_{v} |E|^2\, dv$$

Keyboard Shortcuts

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General Shortcuts

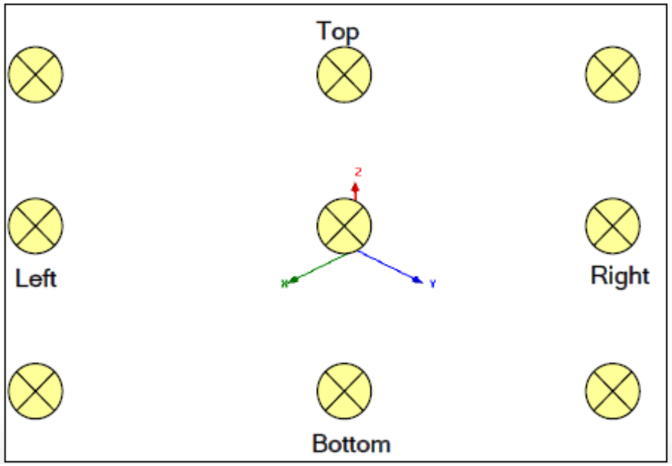
- ***F1***: Help
- ***F1 + Shift***: Context help
- ***F4 + CTRL***: Close window
- ***CTRL + C***: Copy
- ***CTRL + N***: New project
- ***CTRL + O***: Open...
- ***CTRL + S***: Save
- ***CTRL + P***: Print...
- ***CTRL + V***: Paste
- ***CTRL + X***: Cut
- ***CTRL + Y***: Redo
- ***CTRL + Z***: Undo
- ***CTRL + 0***: Cascade windows
- ***CTRL + 1***: Tile windows horizontally
- ***CTRL + 2***: Tile windows vertically

3D Modeller Shortcuts

- ***B***: Select face/object behind current selection
- ***F***: Face select mode
- ***O***: Object select mode
- ***Hold X***: Curser movement restricted to x direction
- ***Hold Y***: Curser movement restricted to y direction
- ***Hold Z***: Curser movement restricted to z direction
- ***CTRL + A***: Select all visible objects
- ***CTRL + SHIFT + A***: Deselect all objects
- ***CTRL + D***: Fit view
- ***CTRL + Left Mouse Click***: Shifts the local coordinate system temporarily
- ***SHIFT + Left Mouse Button***: Drag
- ***Alt + Left Mouse Button***: Rotate model
- ***Alt + SHIFT + Left Mouse Button***: Zoom in / out
- ***F3***: Switch to point entry mode (i.e. draw objects by mouse)
- ***F4***: Switch to dialogue entry mode (i.e. draw object solely by entry in command and attributes box.)
- ***F6***: Render model wire frame
- ***F7***: Render model smooth shaded

- ***Alt + Double Click Left Mouse Button at points on screen***: Sets model projection to standard isometric projections (see diagram to the right).
- ***Alt + Double Click Right Mouse Button at points on screen***: give the nine opposite projections.

Predefined View Angles



ANSYS

Cylindrical Cavity Example

Cylindrical Cavity Example

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- Empty copper cavity
  - Radius = 21 cm
  - Height = 100 cm
- Expected results for TM_{010} mode
  - f_R = 546.42 MHz
  - Q-factor = 61,391 (Li and Jiang, 2006)
  - Form factor C = 0.69 (Peng *et al.*, 2000)
  - Form factor C = 0.692 (Stern *et al.*, 2015)

$$f_{010} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p'_{01}}{r}\right)^2 + \left(\frac{0 \times \pi}{d}\right)^2}$$

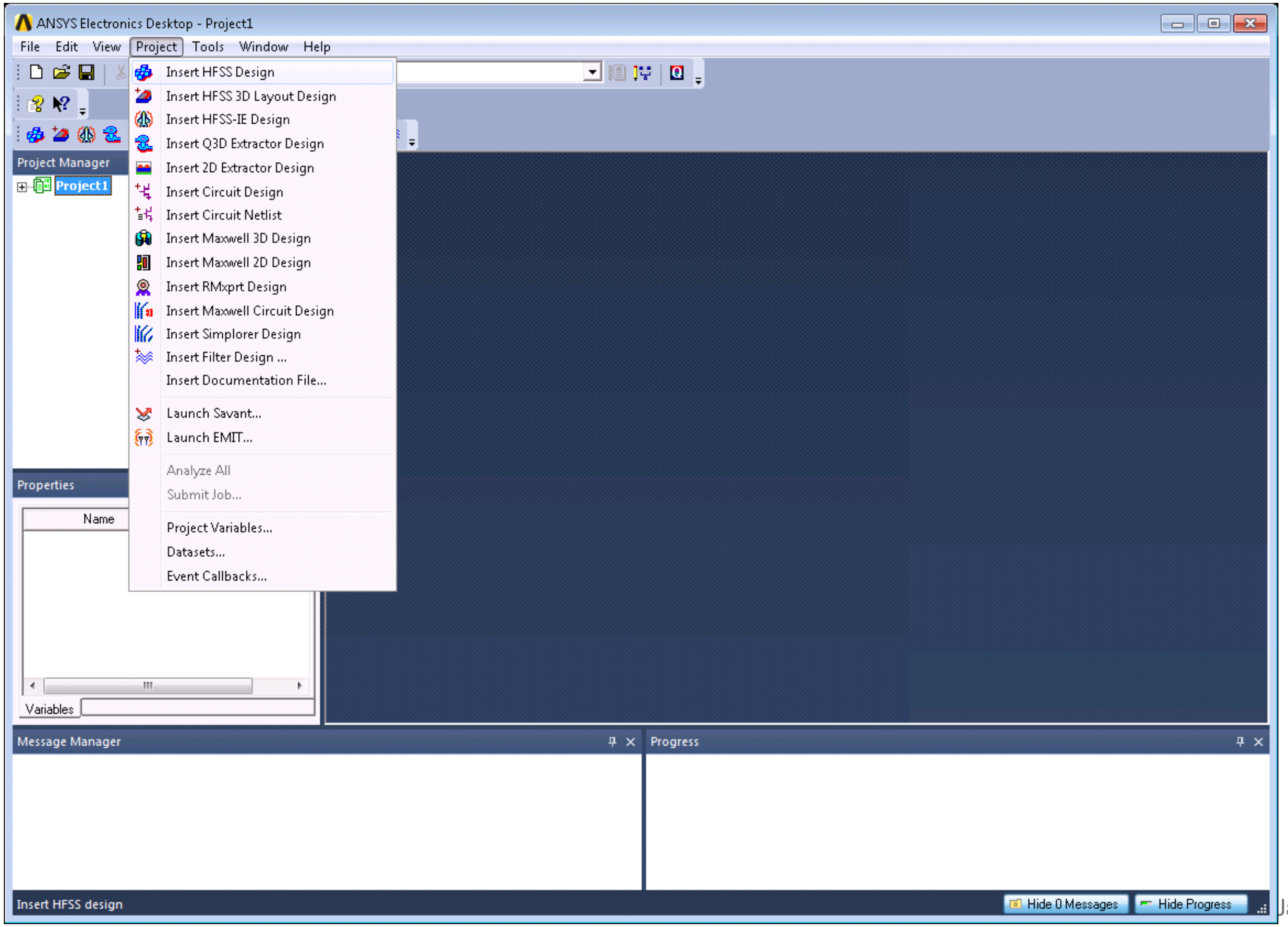
$$f = \frac{c}{2.61r}$$

$$Q_u = \left(\frac{H}{R+H}\right)\left(\frac{R}{\delta}\right) \qquad Q_0 = Q_c = \frac{2V}{S\sqrt{\frac{2}{\omega\mu\sigma}}}$$

$$C = \frac{\left|\int_V d^3x \, \vec{E}_\omega \cdot \vec{B}_0\right|^2}{B_0^2 V \int_V d^3x \, \epsilon |\vec{E}_\omega|^2}$$

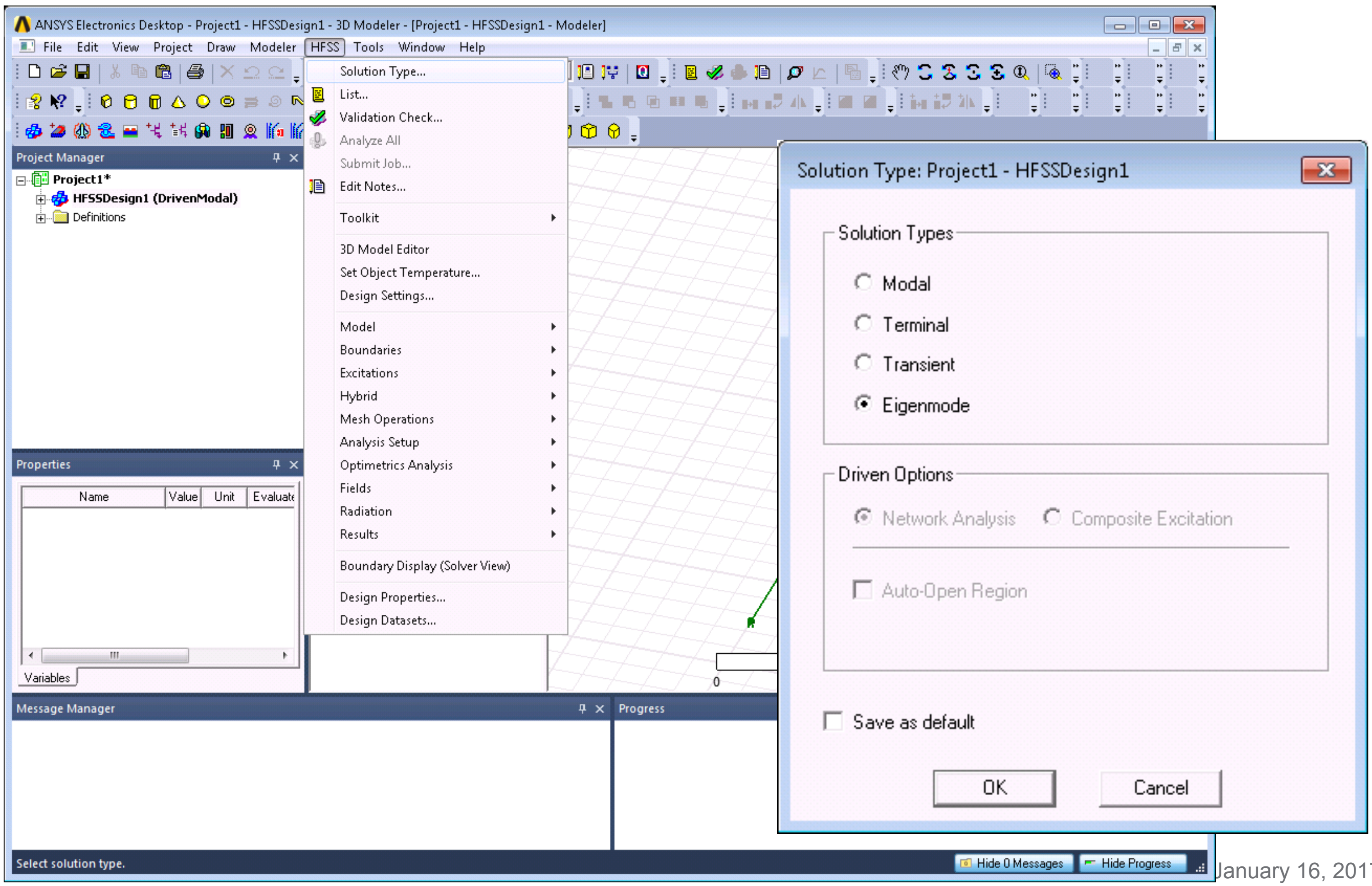
1: Create HFSS Project

- Insert into Electronics Desktop using ***Project > Insert HFSS Design***



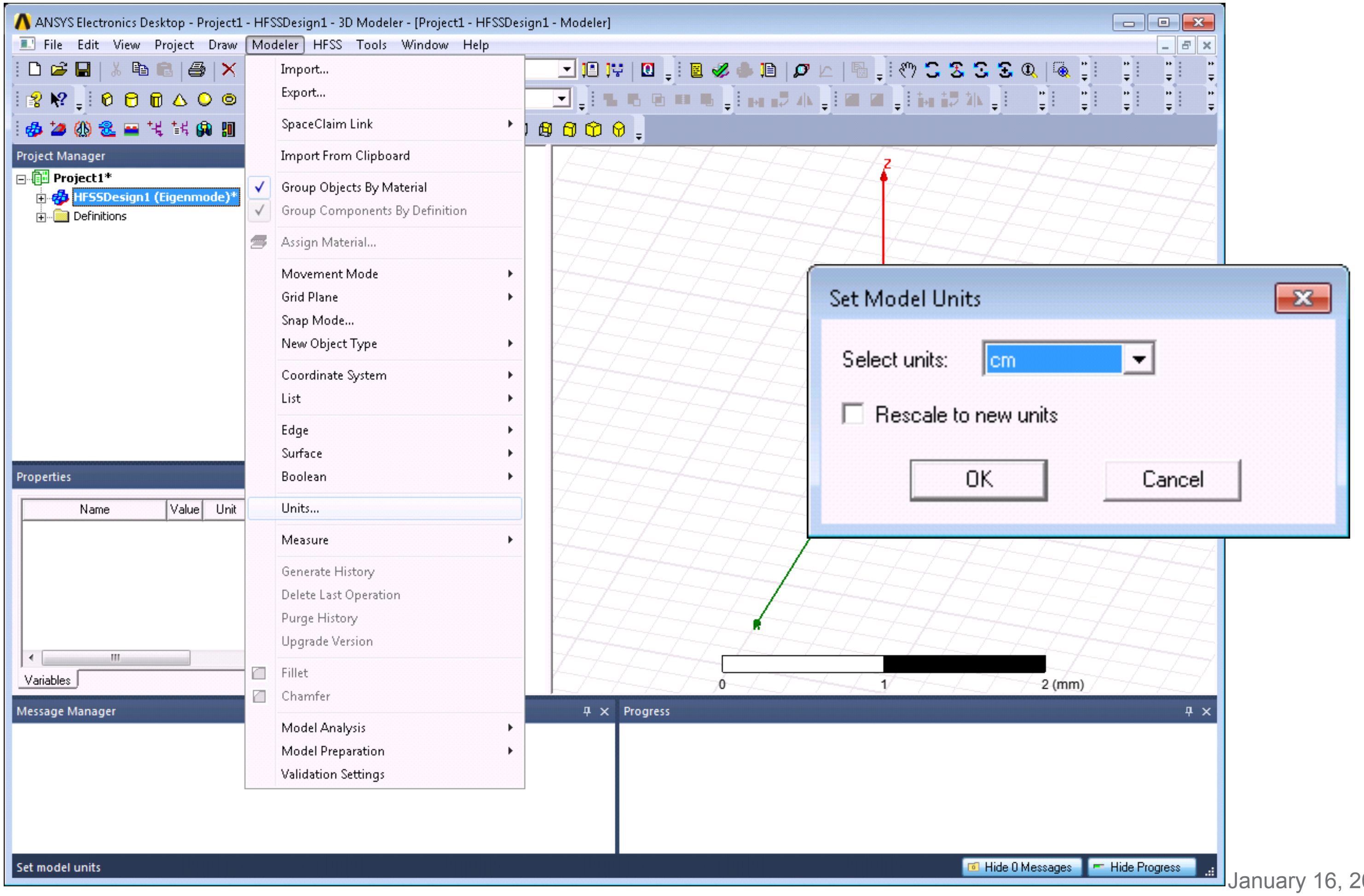
2: Set Eigenmode Solution Type

- Select ***HFSS > Solution Type > Eigenmode***



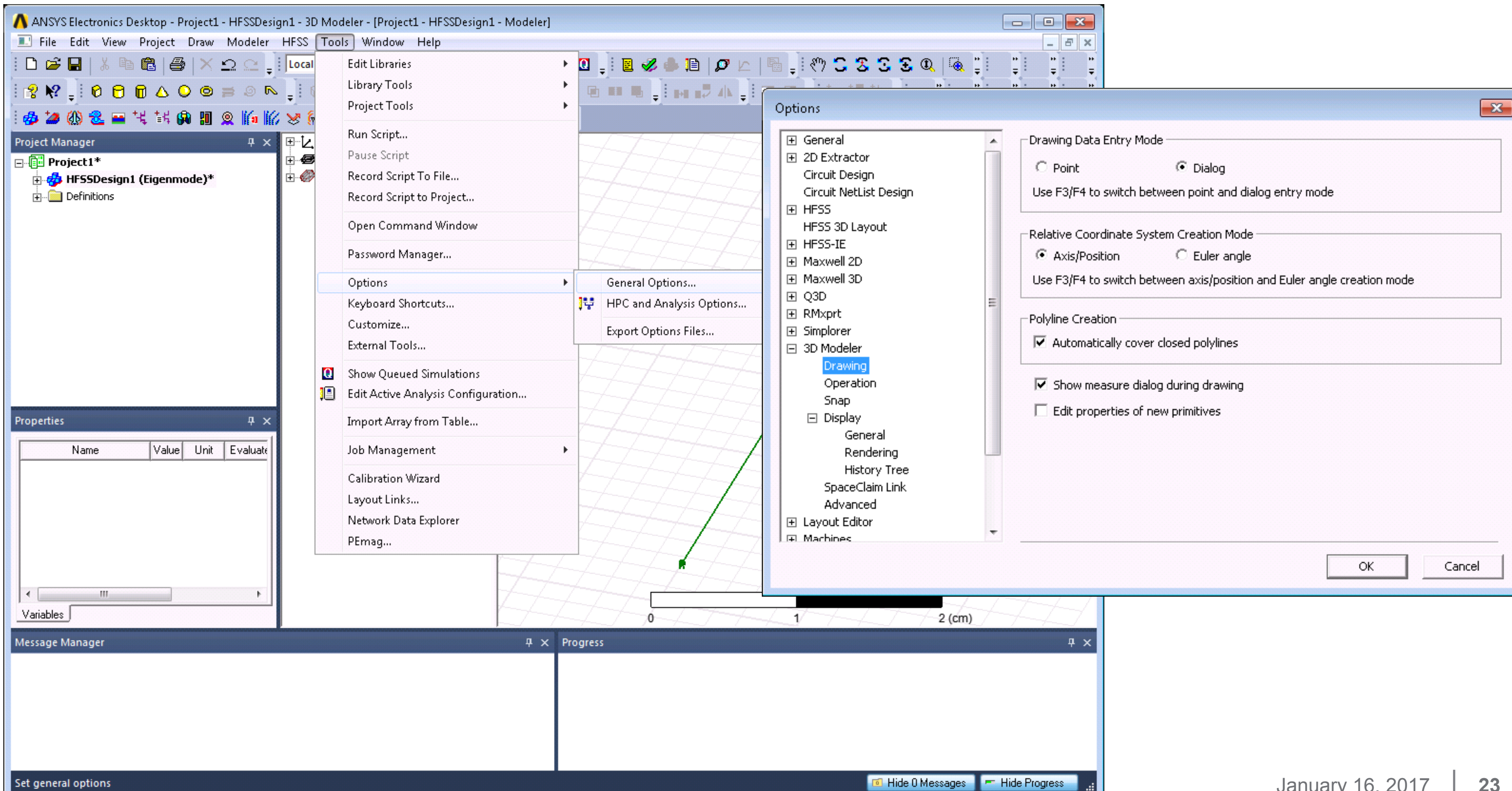
3: Set Model Units

- Select ***Modeler > Units > cm***



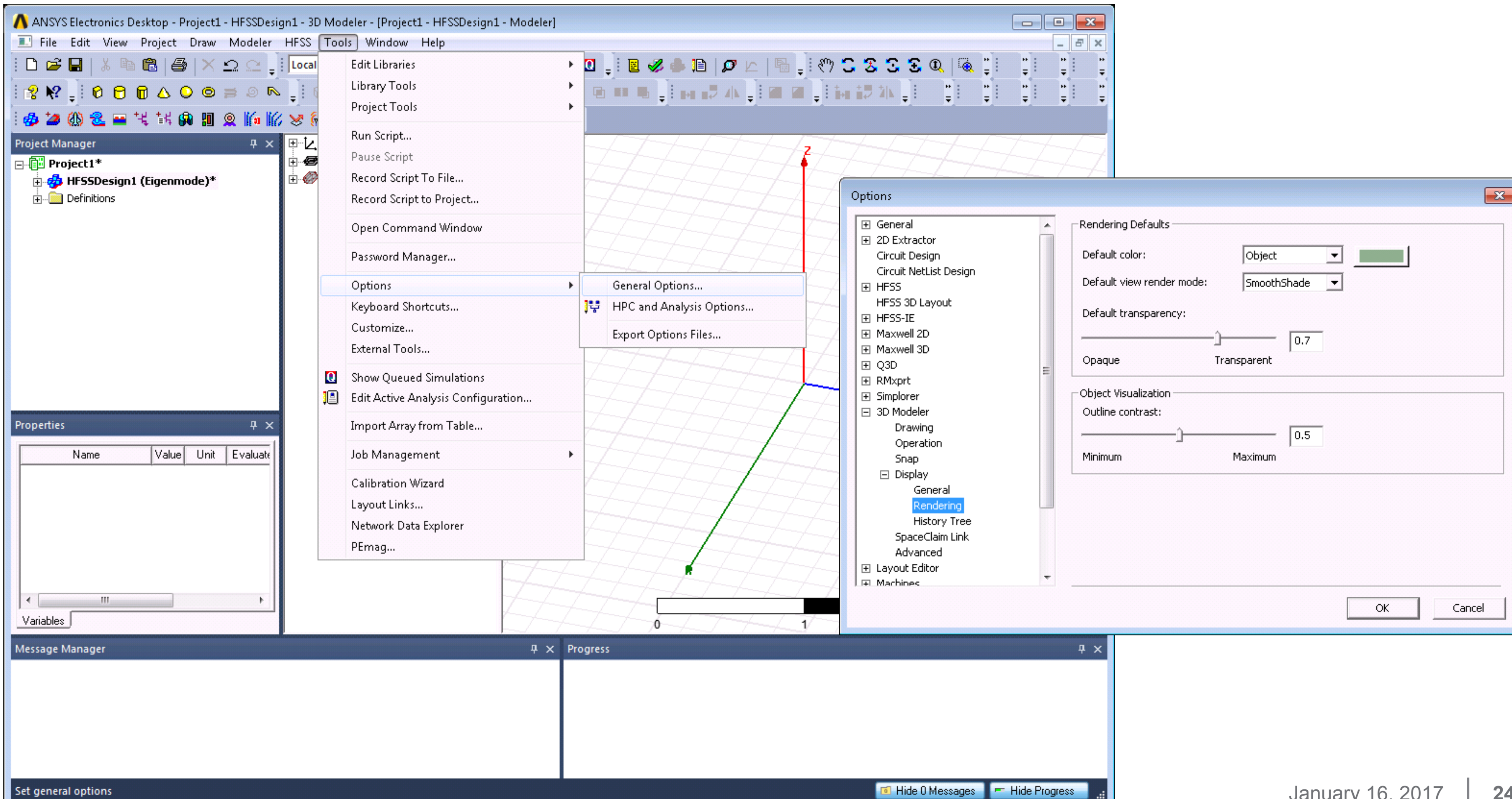
4: Set Dialog Data Entry Mode

- Select ***Tools > Options > General Options > 3D Modeler > Drawing > Dialog***



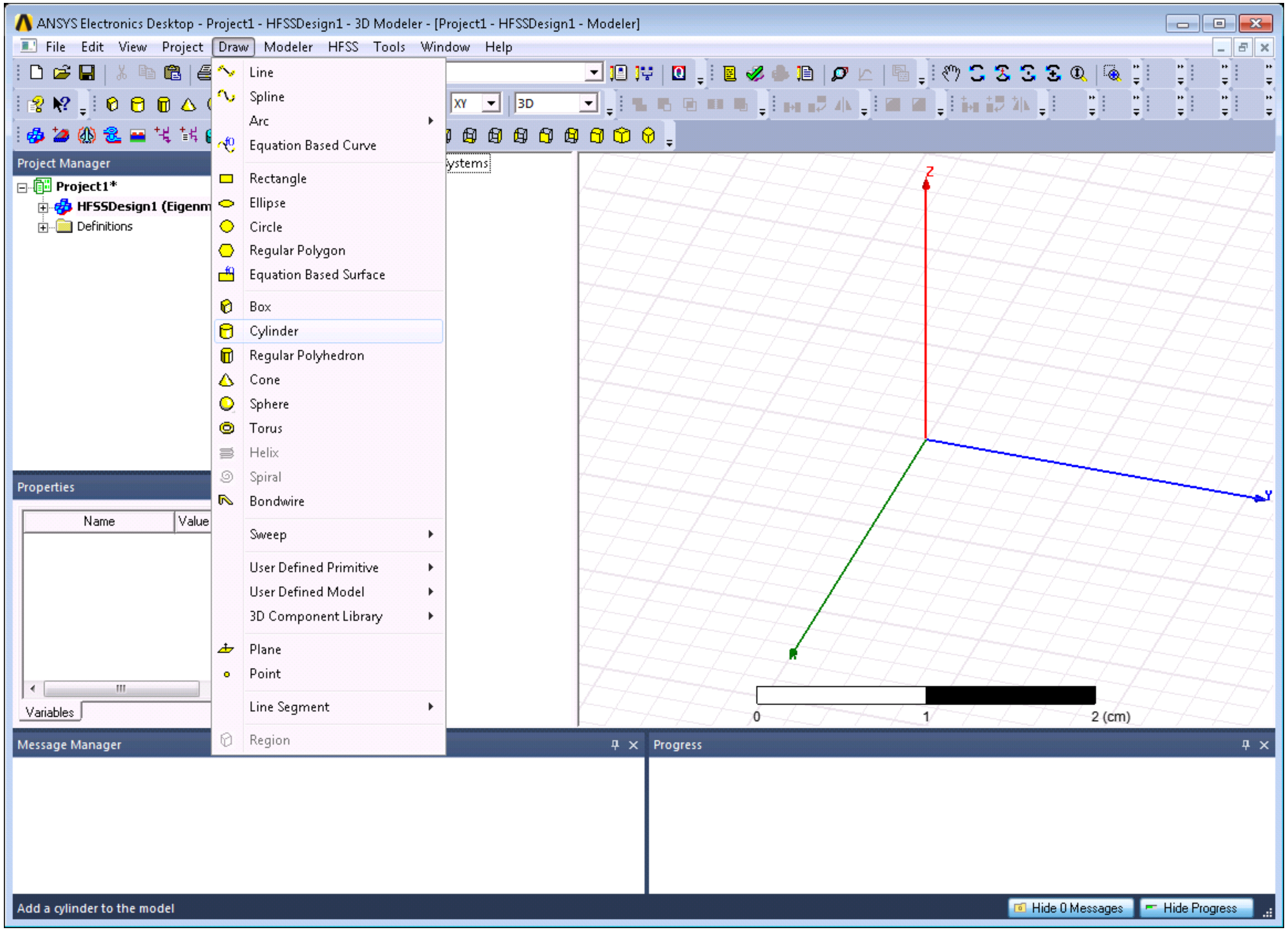
5: Set Default Transparency of 0.7

- Select ***Tools > Options > General Options > Display > Rendering***



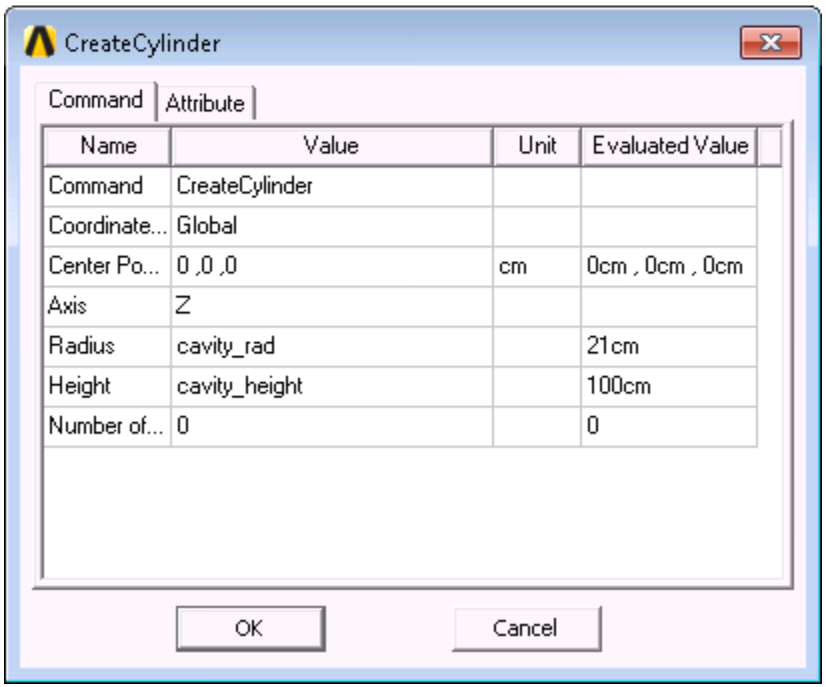
6: Create Parameterized Cavity

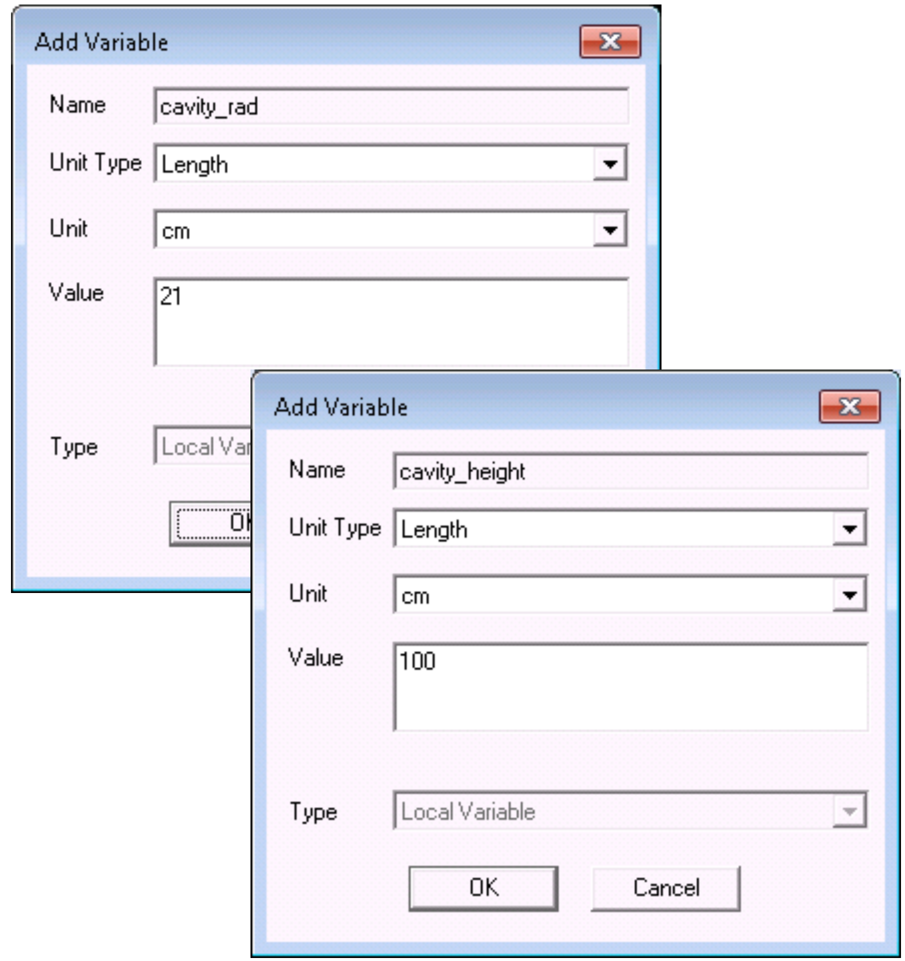
- Select ***Draw > Cylinder***



6: Create Parameterized Cavity

- Cavity_rad = 21 cm
- Cavity_height = 100 cm





6: Create Parameterized Cavity

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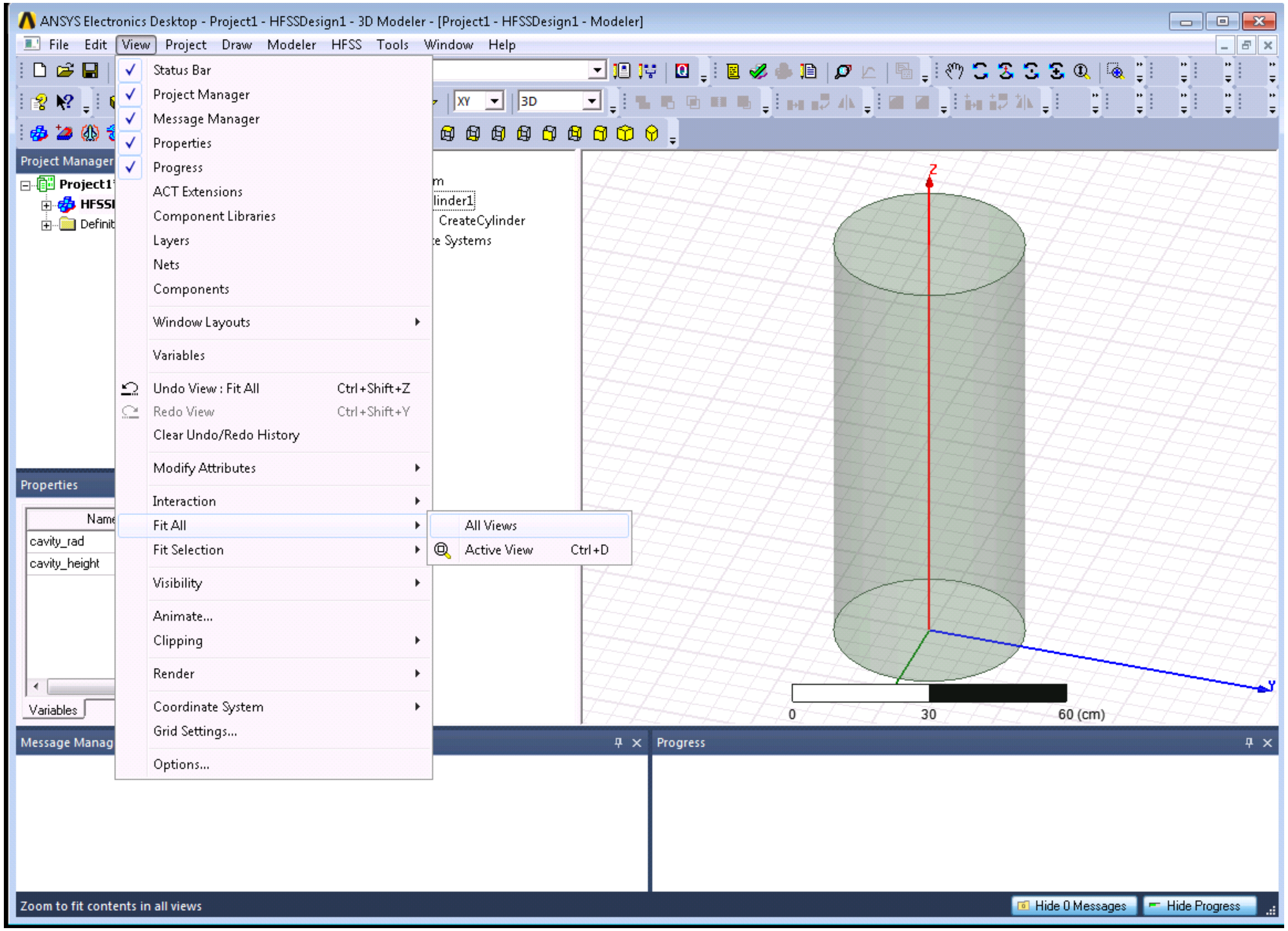
- Fit cavity to view using ***View > Fit All > All Views***



7: Assign Cavity Wall Conductivity

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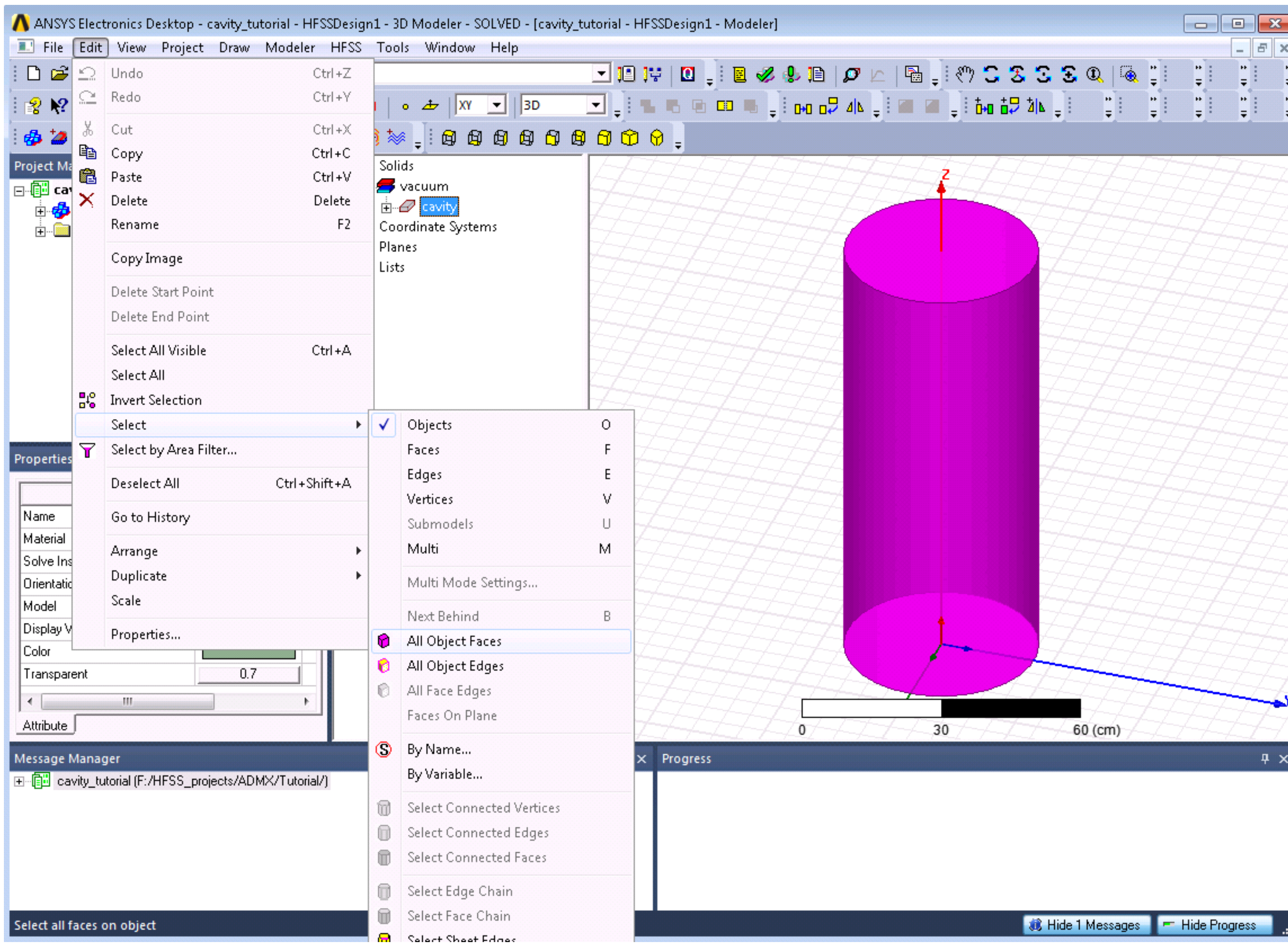
- Select cavity in 3D modeler tree and ***Edit > Select > All Object Faces***



7: Assign Cavity Wall Conductivity

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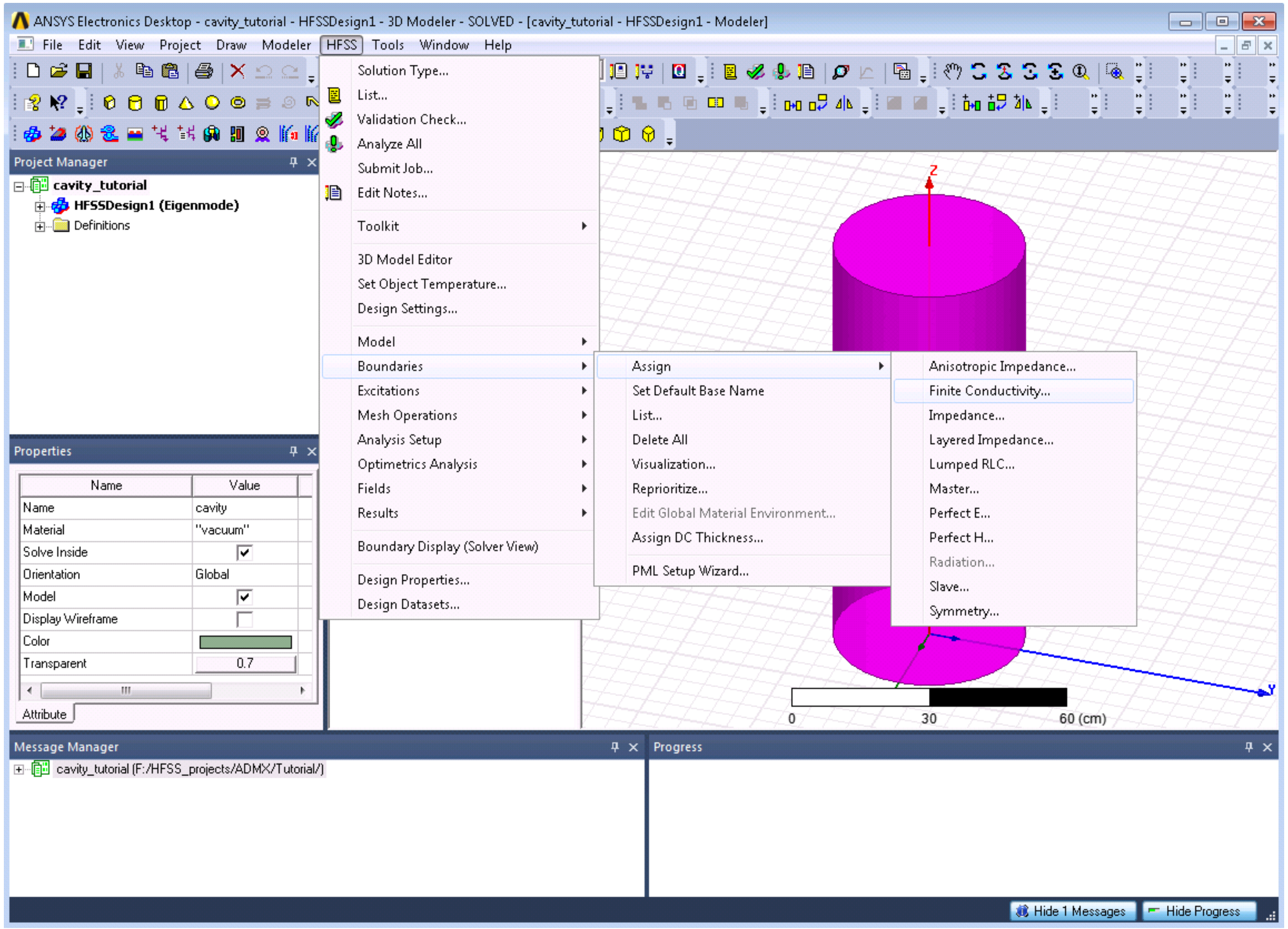
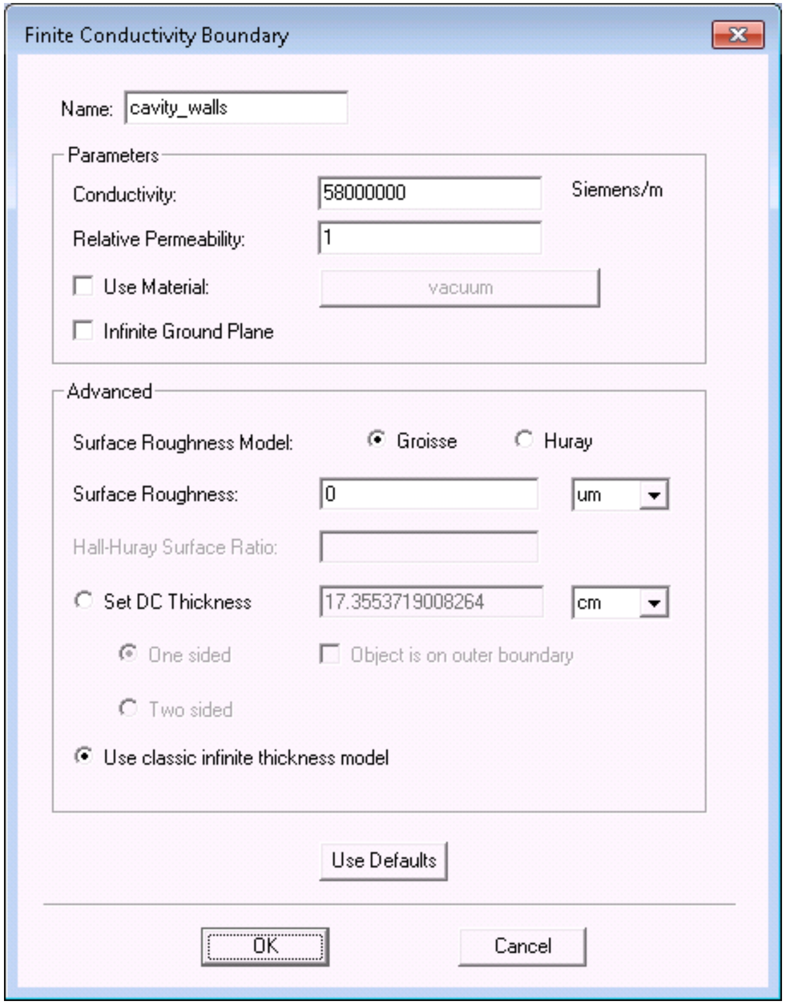
- Select ***HFSS > Boundaries > Assign > Finite Conductivity***



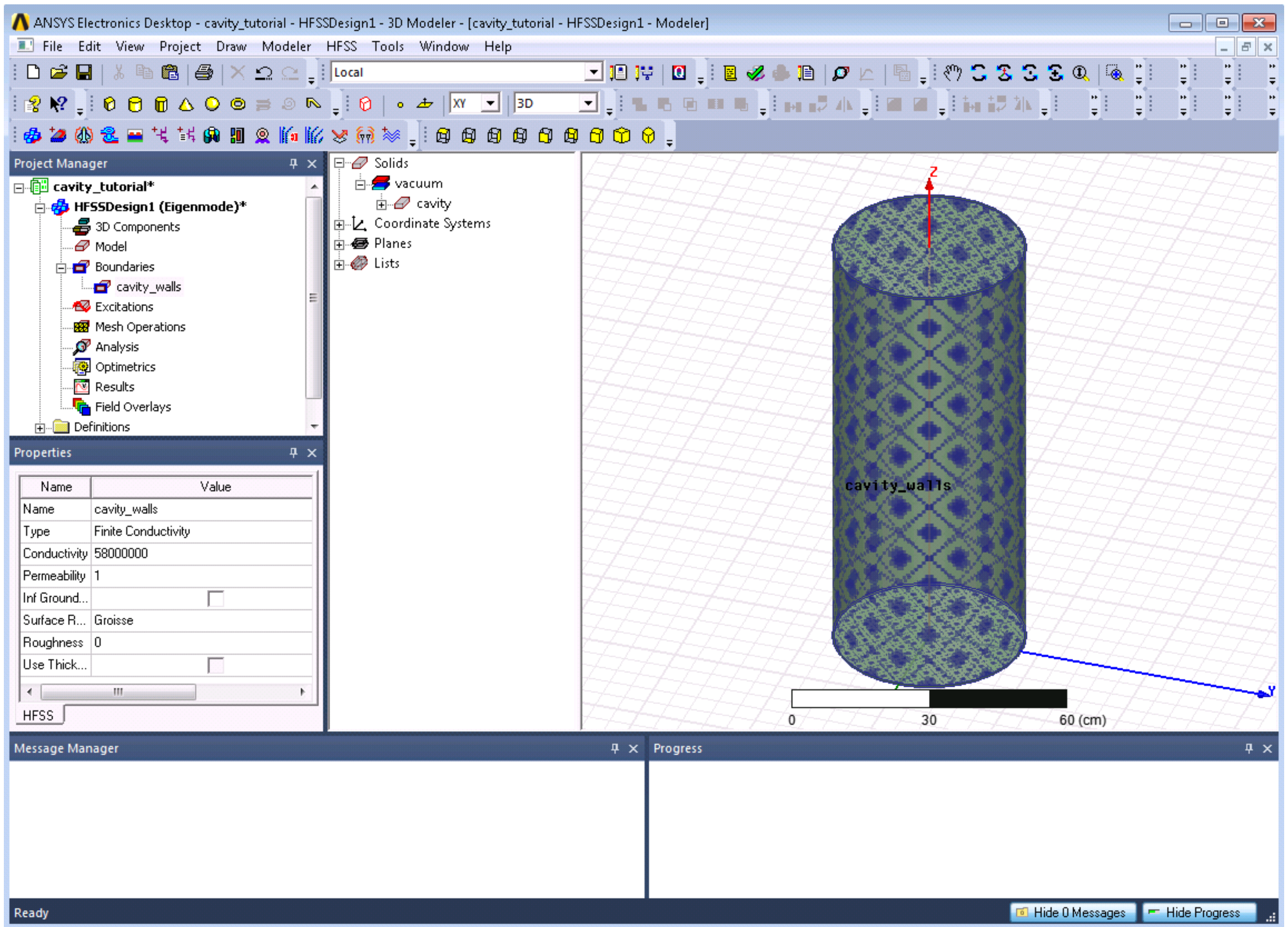
7: Assign Cavity Wall Conductivity

- Enter name “cavity_walls” and use default 5.8E7 S/m



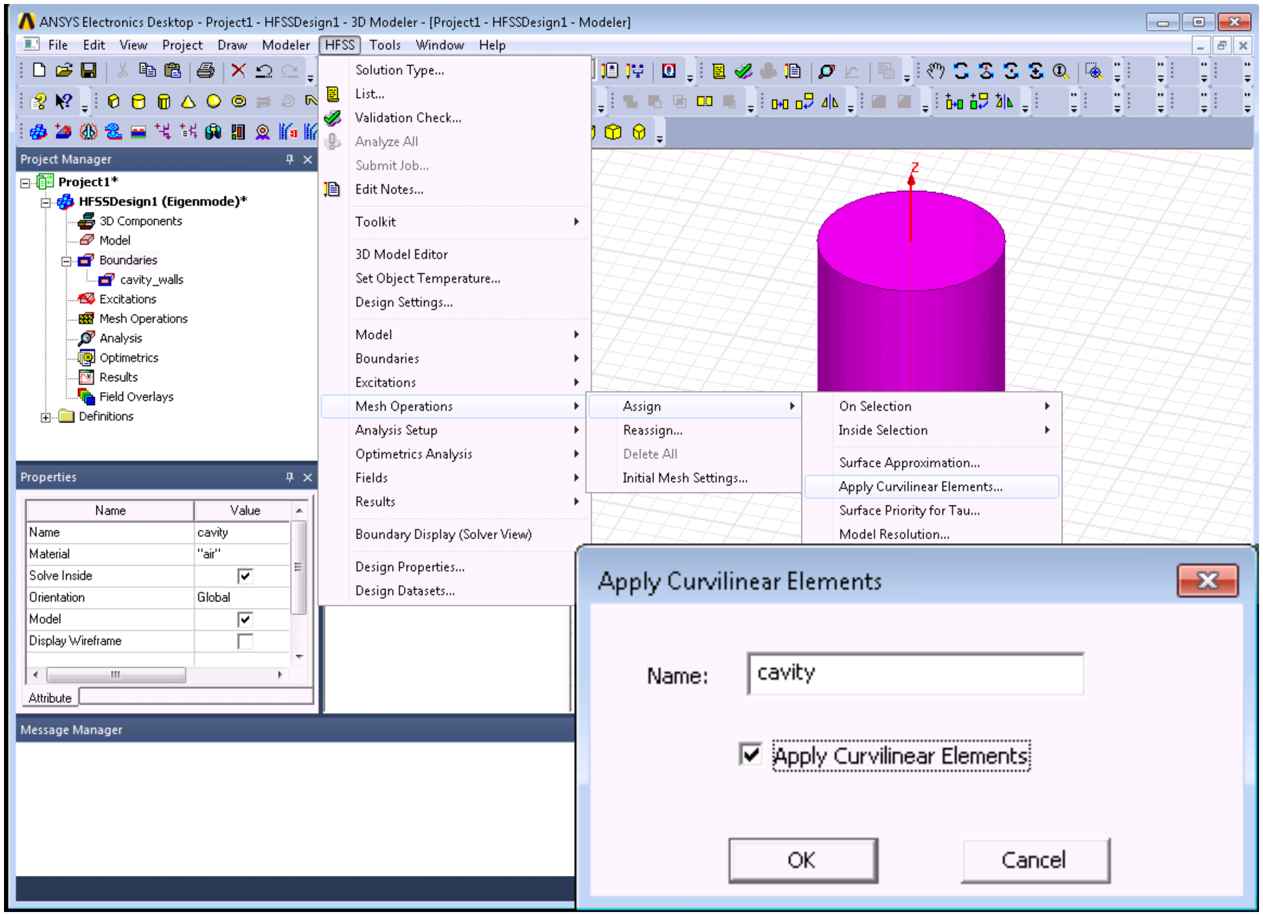
7: Assign Cavity Wall Conductivity

- Should have boundary condition as shown here



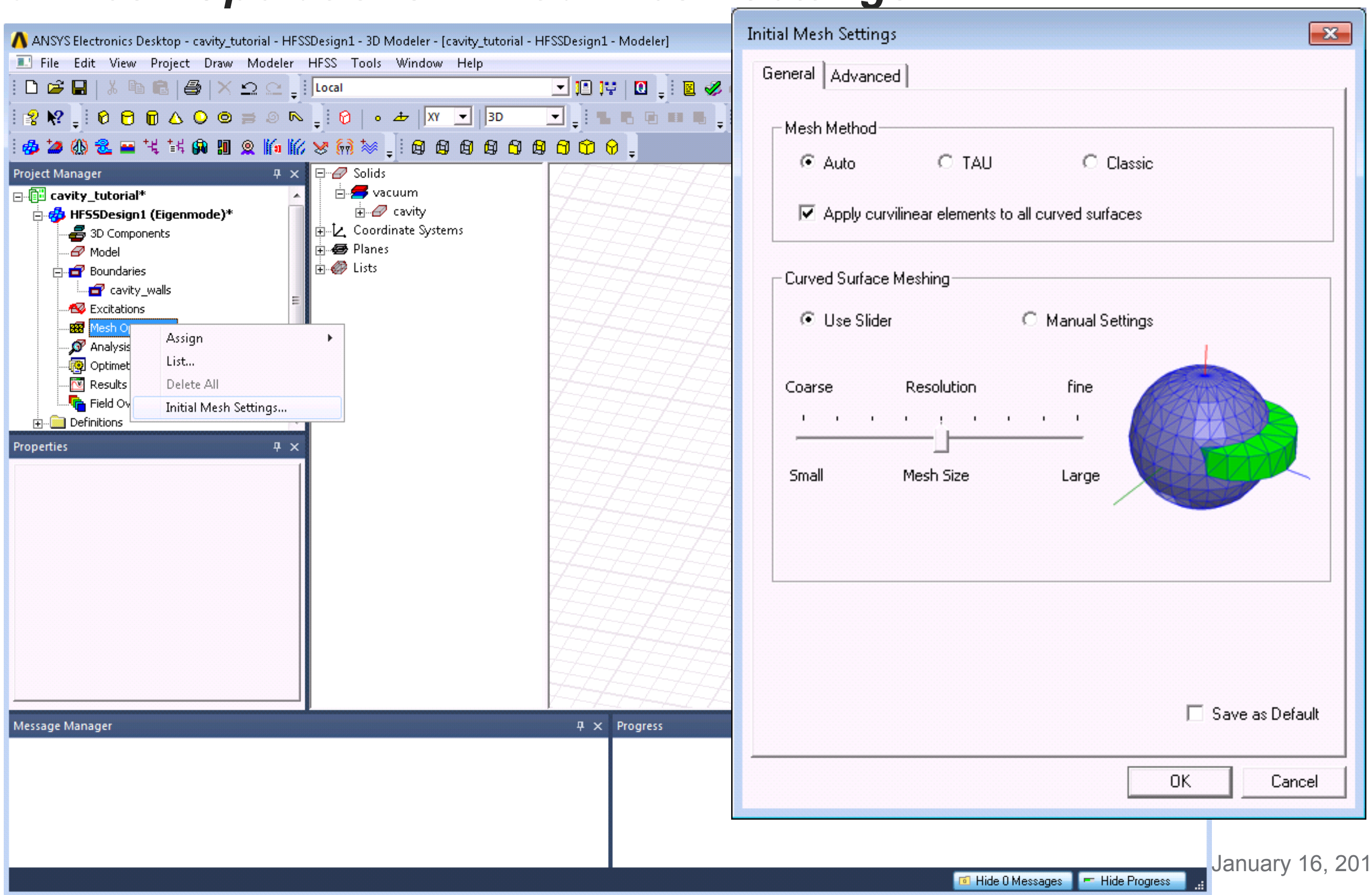
8: Apply Curvilinear Mesh Elements

- Select cavity in 3D modeler tree and apply curvilinear elements
- Select ***HFSS > Mesh Operations > Assign > Apply Curvilinear Elements***



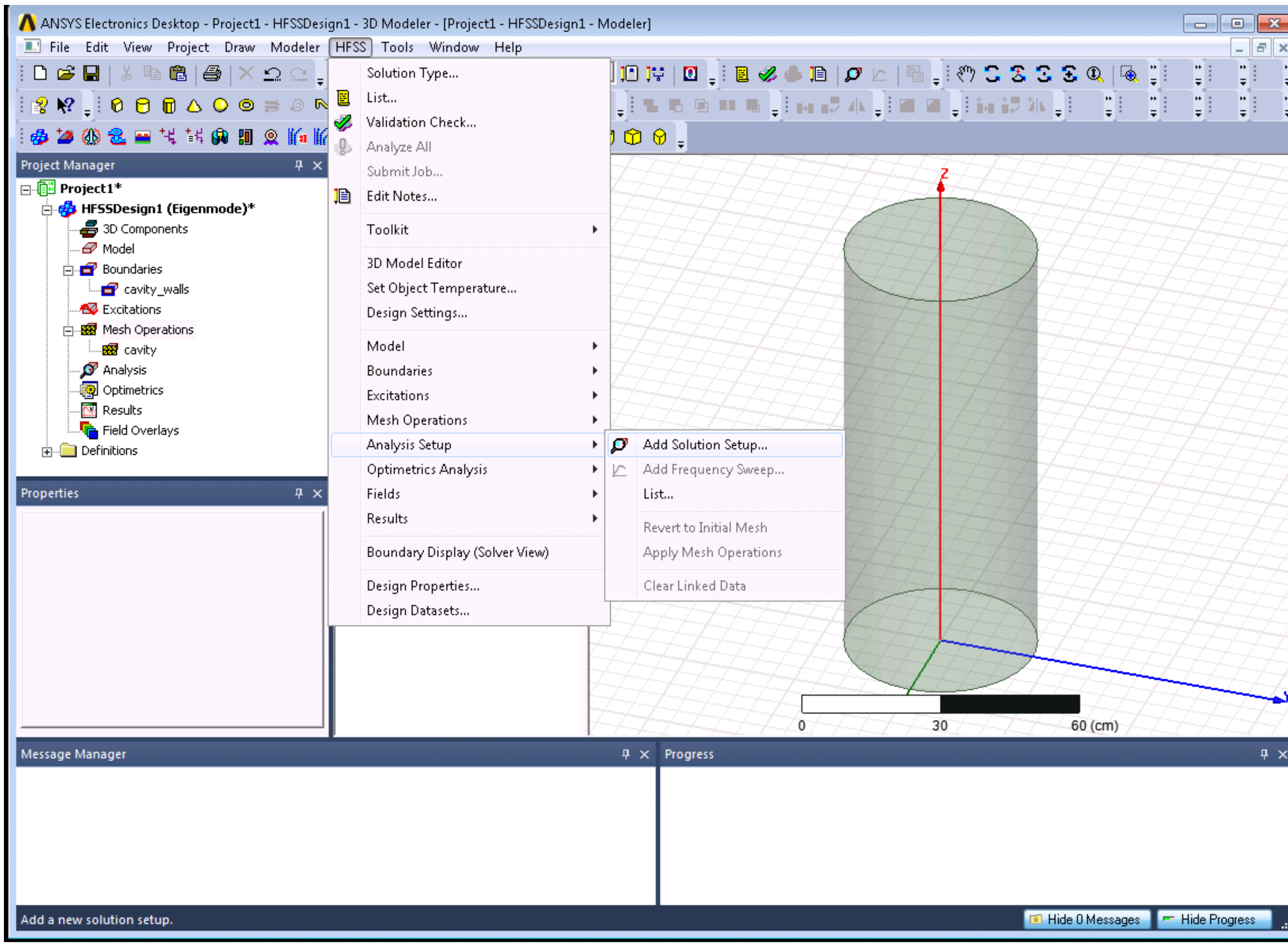
8: Apply Curvilinear Mesh Elements

- Can also apply curvilinear elements as global setting
- Right-click ***Mesh Operations > Initial Mesh Settings***



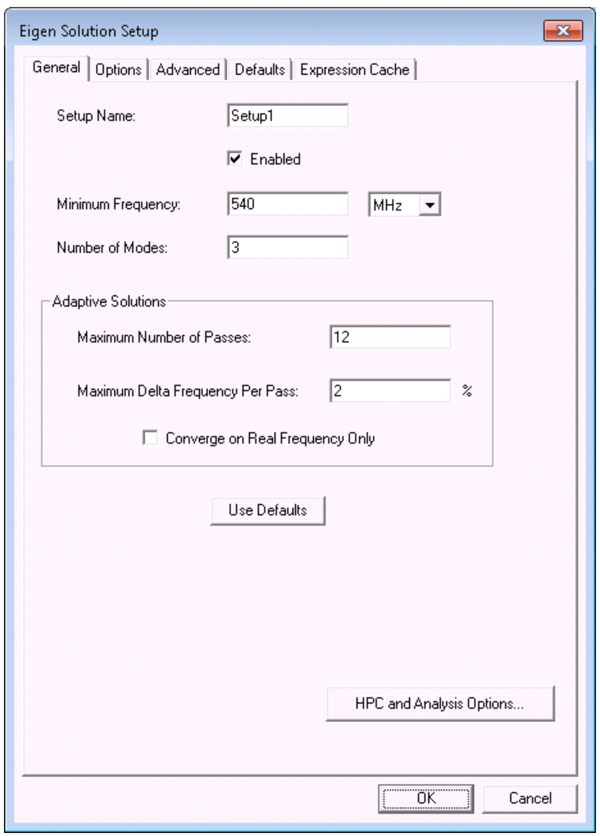
9: Add Solution Setup

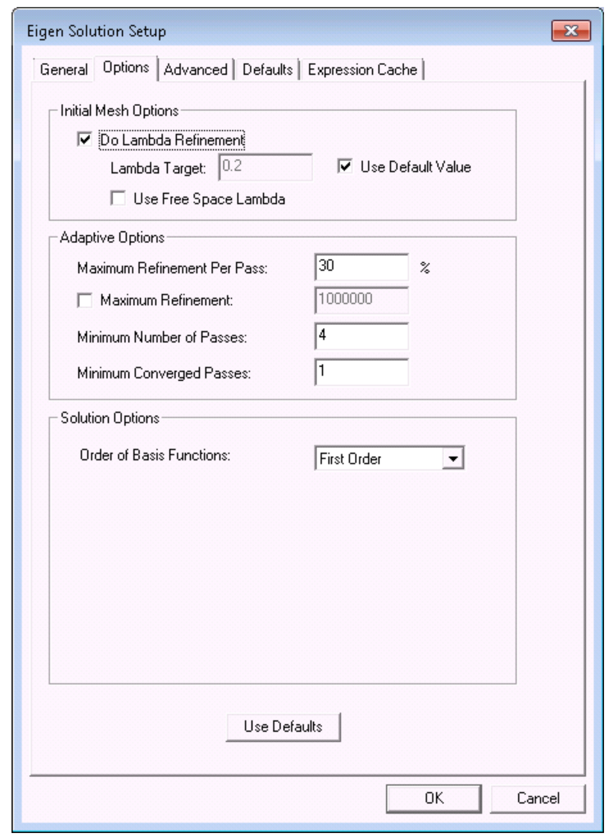
- Select ***HFSS > Analysis Setup > Add Solution Setup***



9: Add Solution Setup

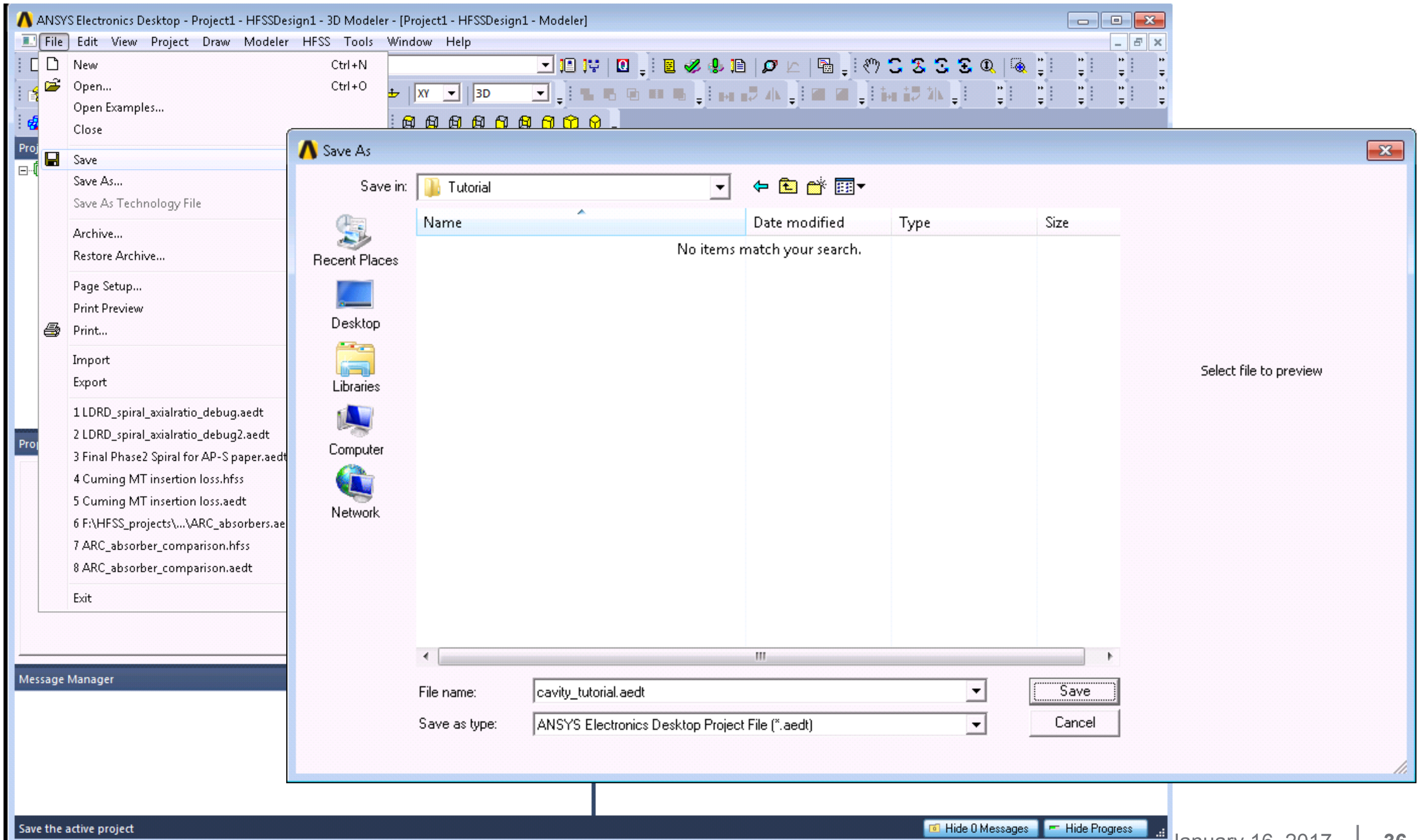
- Enter Minimum frequency = 540 MHz, Number of Modes = 3, Maximum Number of Passes = 12, Max Delta Frequency / Pass = 2%, Minimum Passes = 4





10: Save Project

- Select ***File*** **>** ***Save*** and save project as "cavity_tutorial.aedt"



11: Perform Validation Check

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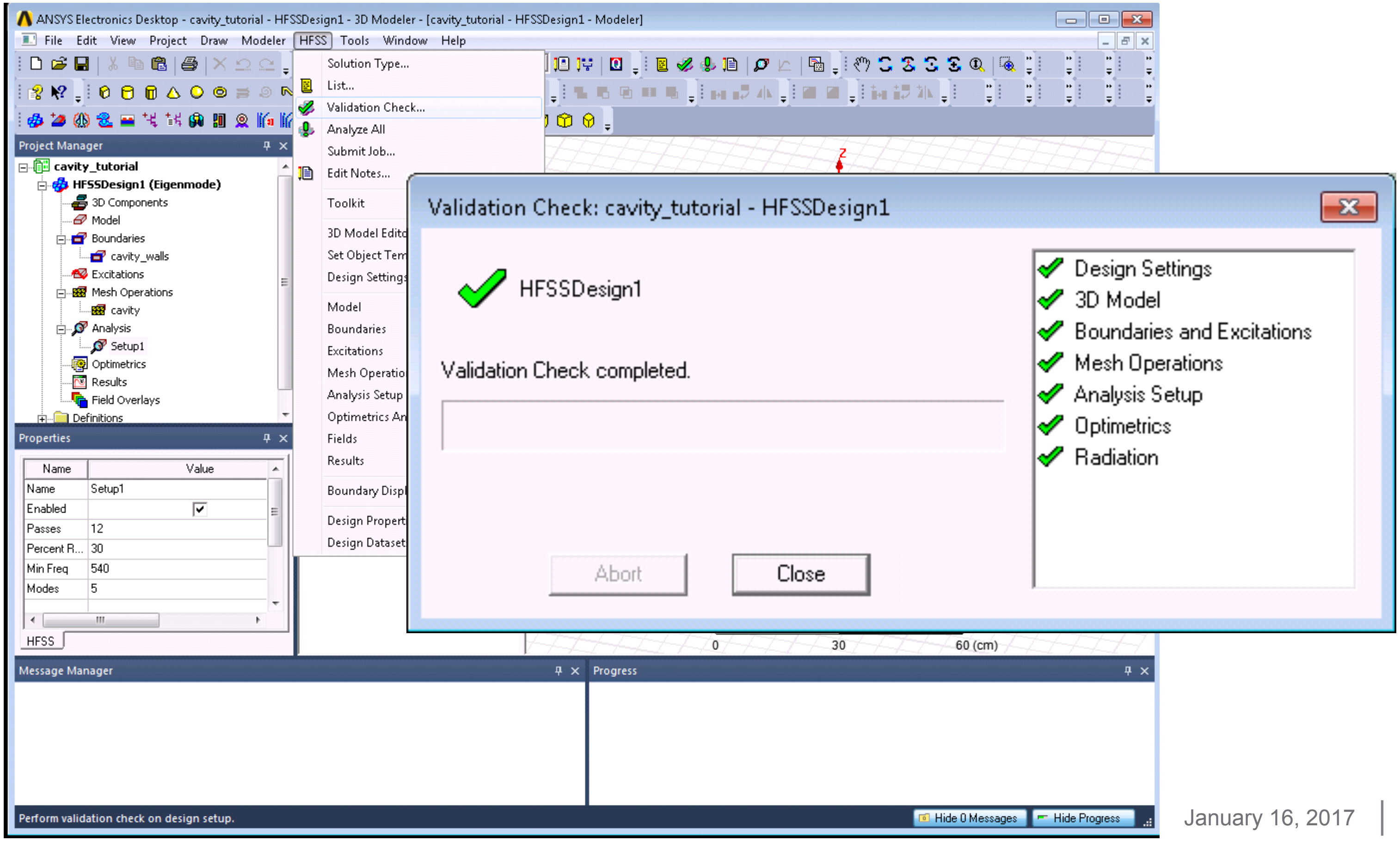
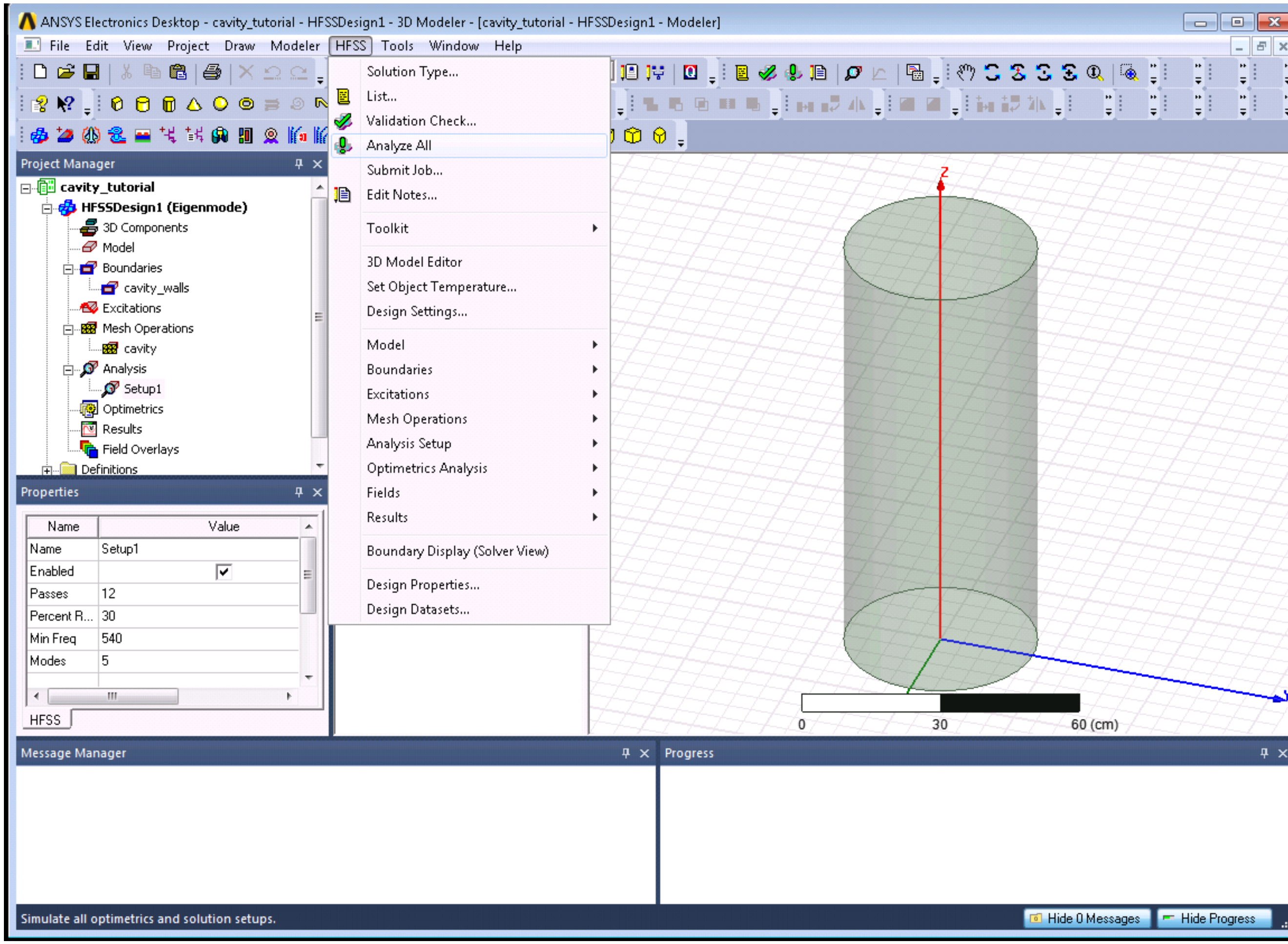
- Select ***HFSS > Validation Check***
- Confirms that required steps to solve model have been performed



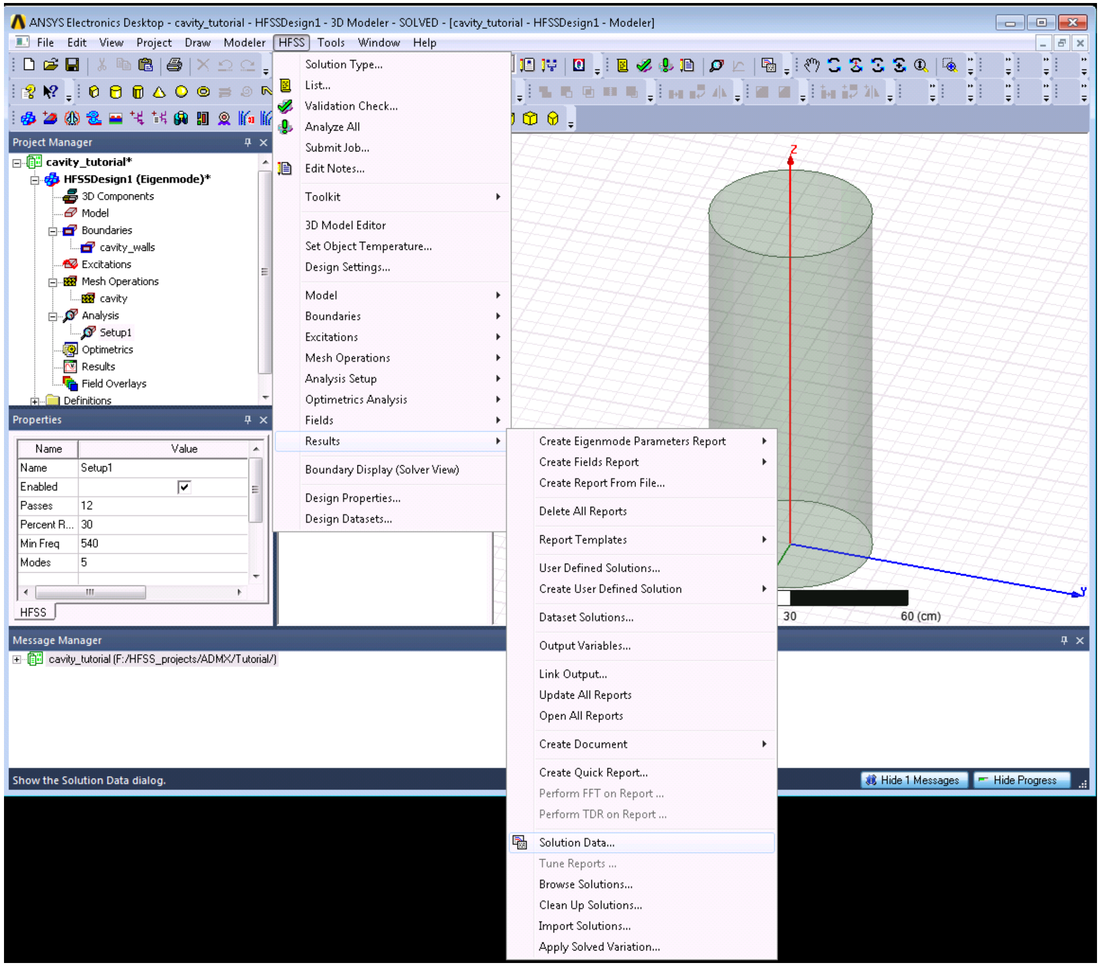
12: Solve Model

- Select ***HFSS > Analyze All***



13: View Solution Data

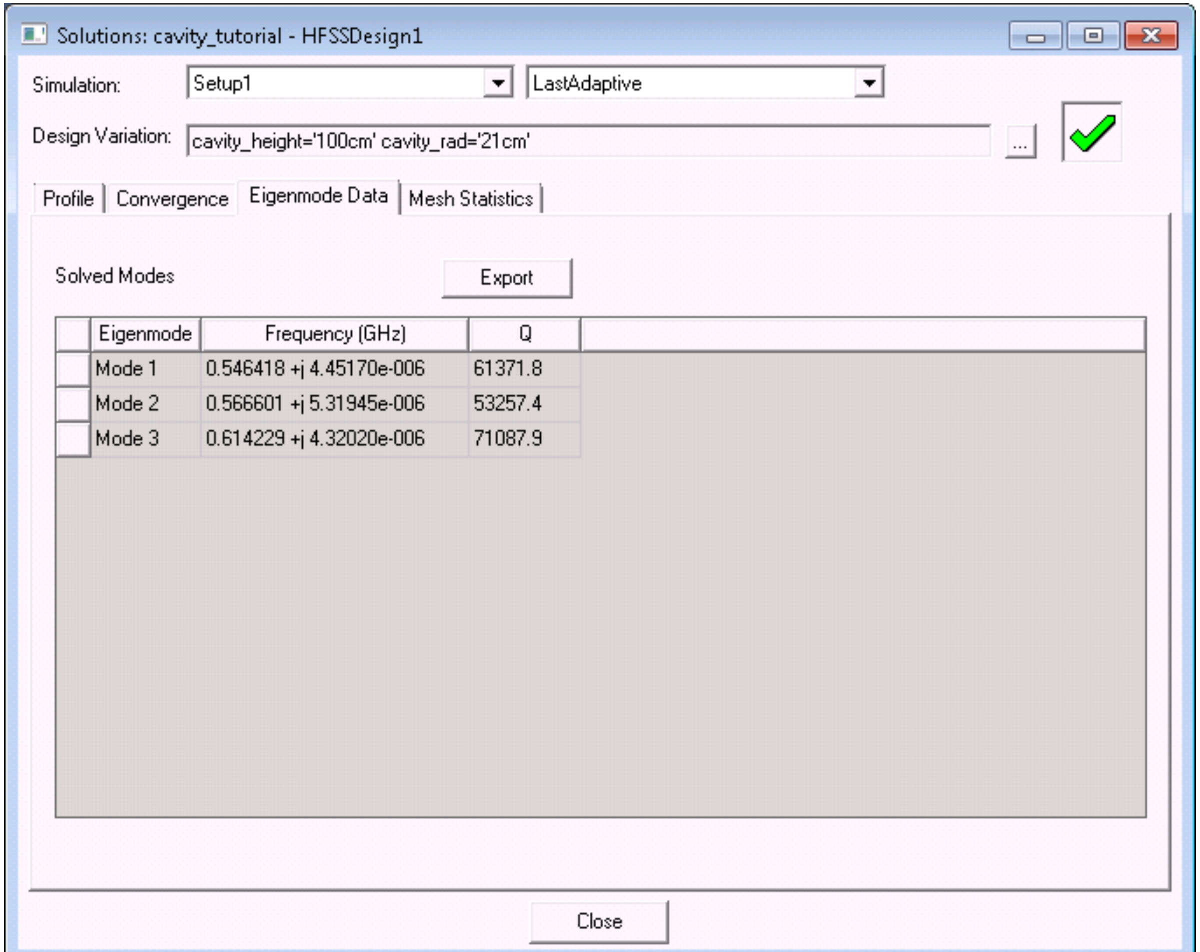
- Select ***HFSS > Results> Solution Data***



13: View Solution Data

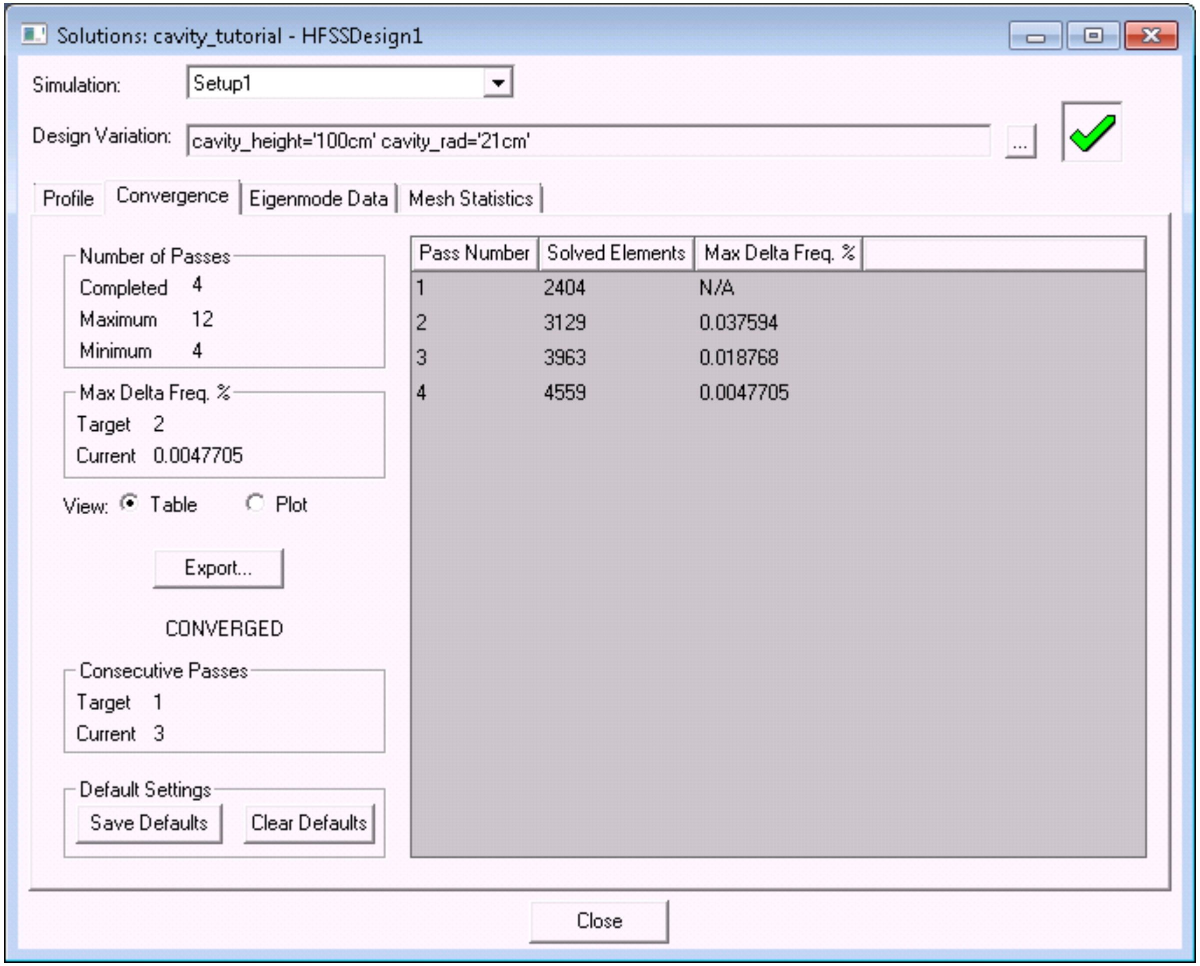
- Select ***Eigenmode Data*** tab to view modal frequencies and Q-factors

TM_{010}
TM_{011}
TE_{113}



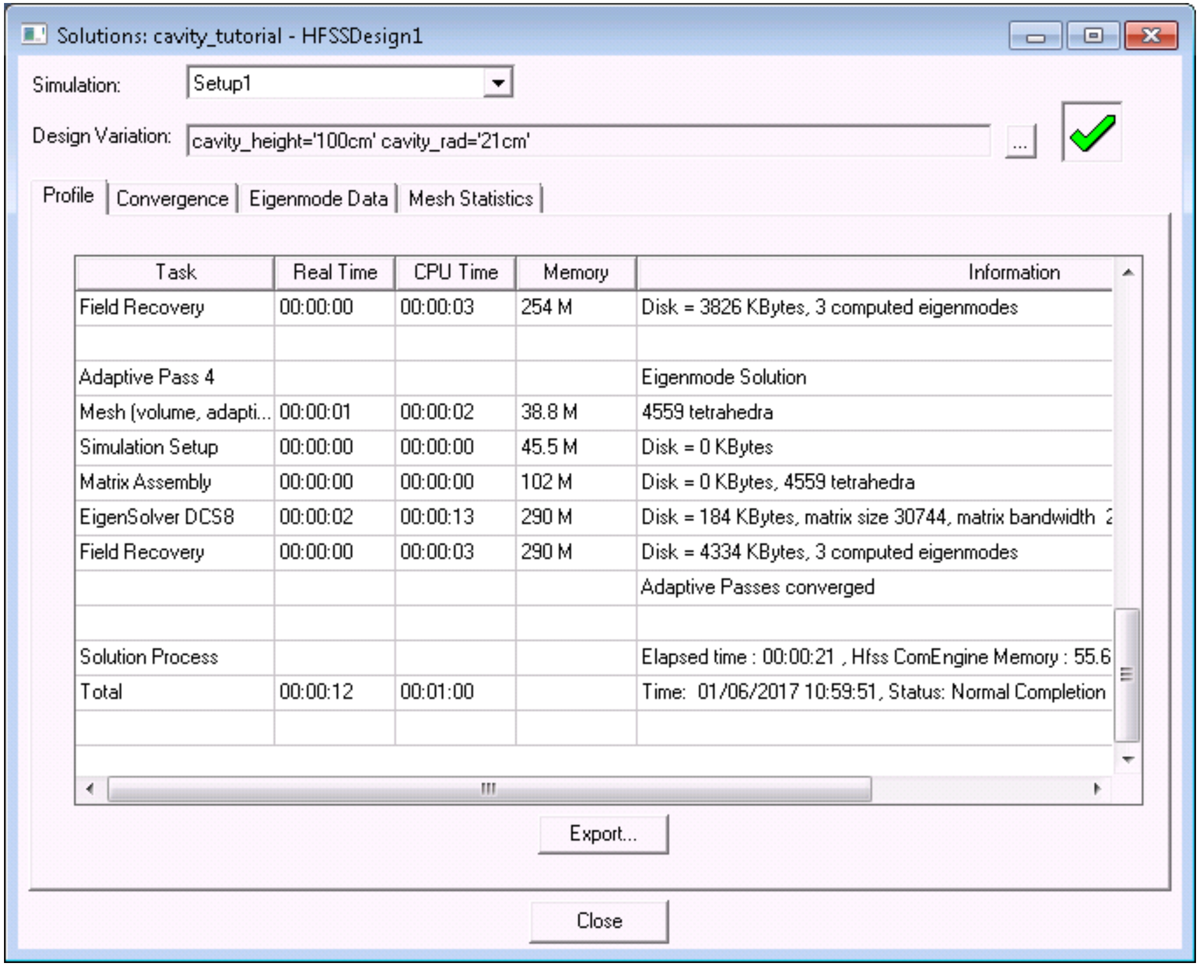
13: View Solution Data

- Select ***Convergence*** tab to view adaptive pass information



13: View Solution Data

- Select ***Profile*** tab to view run log file (21 sec runtime)



Task	Real Time	CPU Time	Memory	Information
Field Recovery	00:00:00	00:00:03	254 M	Disk = 3826 KBytes, 3 computed eigenmodes
Adaptive Pass 4				Eigenmode Solution
Mesh (volume, adapti...	00:00:01	00:00:02	38.8 M	4559 tetrahedra
Simulation Setup	00:00:00	00:00:00	45.5 M	Disk = 0 KBytes
Matrix Assembly	00:00:00	00:00:00	102 M	Disk = 0 KBytes, 4559 tetrahedra
EigenSolver DCS8	00:00:02	00:00:13	290 M	Disk = 184 KBytes, matrix size 30744, matrix bandwidth 2
Field Recovery	00:00:00	00:00:03	290 M	Disk = 4334 KBytes, 3 computed eigenmodes
				Adaptive Passes converged
Solution Process				Elapsed time : 00:00:21 , Hfss ComEngine Memory : 55.6
Total	00:00:12	00:01:00		Time: 01/06/2017 10:59:51, Status: Normal Completion

14: View E-Field Phase Animation

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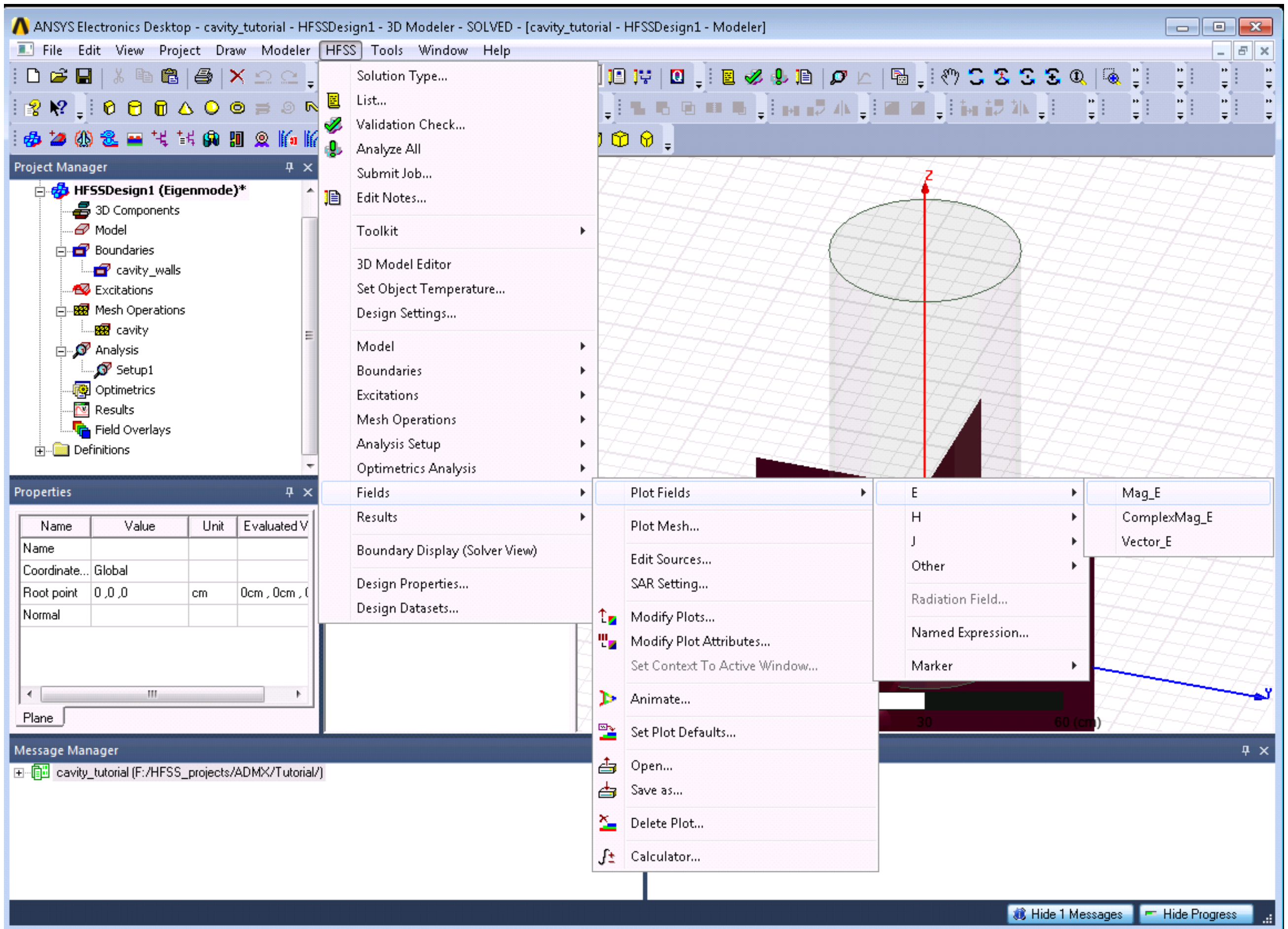
- Select XZ and YZ planes in 3D modeler tree and select ***HFSS > Fields > Plot Fields > E > Mag_E***



14: View E-Field Phase Animation

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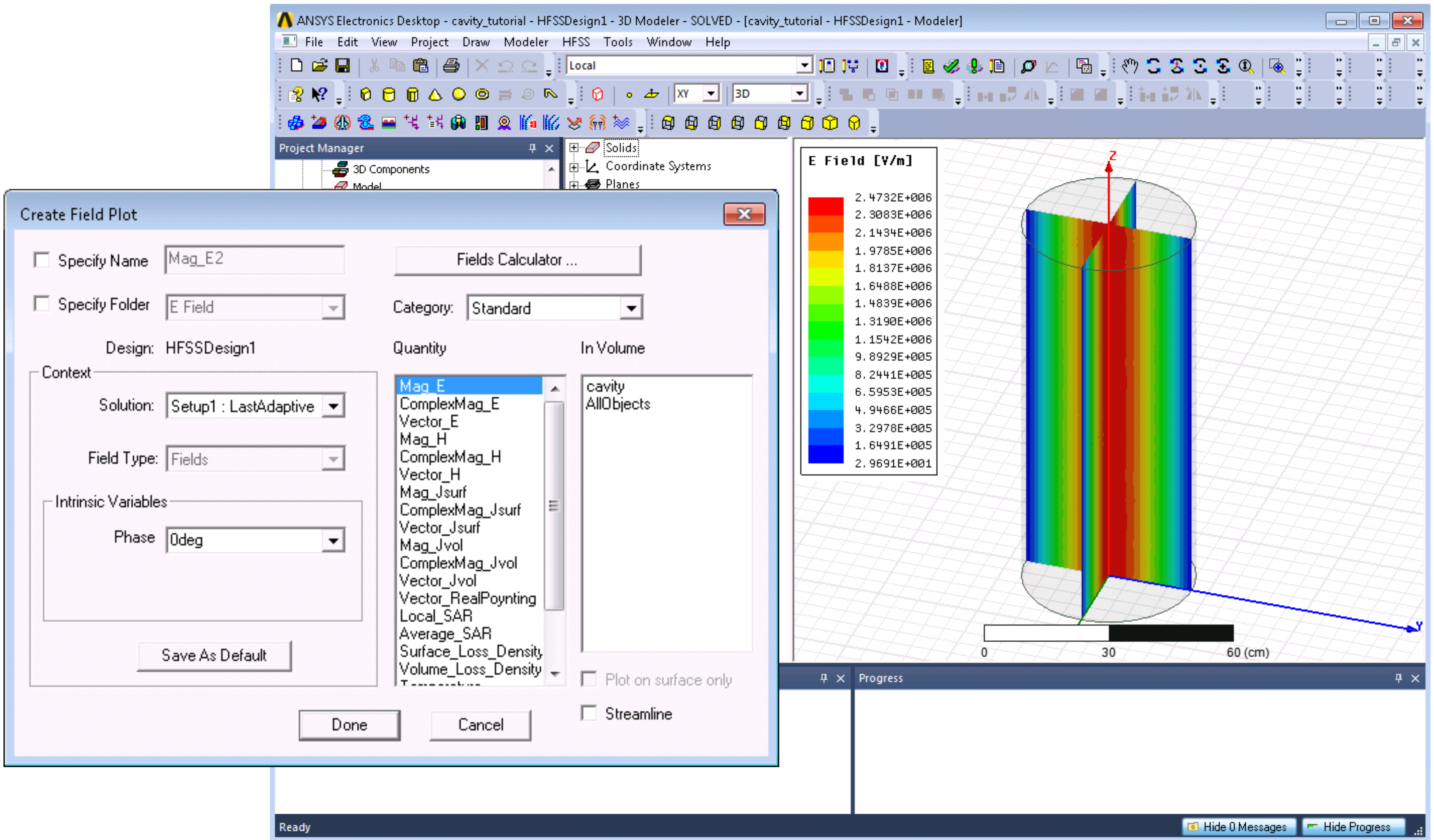
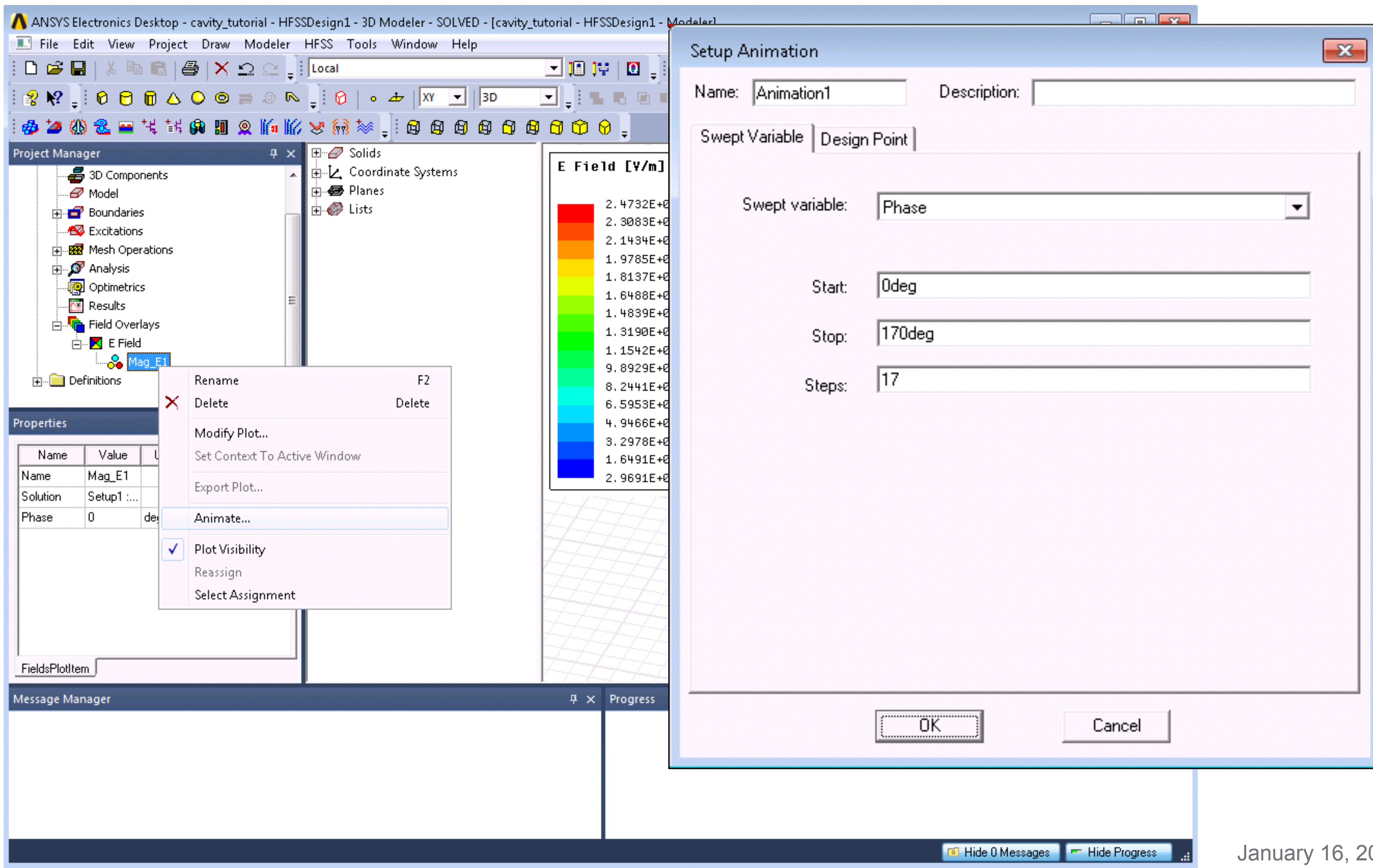
- Select Done to create plot of electric field magnitude



14: View E-Field Phase Animation

- Right-click on Mag_E1 plot to animate phasor field



15: View E-Field Vector Animation

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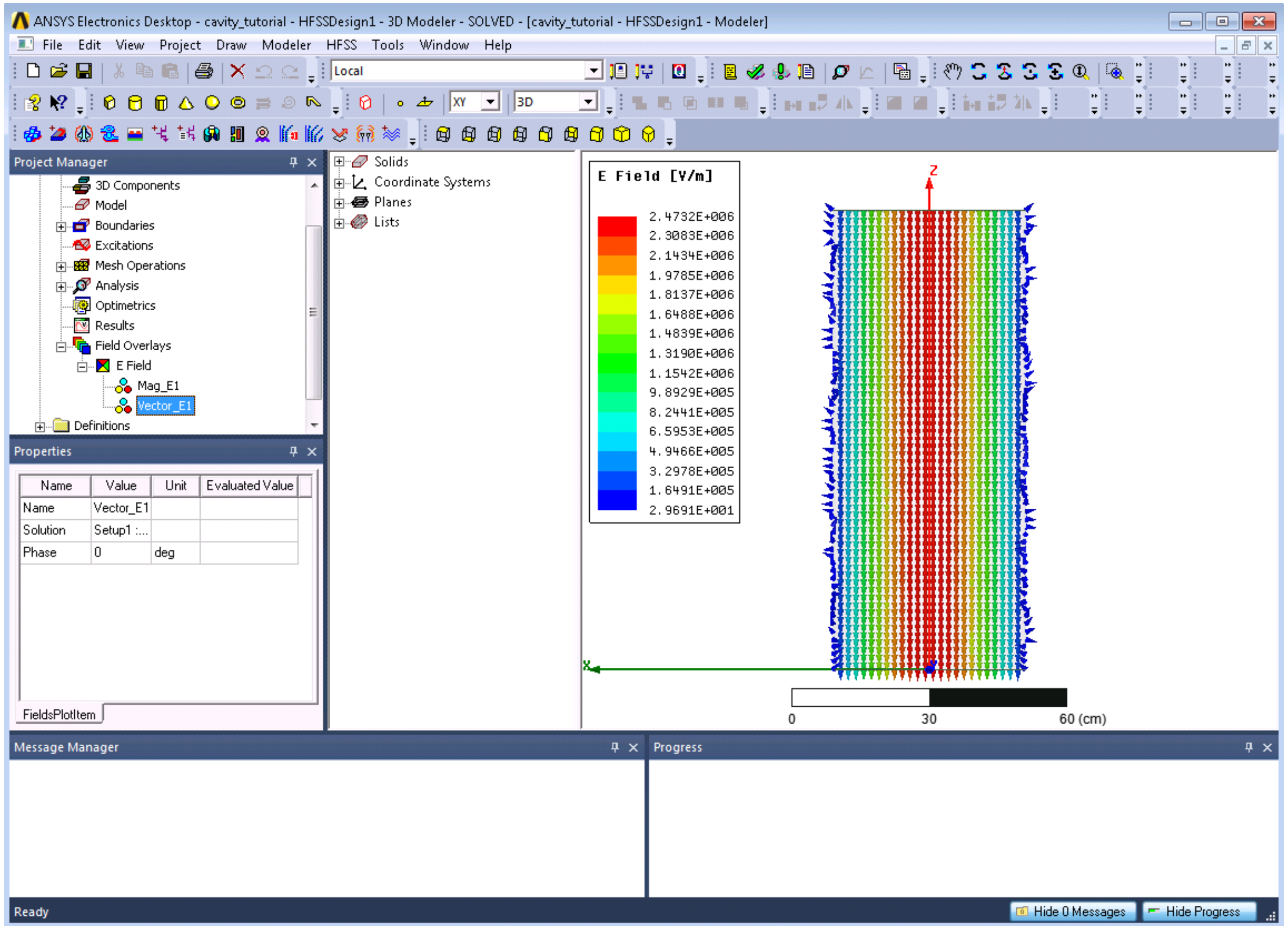
- Select XZ and YZ planes in 3D modeler tree and select ***HFSS > Fields > Plot Fields > E > Vector_E***



How to Activate Mode of Interest for Field Plots and Calculations

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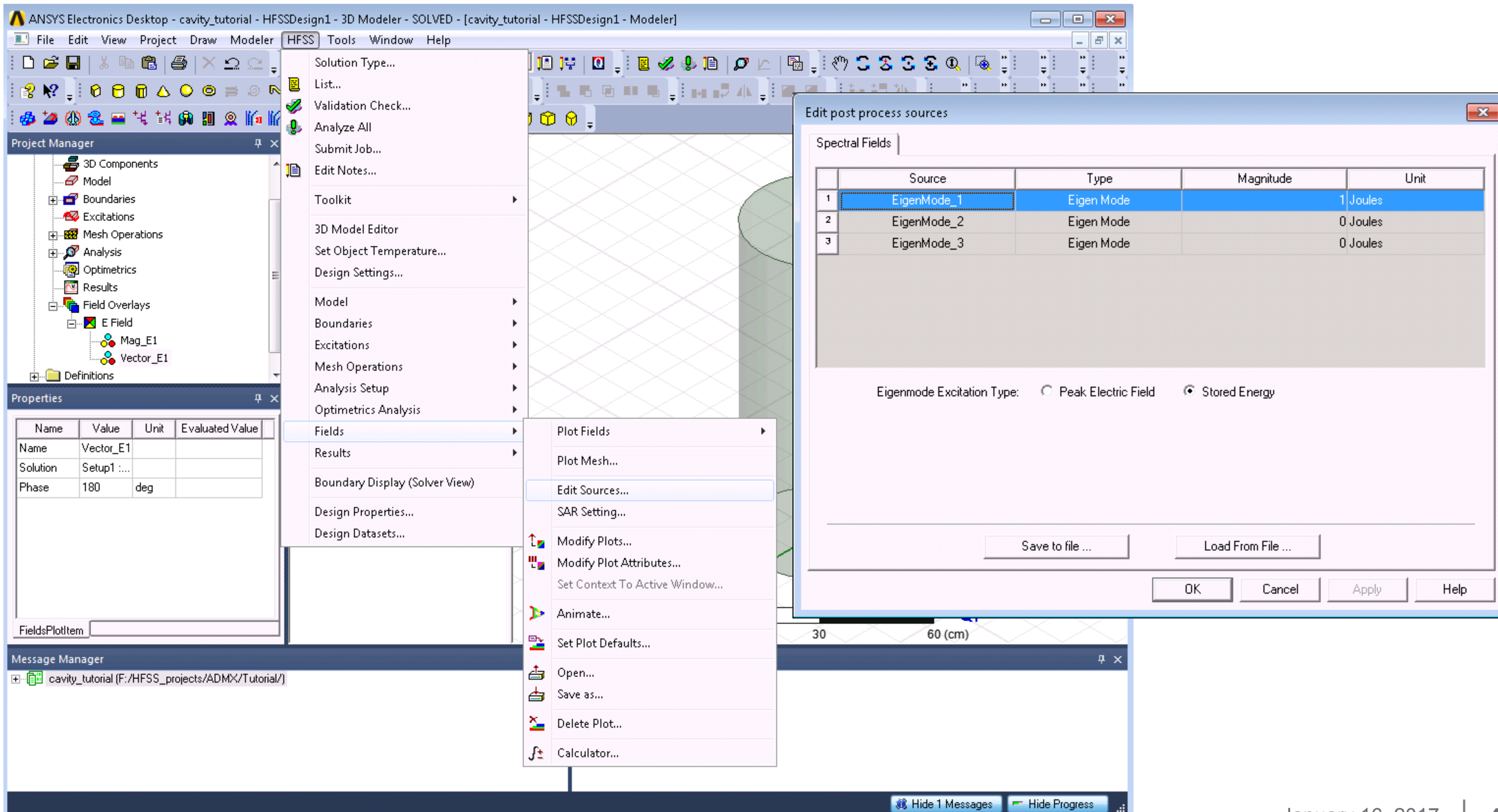
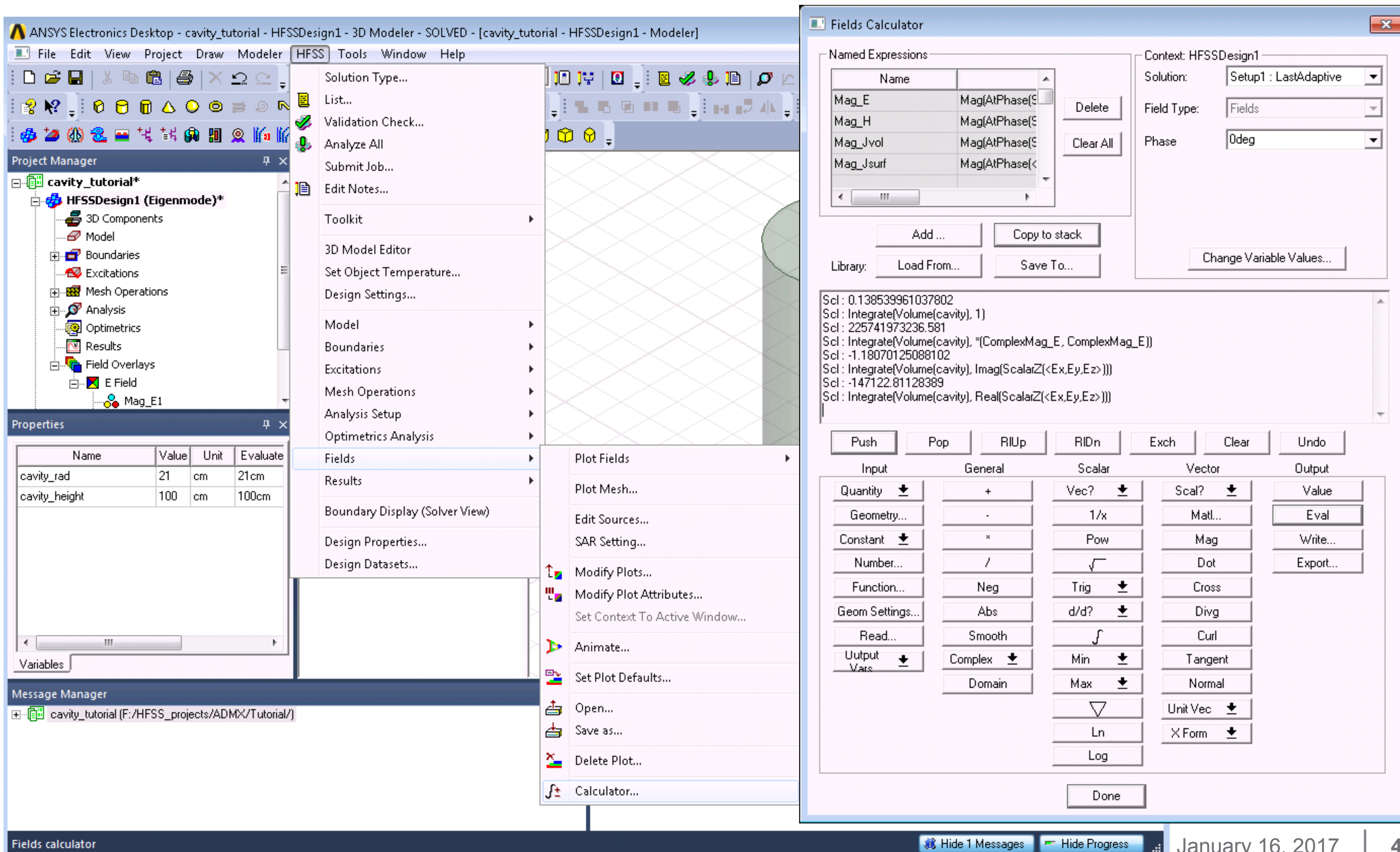
- Select ***HFSS > Fields > Edit Sources***



16: Calculate Form Factor

- Open field calculator using ***HFSS > Fields > Calculator***



16: Calculate Form Factor

- Calculate integral of real(E_z)
  - Quantity > E
  - Scal? > ScalarZ
  - Complex > Real
  - Geometry > Volume > cavity
  - Integrate, Eval
- Calculate integral of imag(E_z)
  - Quantity > E
  - Scal? > ScalarZ
  - Complex > Imag
  - Geometry > Volume > cavity
  - Integrate, Eval
- Calculate integral of $|E|^2$
  - Copy ComplexMag_E to stack
  - Push
  - Multiply (*)
  - Geometry > Volume > cavity
  - Integrate, Eval
- Calculate cavity volume
  - Number -> 1
  - Geometry > Volume > cavity
  - Integrate, Eval
- Form factor = $(147123^2+1.1807^2)$ / (0.1385*225741973237) = 0.692

$$\mathrm{C_E} = \frac{\left| \int dV_c \vec{E}_c \cdot \vec{\hat{z}} \right|^2}{V \int dV_c \mid E_c \mid^2}.$$

Fields Calculator

Named Expressions

Name	Expression
Surface_Force_Density	<SurfaceForceDensityx,SurfaceForceDensityy,SurfaceForceDensityz>
Ez	Abs(Integrate(Volume(Cylinder1), Real(ScalarZ(<Ex,Ey,Ez>))))
Etot	Integrate(Volume(Cylinder1), *(ComplexMag_E, ComplexMag_E))
V	Integrate(Volume(Cylinder1), 1)
Form_Factor	/(*(Ez, Ez), *(Etot, V))

Cavity Simulation Results

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- Good agreement between simulated and analytical results

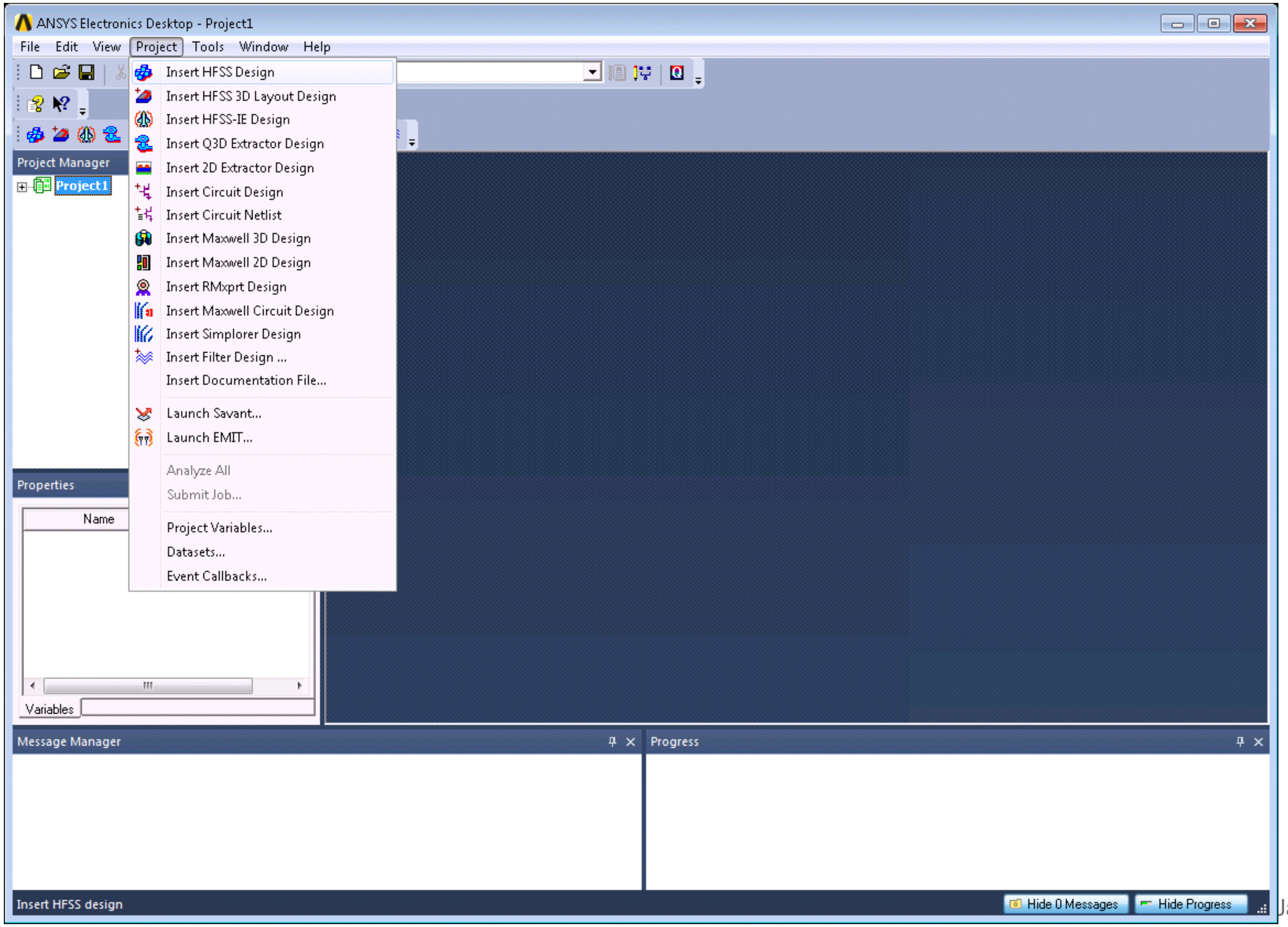
Quantity	Calculation	Simulation	% Difference
Frequency	546.42 MHz	546.42 MHz	0.00%
Unloaded Q-factor	61,391	61,372	0.03%
Form Factor	0.692	0.692	0.00%

$Q0= /?//2?i$

Dipole Antenna Example

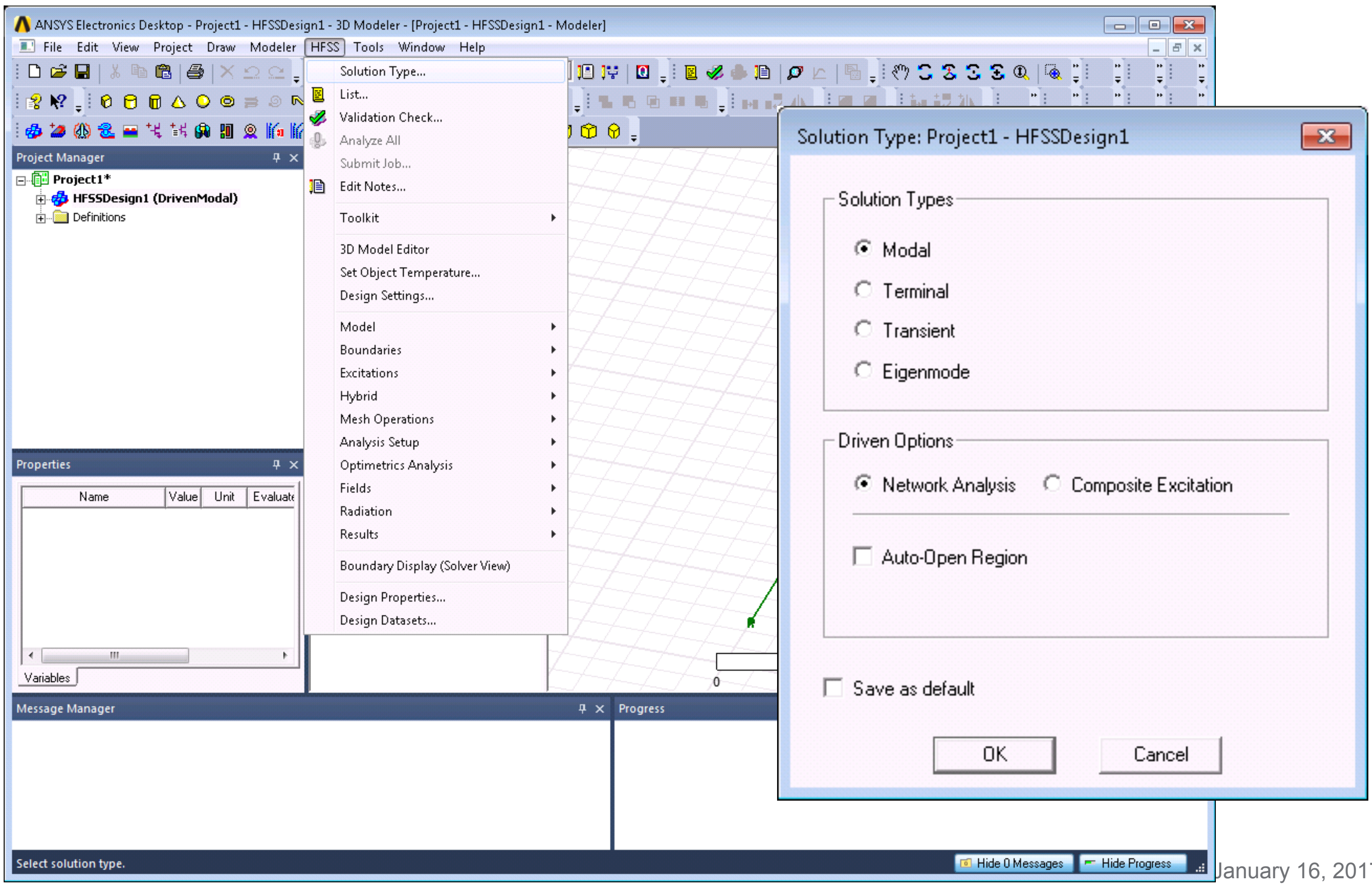
1: Create HFSS Project

- Insert into Electronics Desktop using ***Project > Insert HFSS Design***



2: Set Driven Modal Solution Type

- Select ***HFSS > Solution Type > Modal***



3: Set Model Units

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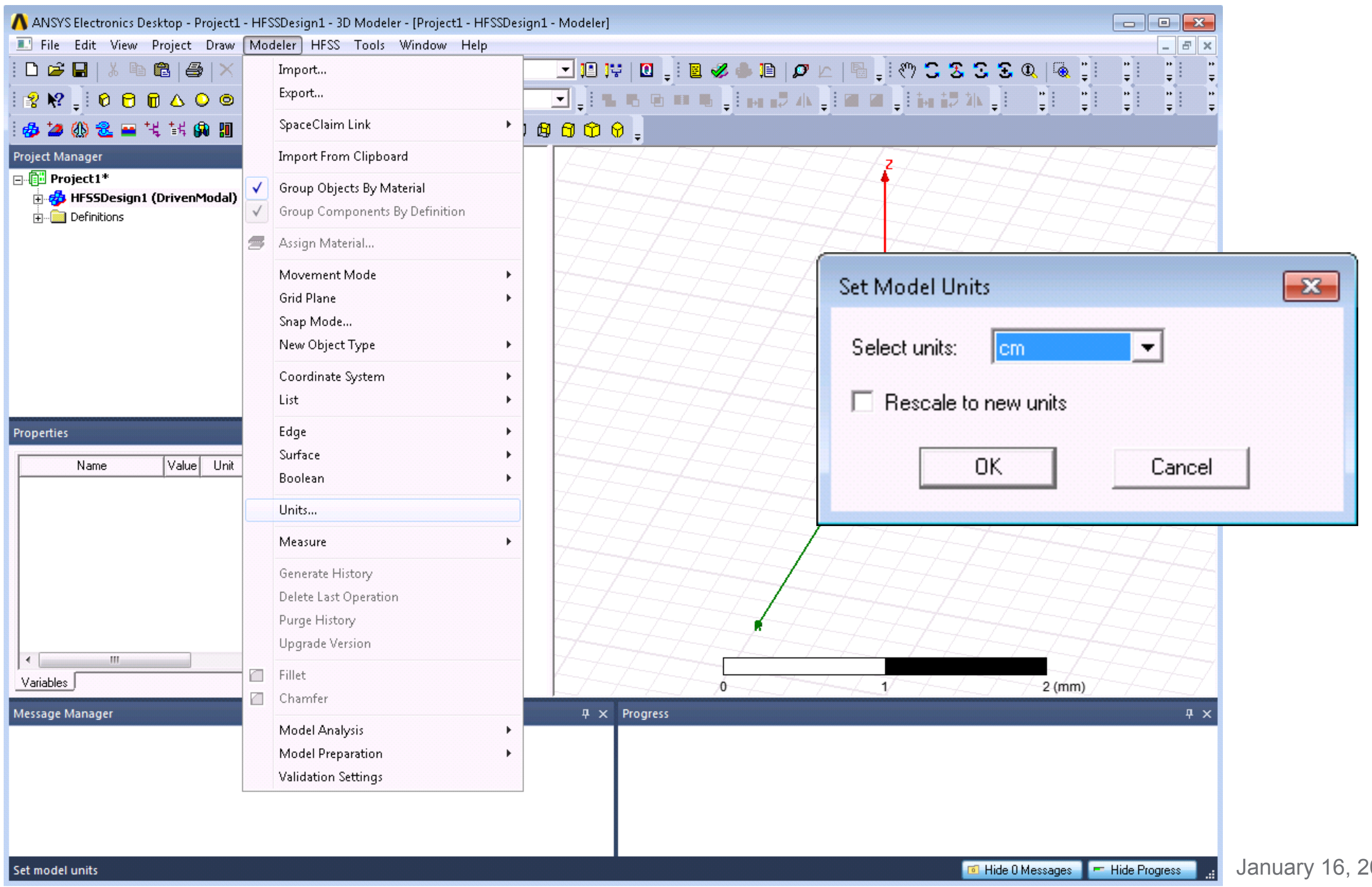
- Select ***Modeler > Units > cm***



4: Set Dialog Data Entry Mode

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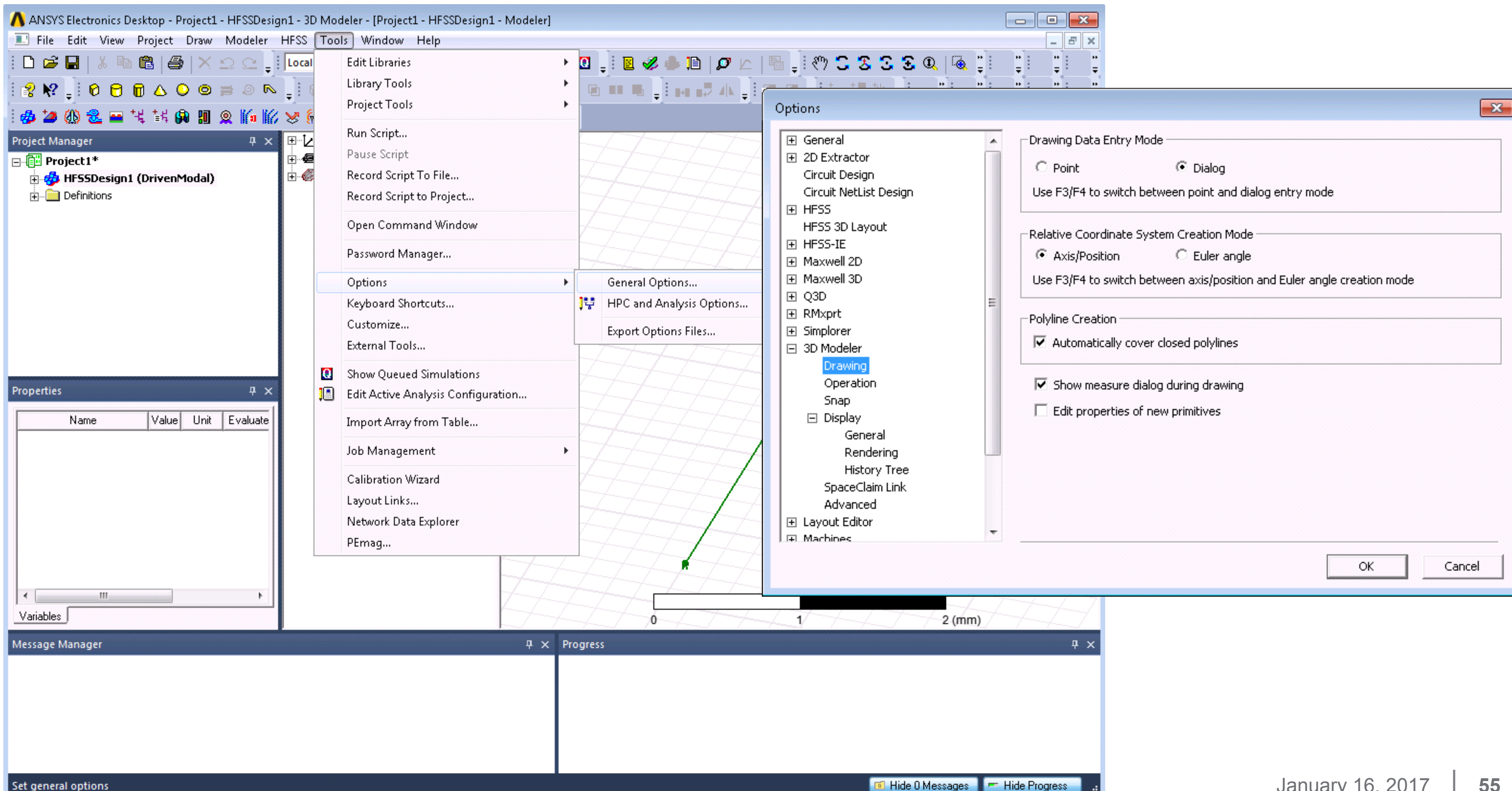
- Select ***Tools > Options > General Options > 3D Modeler > Drawing > Dialog***



5: Set Default Transparency of 0.7

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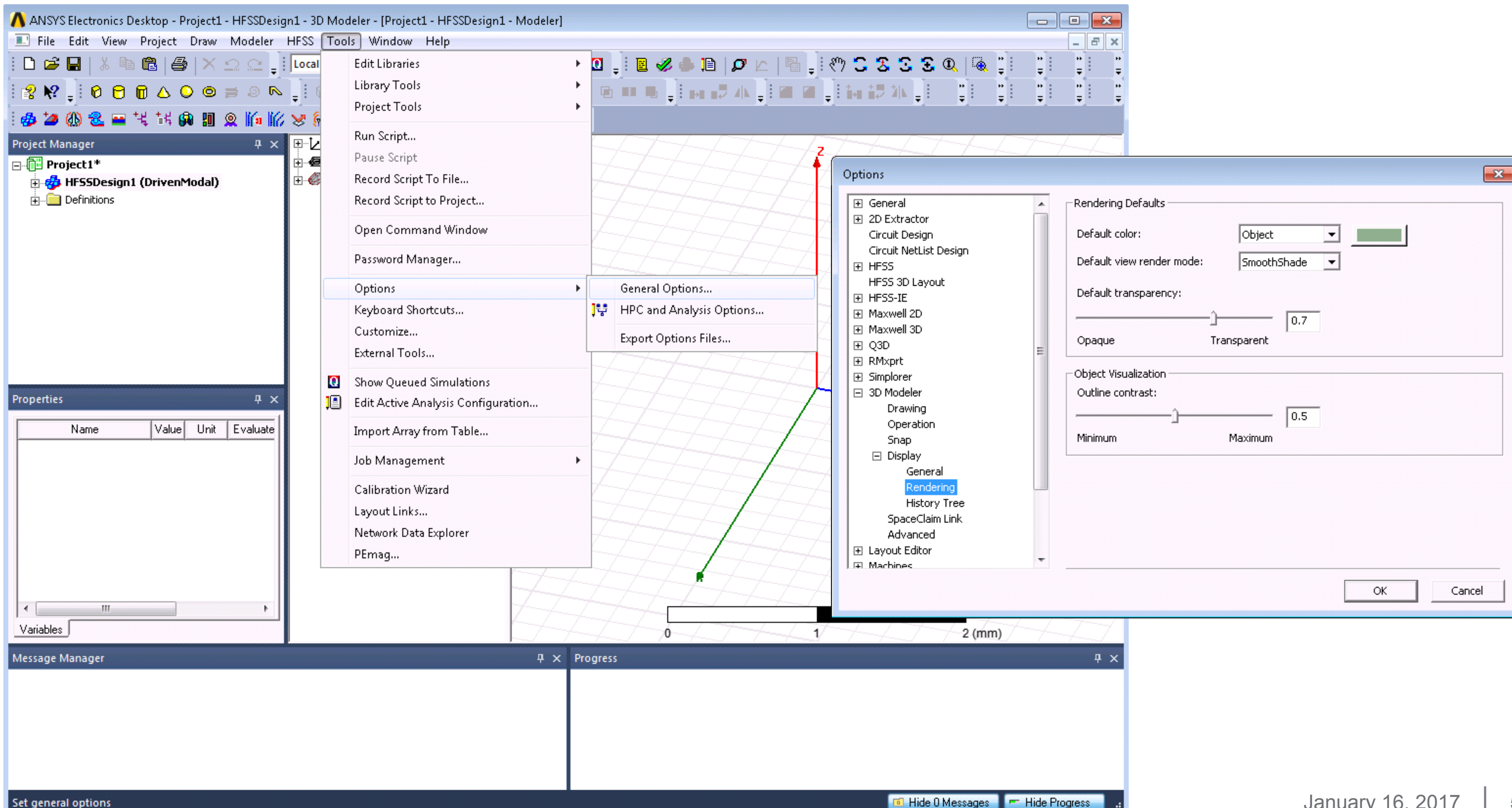
- Select ***Tools > Options > General Options > Display > Rendering***



6: Create Parameterized Antenna

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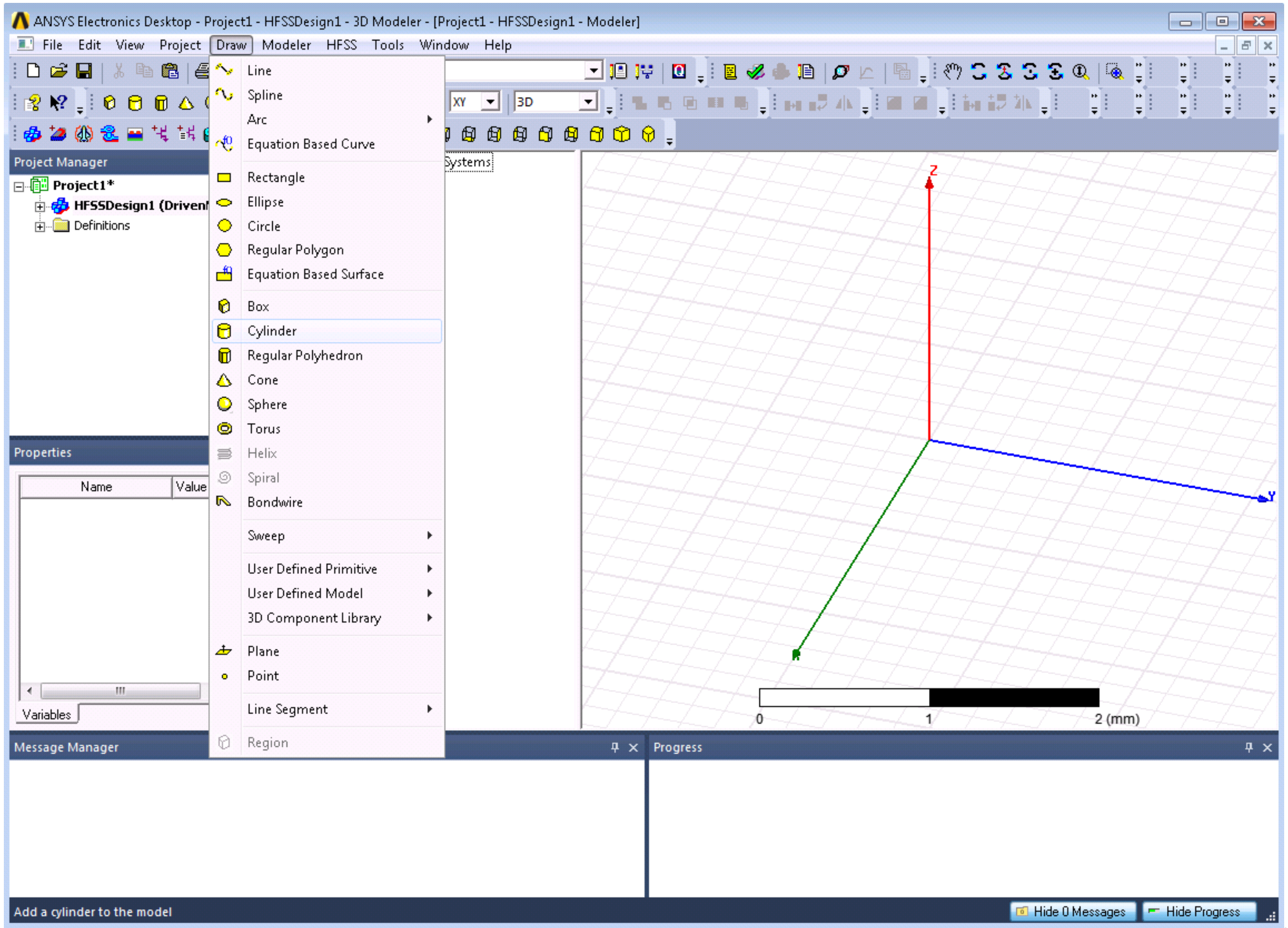
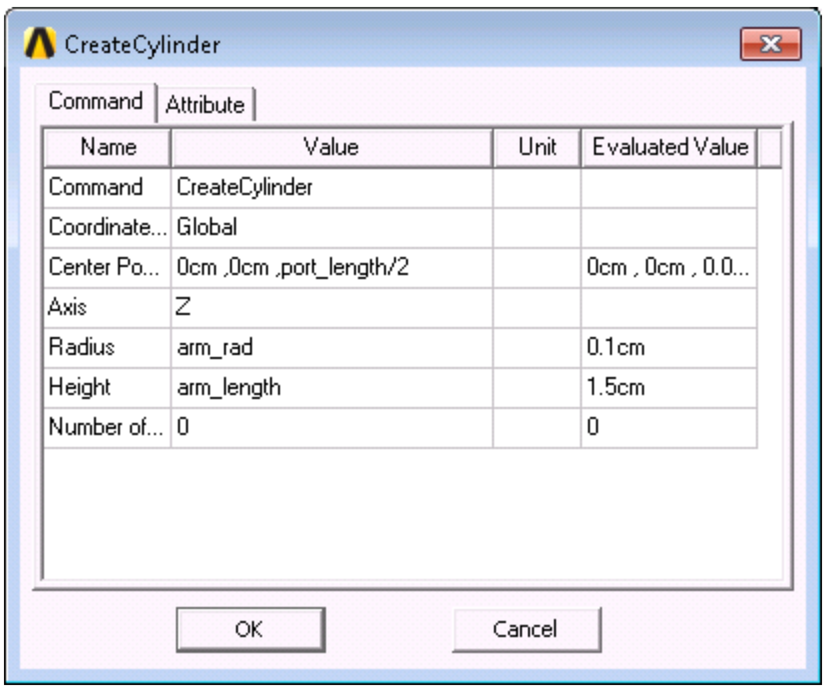
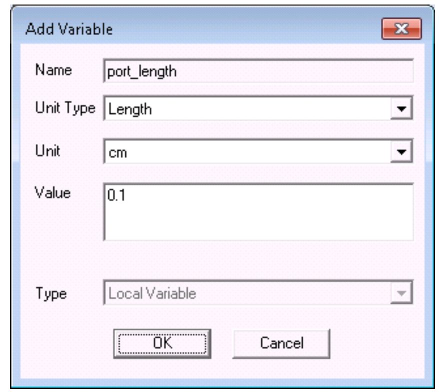
- Select ***Draw > Cylinder***

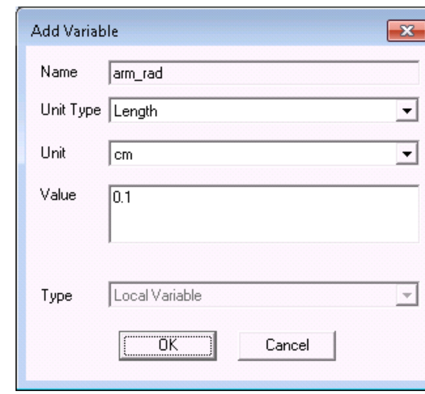


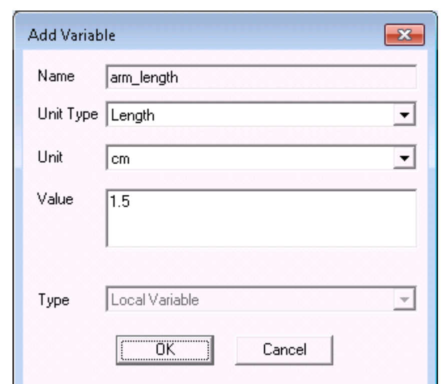
6: Create Parameterized Antenna

- port_length = 0.1 cm
- arm_rad = 0.1 cm
- arm_length = 1.5 cm



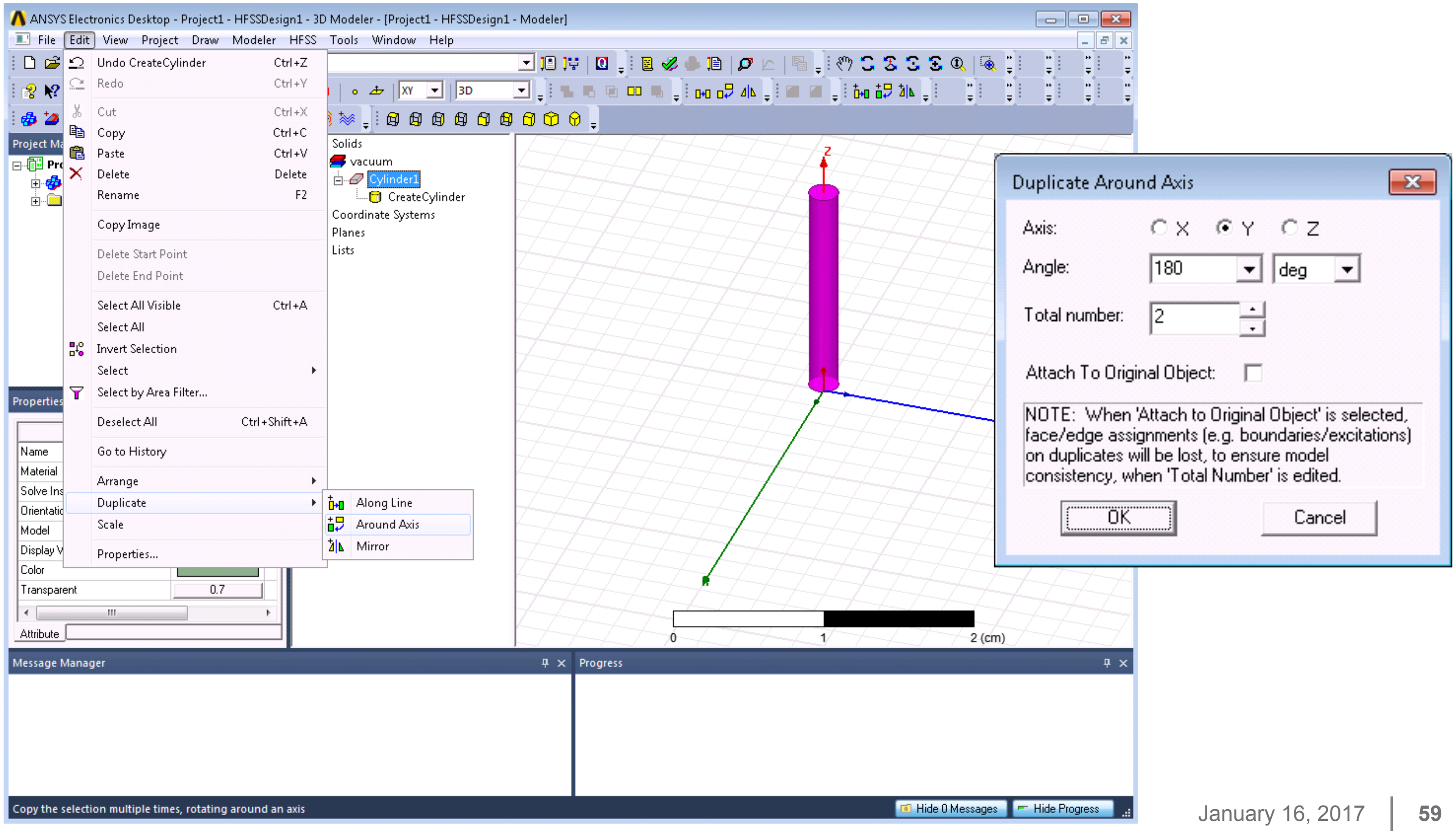






6: Create Parameterized Antenna

- Select Cylinder1 in 3D modeler tree and ***Edit > Duplicate > Around Axis***
- Axis = y-axis, Angle = 180 degrees, Total number = 2



7: Assign Material to Antenna

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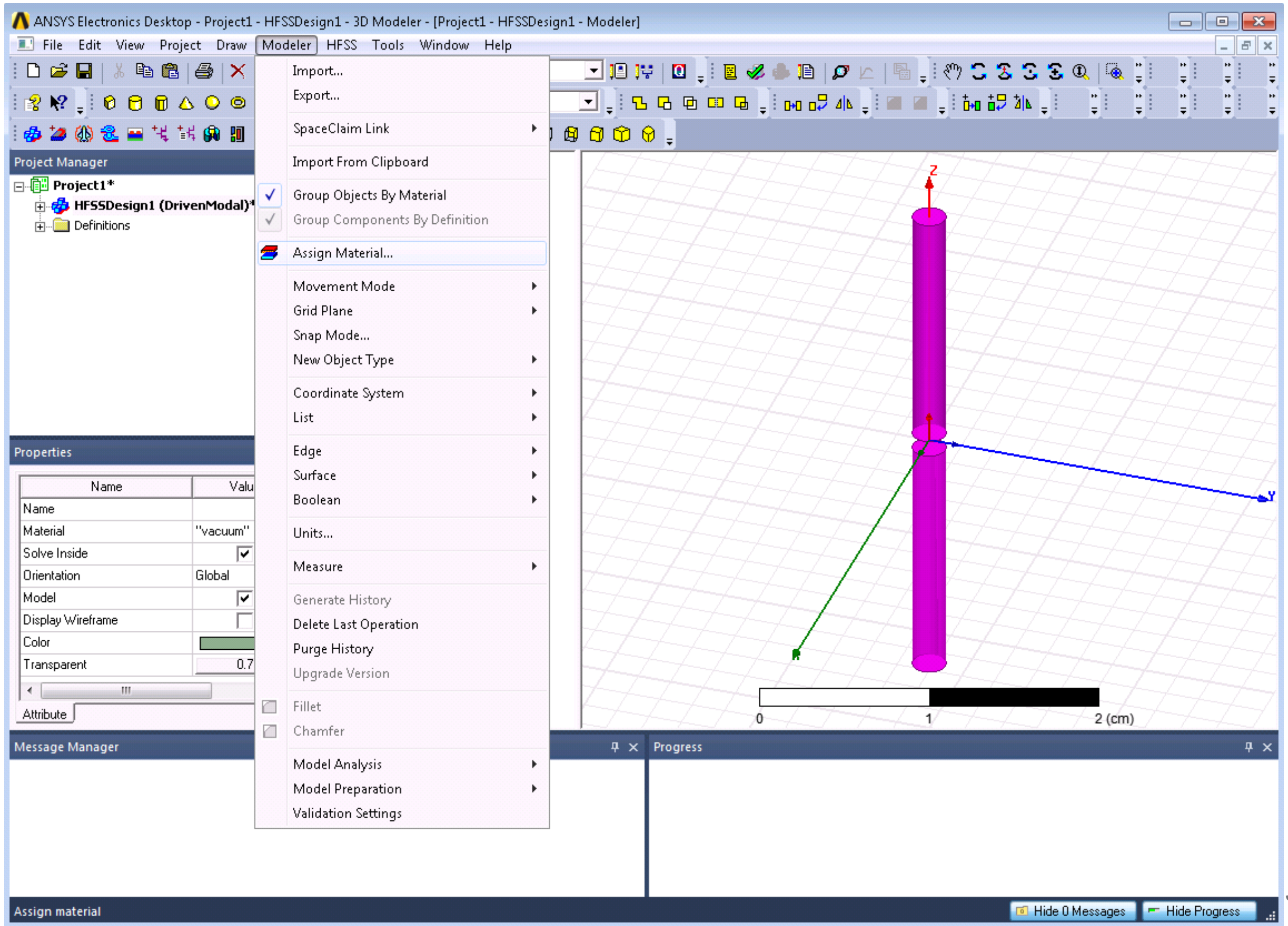
- Select Cylinder1 and Cylinder1_1 in 3D modeler tree
- Select ***Modeler > Assign Material***



7: Assign Material to Antenna

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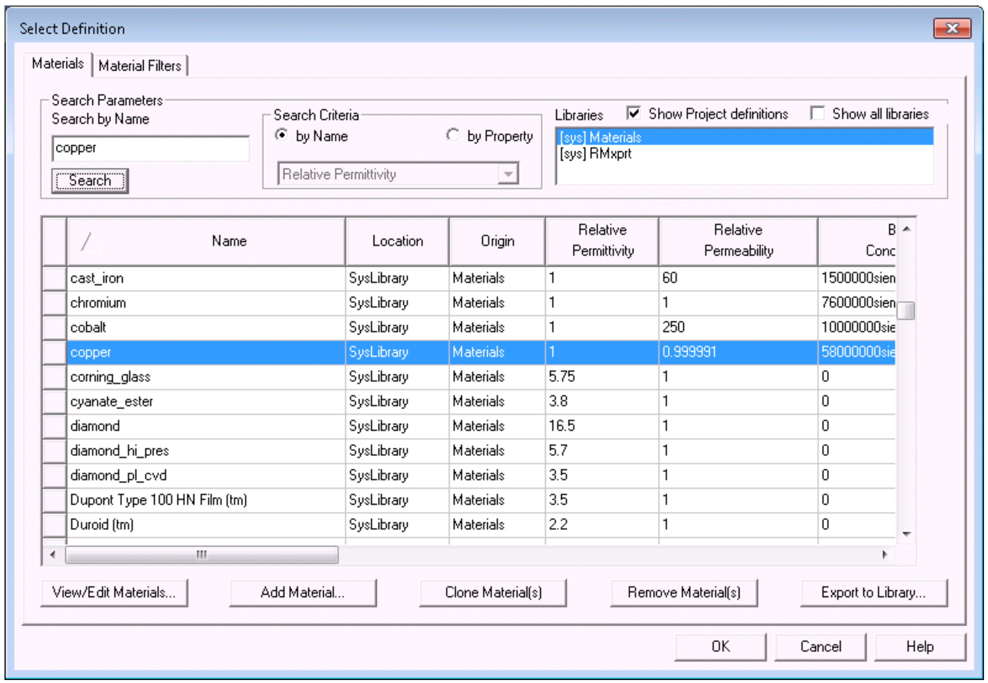
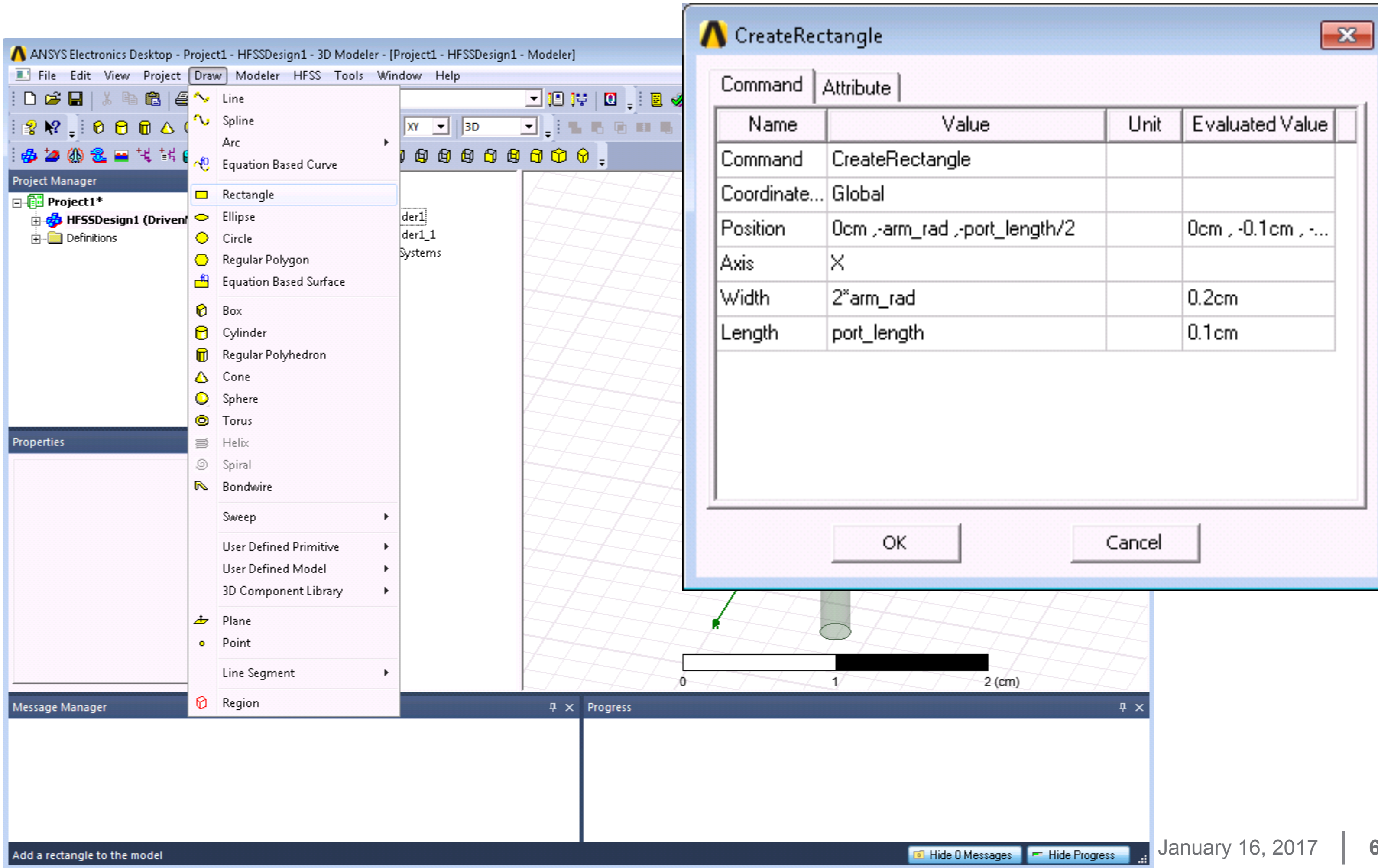
- Enter “copper” in Search field of Materials Database and press OK



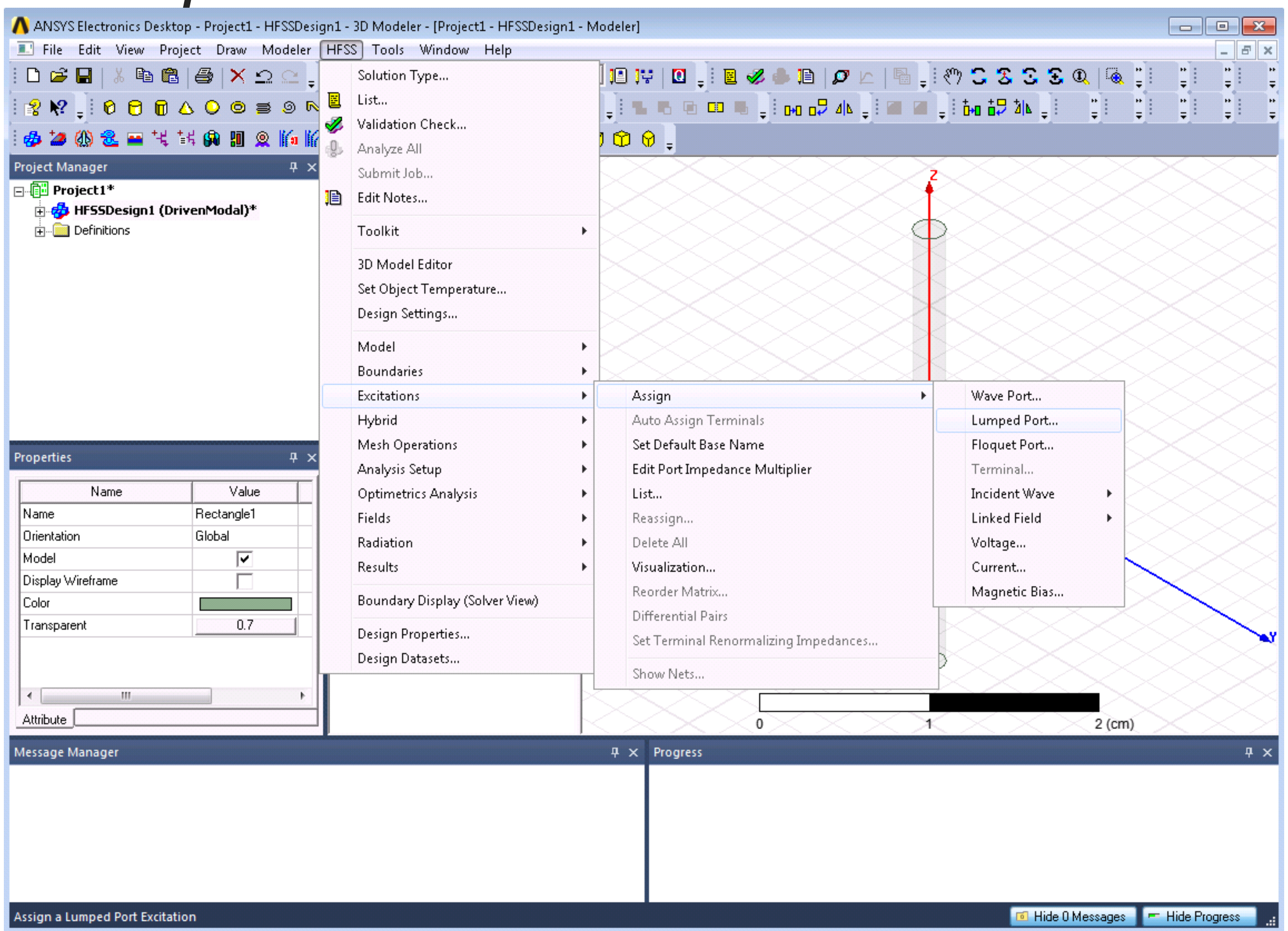
8: Create Port

- Select **Draw > Rectangle**



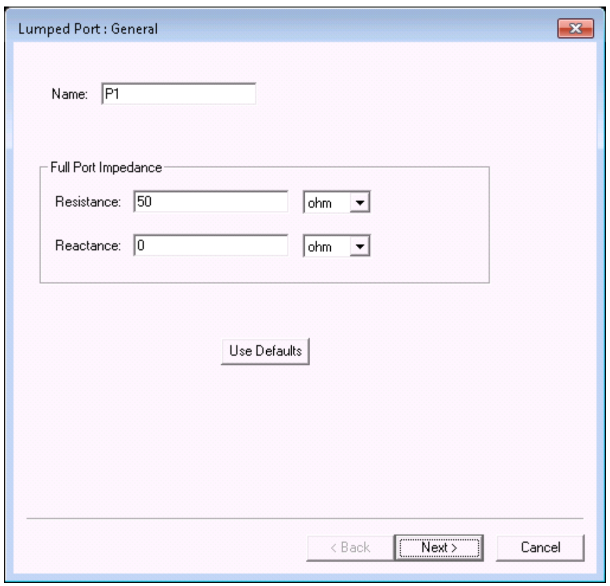
8: Create Port

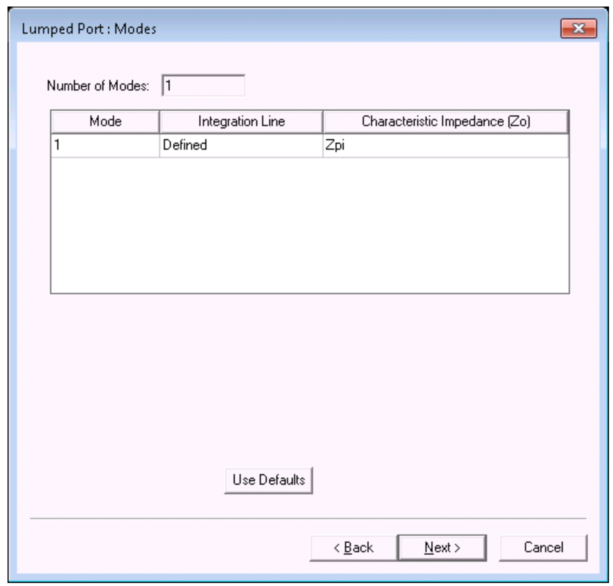
- Select Rectangle1 in 3D modeler tree and then ***HFSS > Excitations > Assign > Lumped Port***

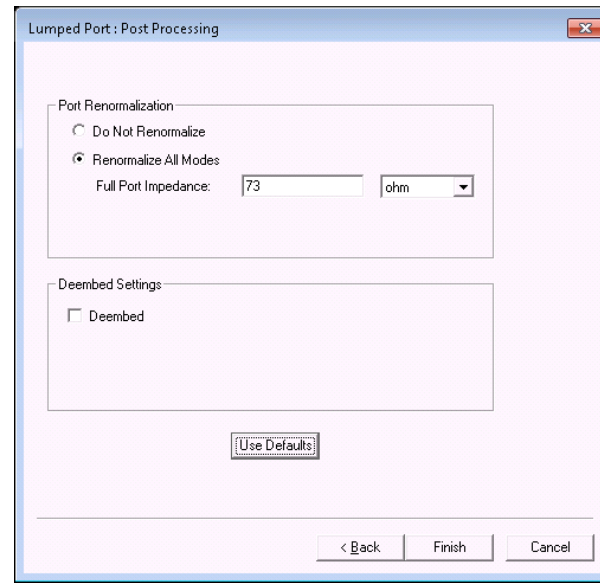


8: Create Port

- Name Port P1
- Draw integration line along center of port between antenna arms
- Enter 73 Ohms for renormalization impedance







8: Create Port

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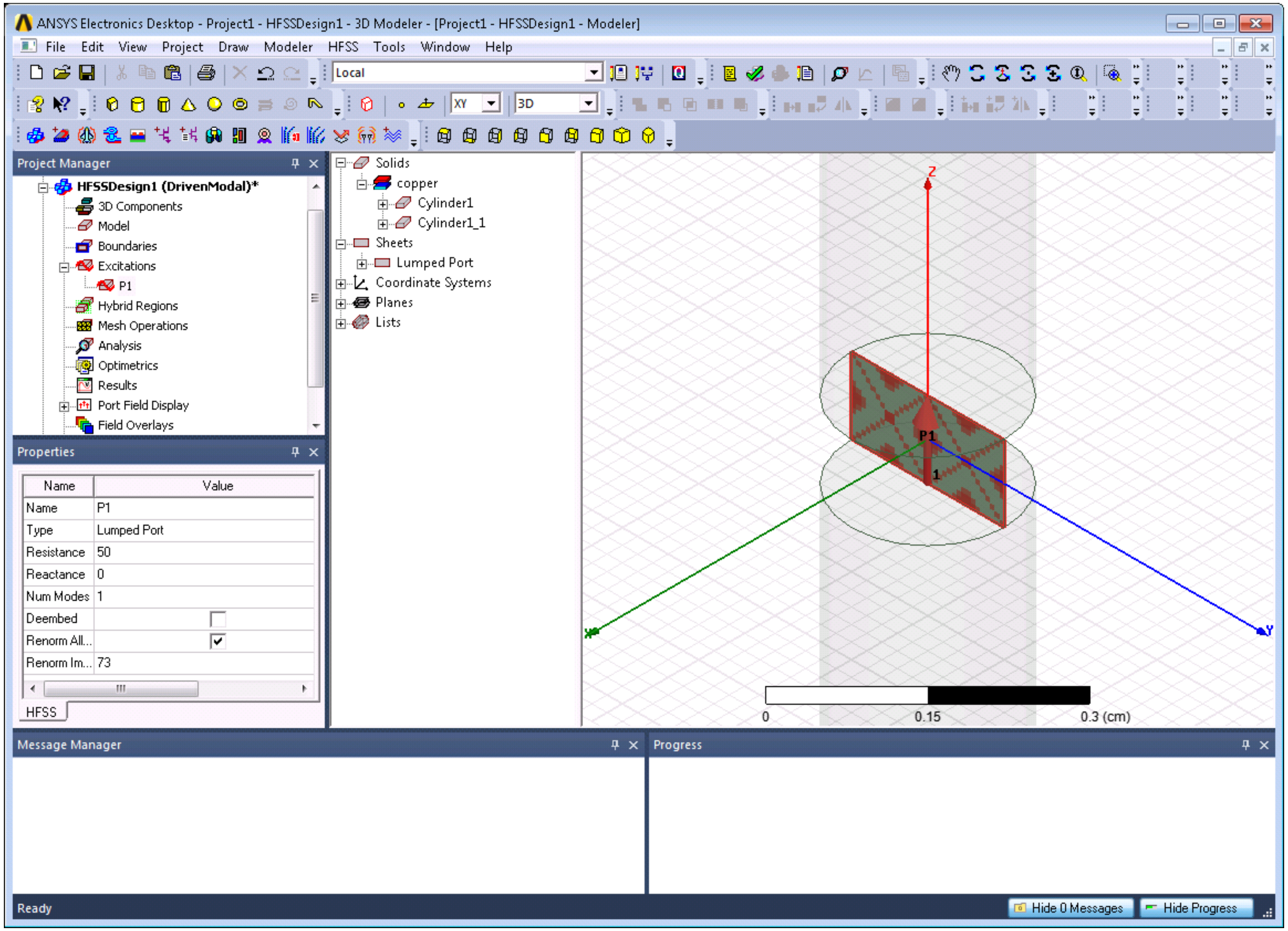
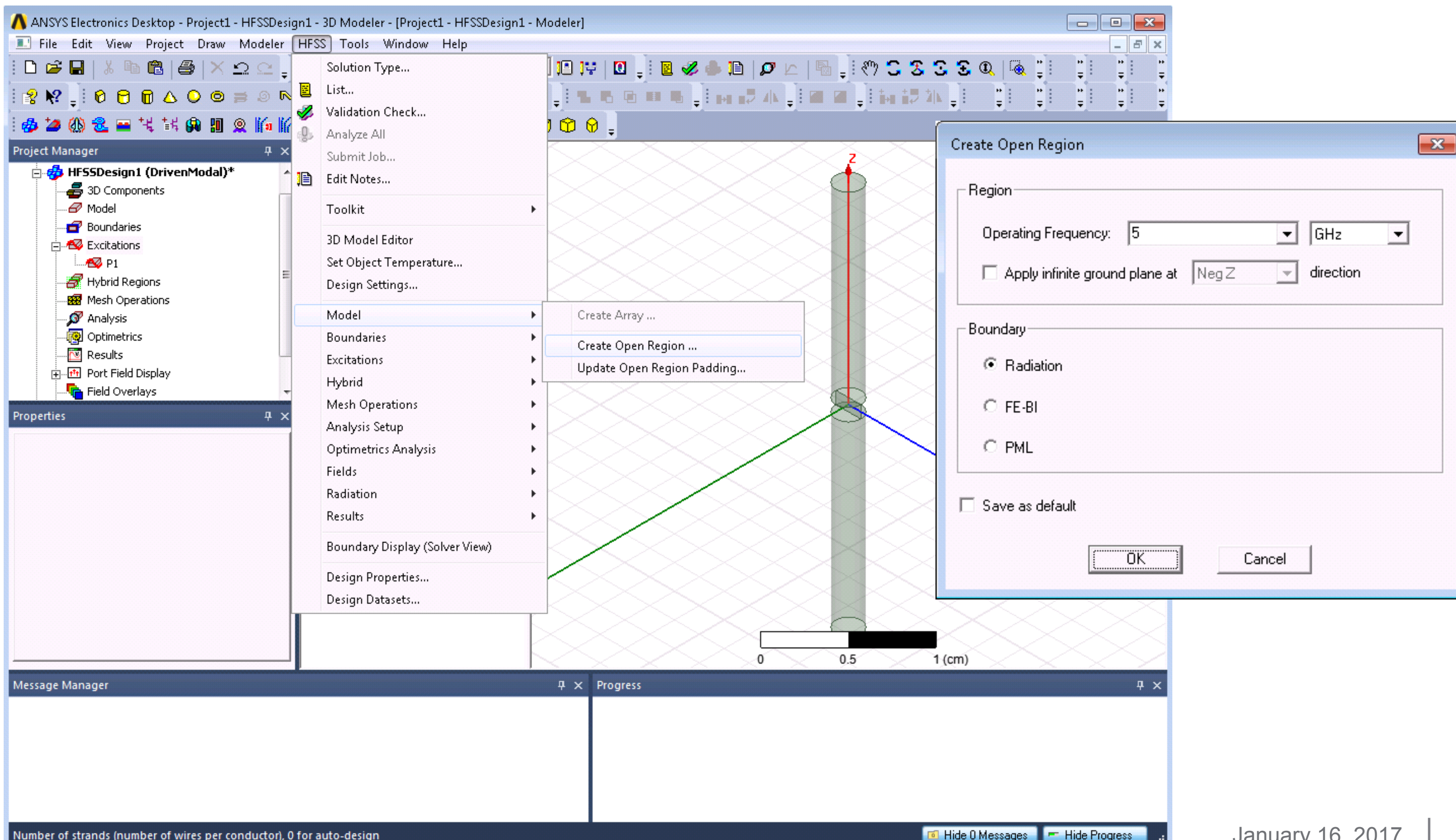
- Should have port assignment as shown below



9: Create Open Region

- Select ***HFSS > Model > Create Open Region***
- Enter Operating Frequency = 5 GHz and Radiation Boundary



9: Create Open Region

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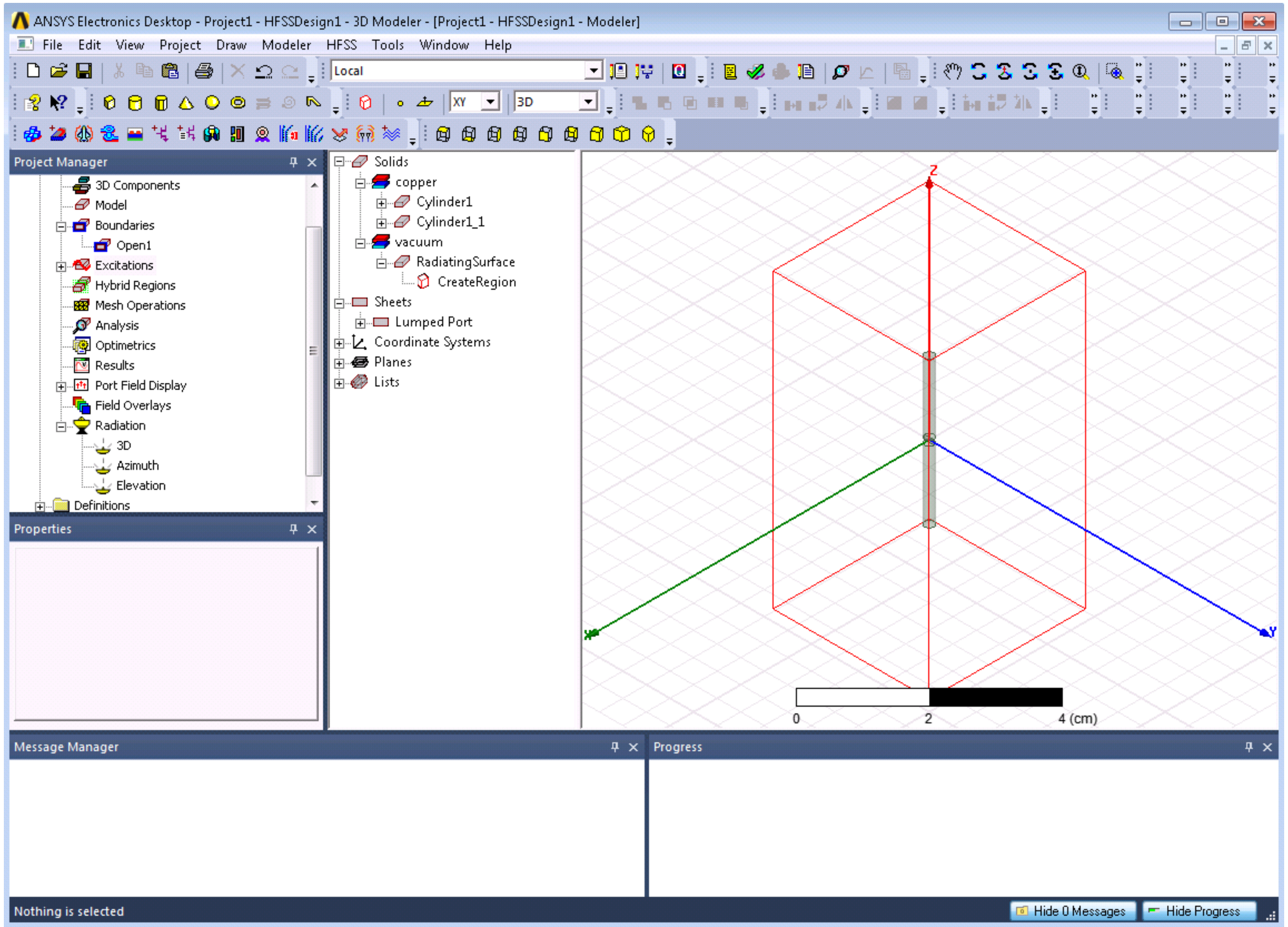
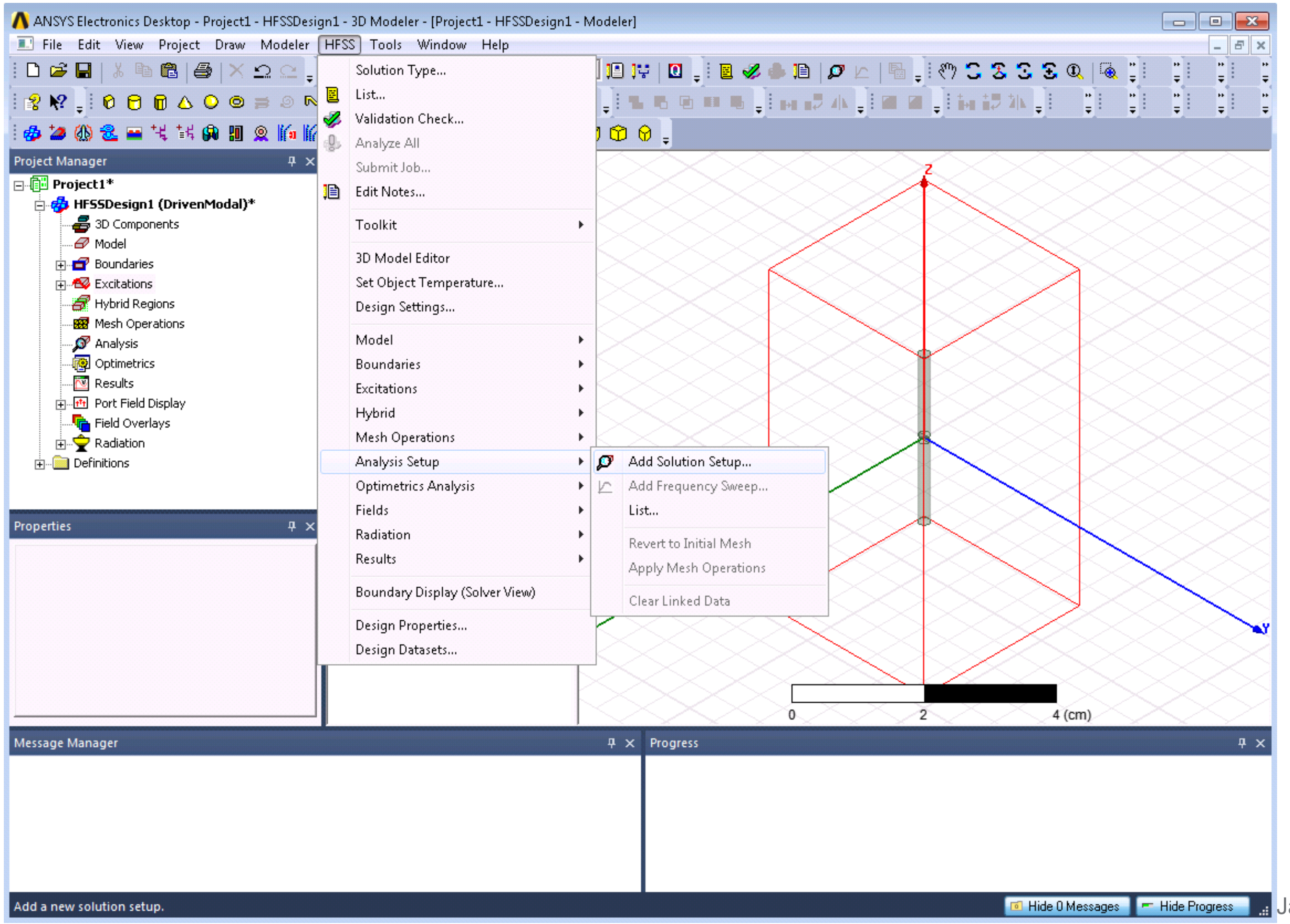
- Should have radiation boundary and far-field setups as shown below



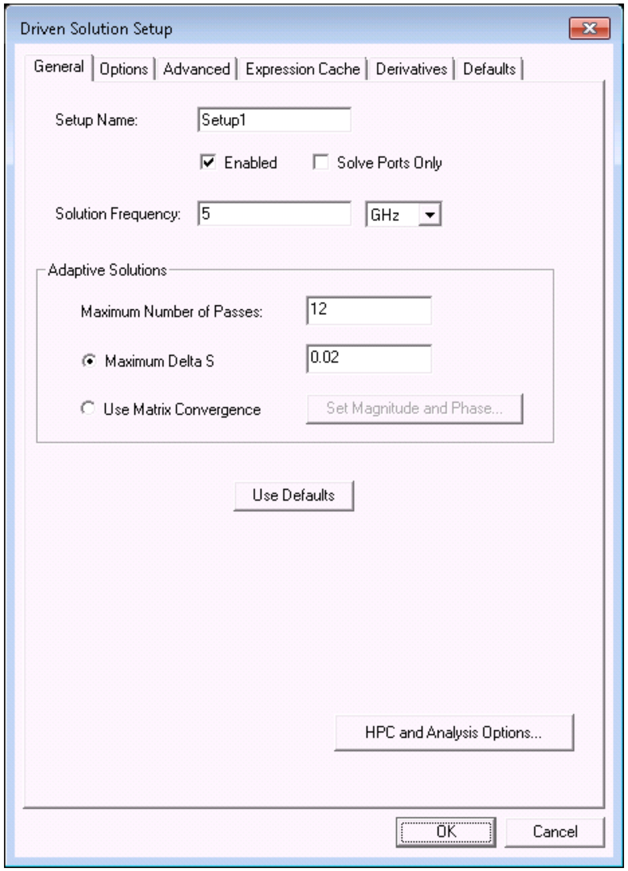
10: Add Solution Setup

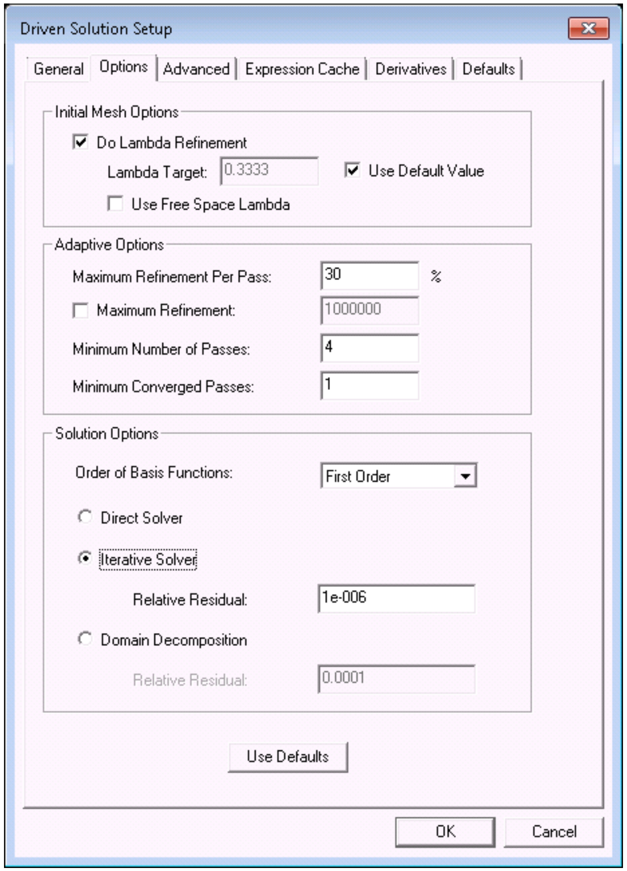
- Select ***HFSS > Analysis Setup > Add Solution Setup***



10: Add Solution Setup

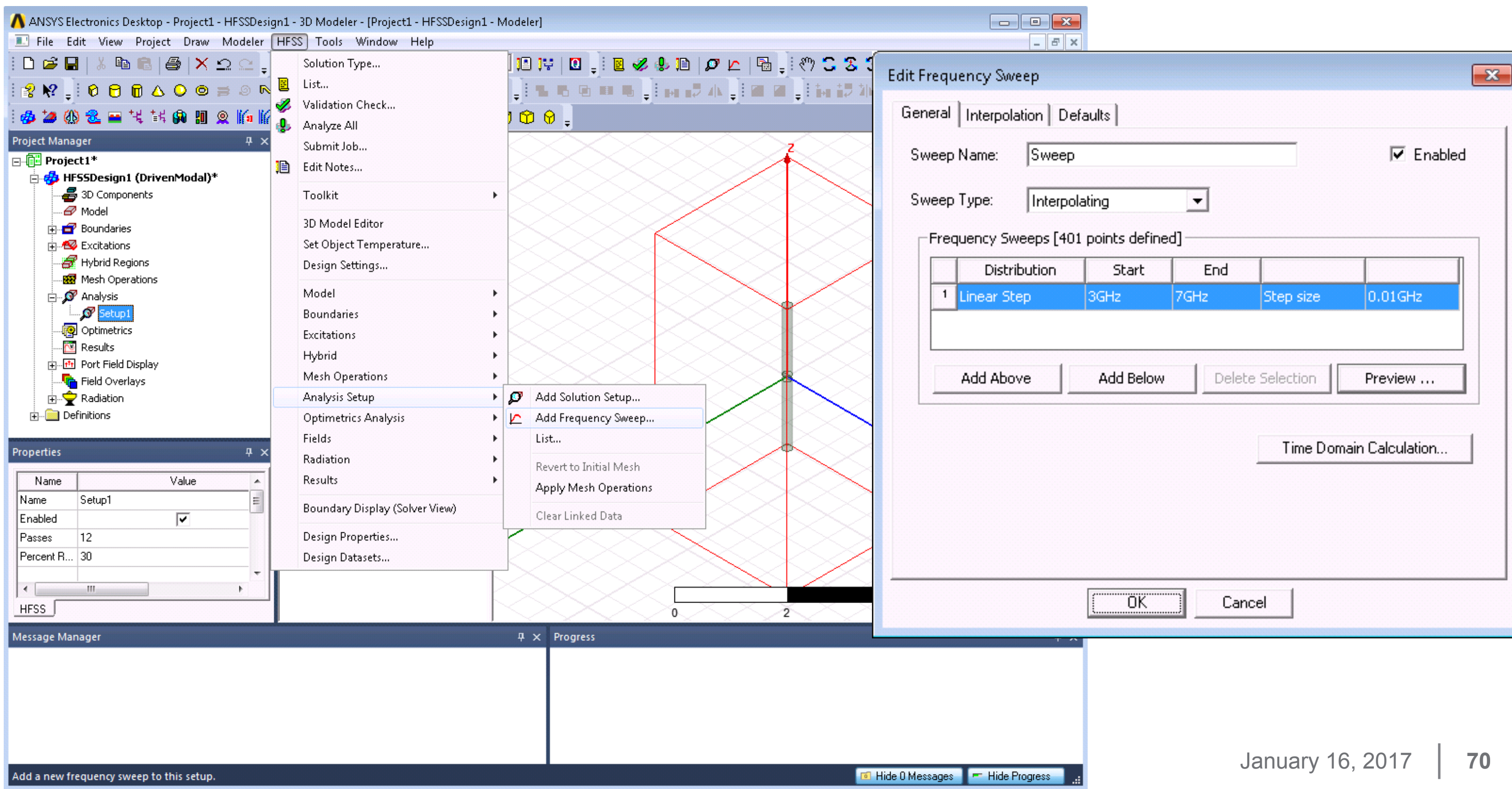
- Solution Frequency = 5 GHz, Maximum Passes = 12, Minimum Passes = 4
- Select Iterative Solver





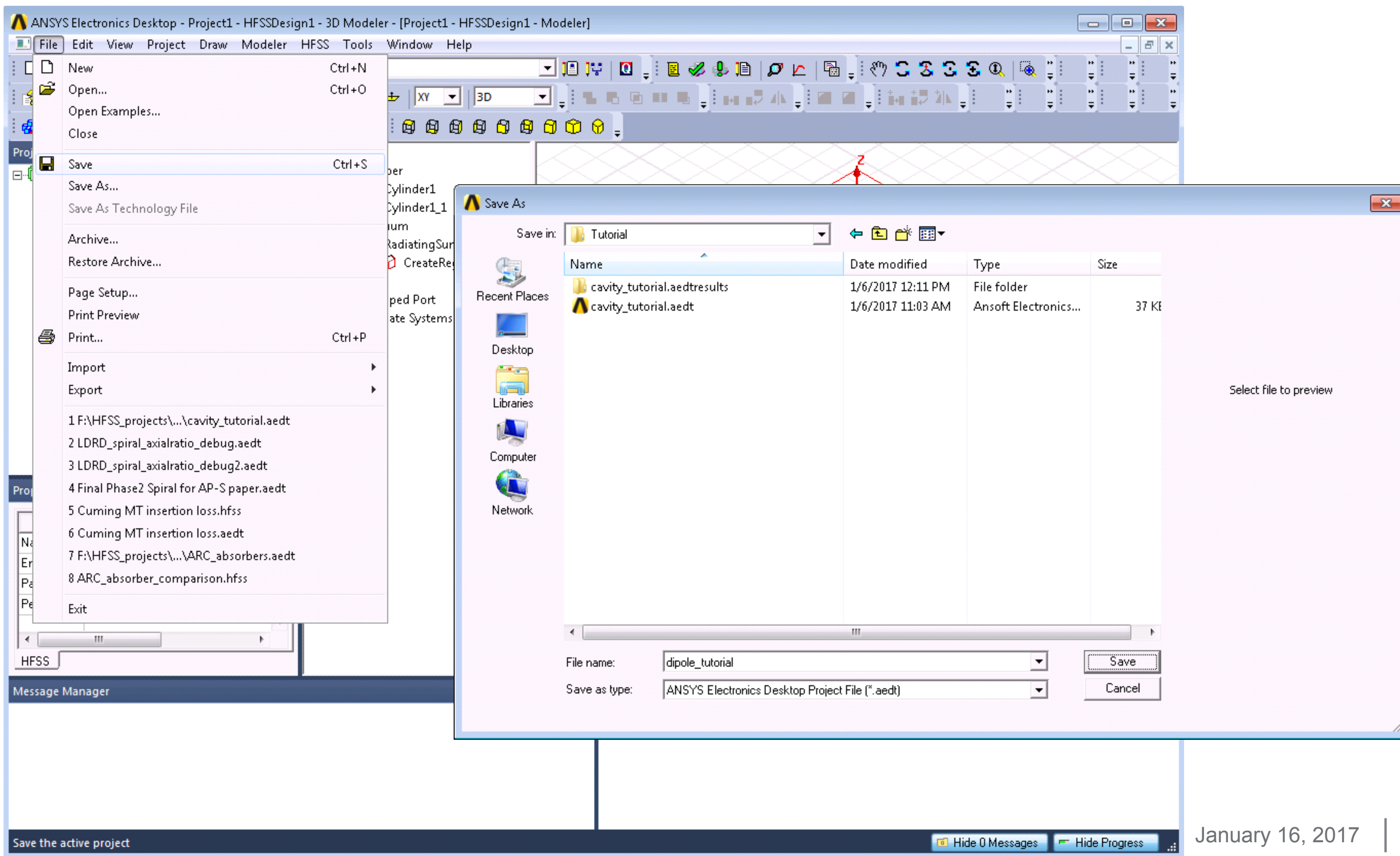
11: Add Frequency Sweep

- Select Setup1 in Project Manager and then ***HFSS > Analysis Setup > Add Frequency Sweep***
- Interpolating sweep, Start = 3 GHz, End = 7 GHz, Step size = 0.01 GHz



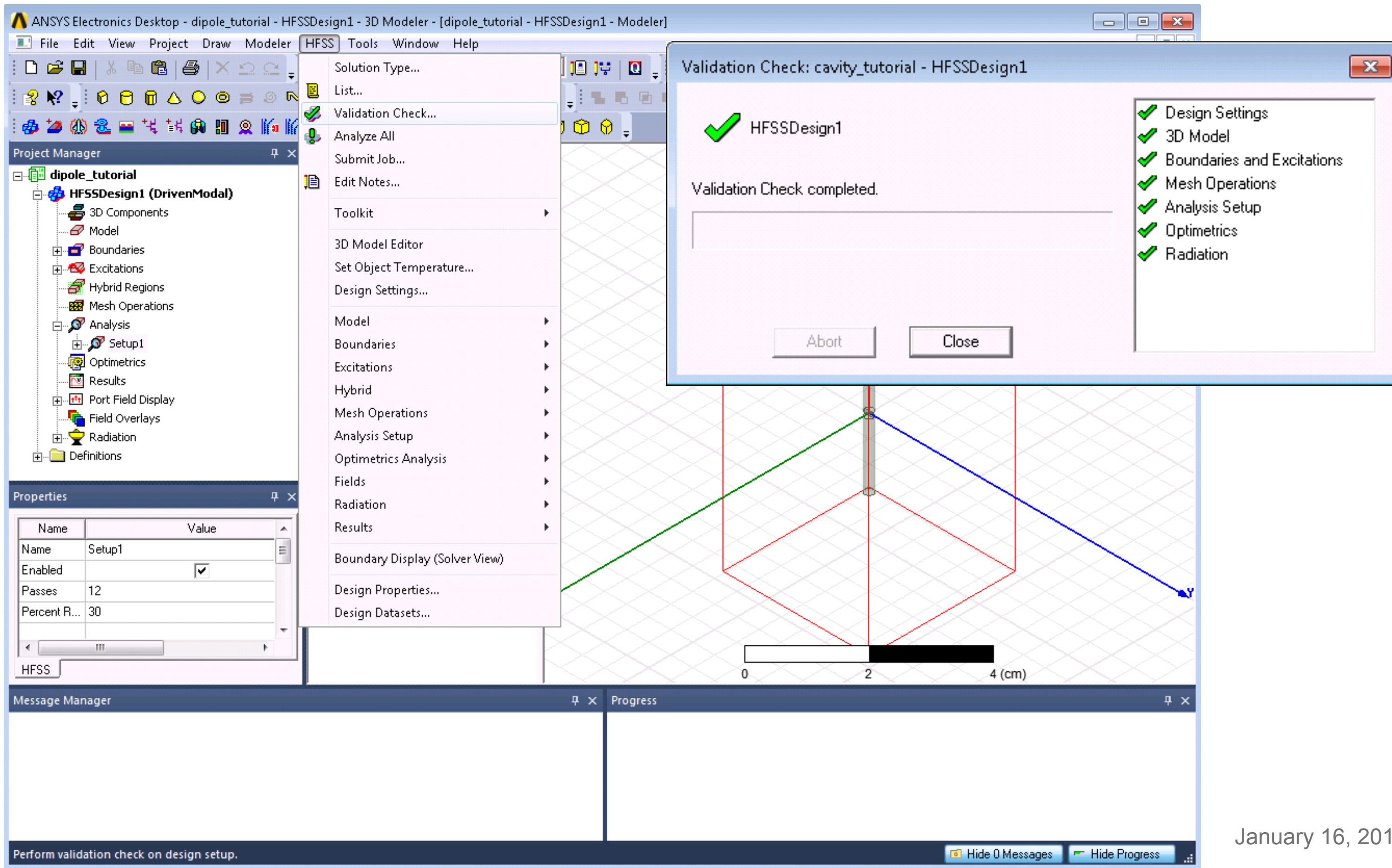
12: Save Project

- Select ***File* > *Save*** and save project as “dipole_tutorial.aedt”



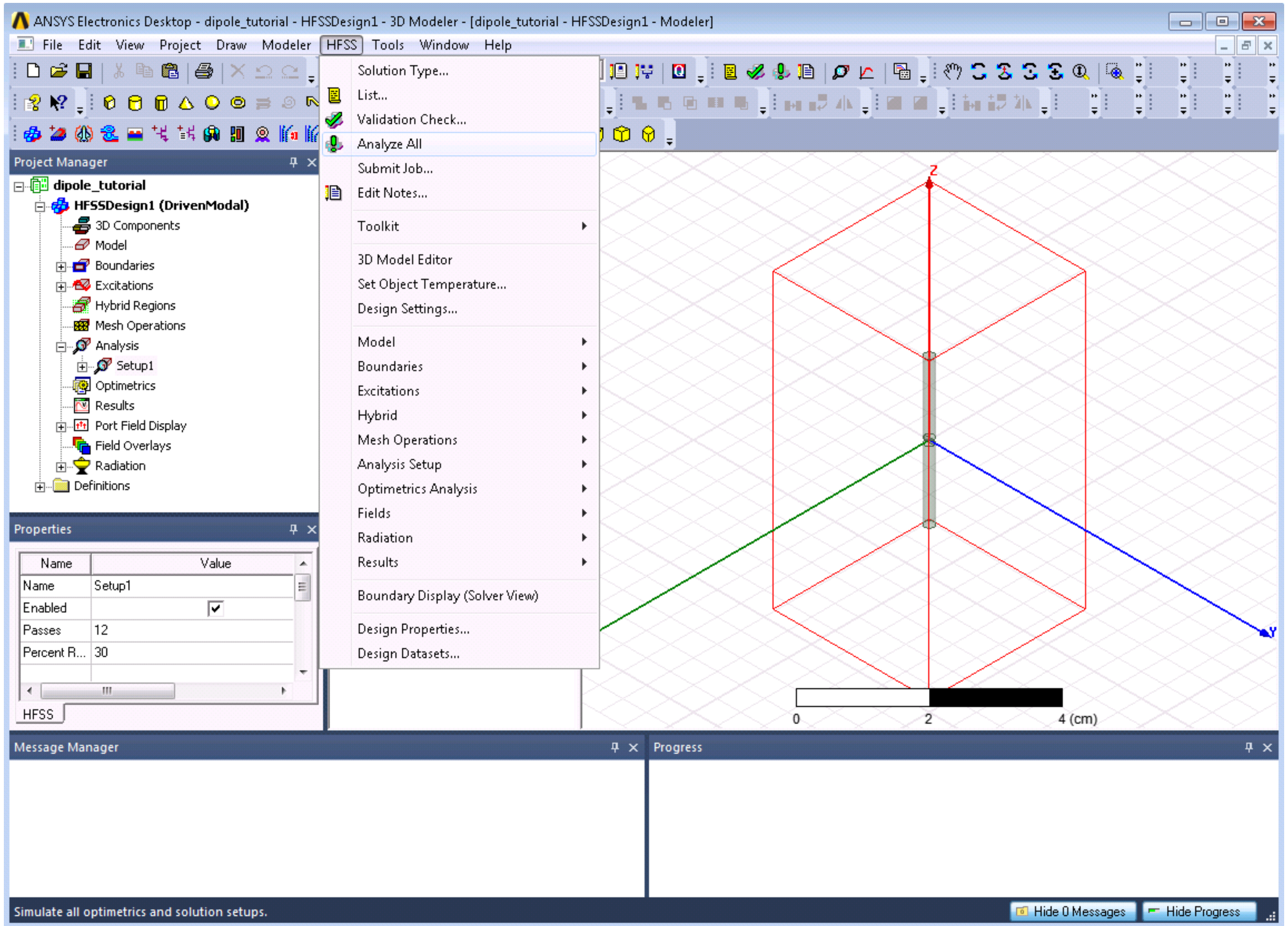
13: Perform Validation Check

- Select ***HFSS > Validation Check***
- Confirms that required steps to solve model have been performed



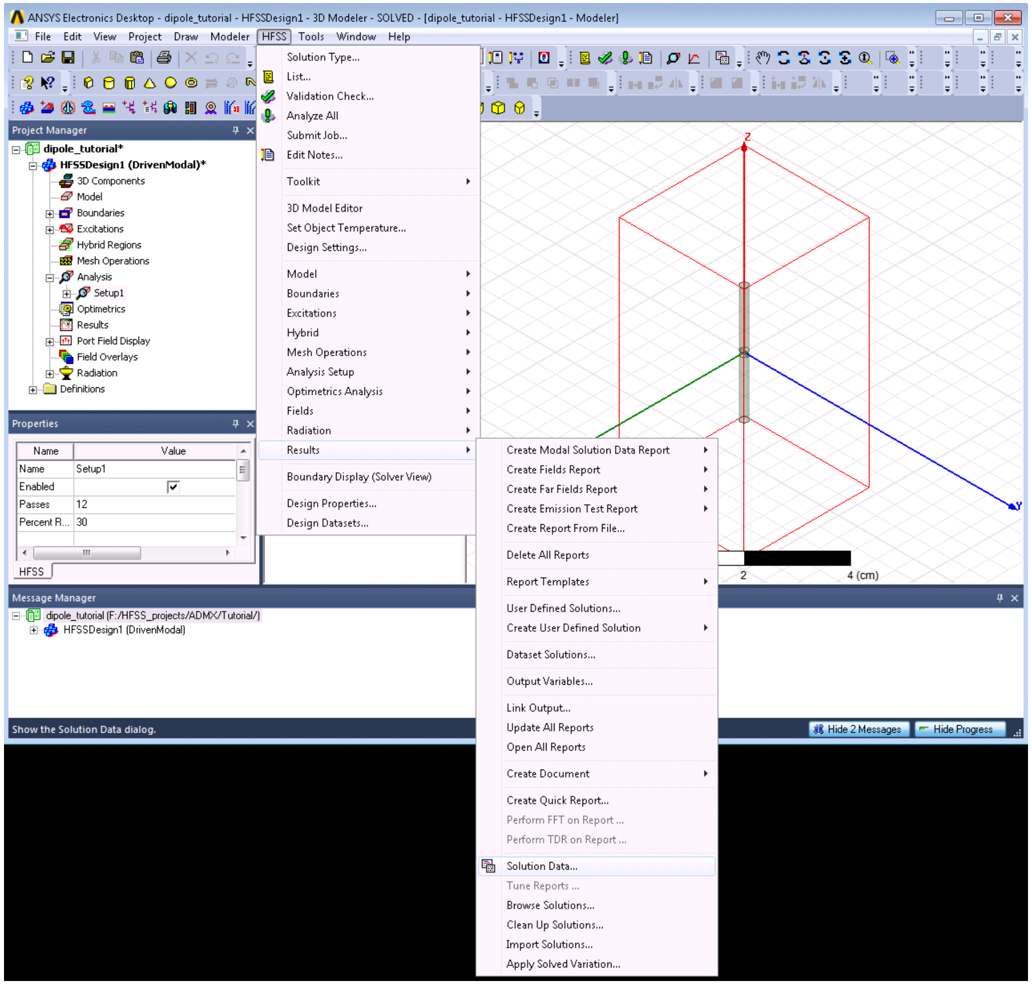
14: Solve Model

- Select ***HFSS > Analyze All***



15: View Solution Data

- Select ***HFSS > Results> Solution Data***



15: View Solution Data

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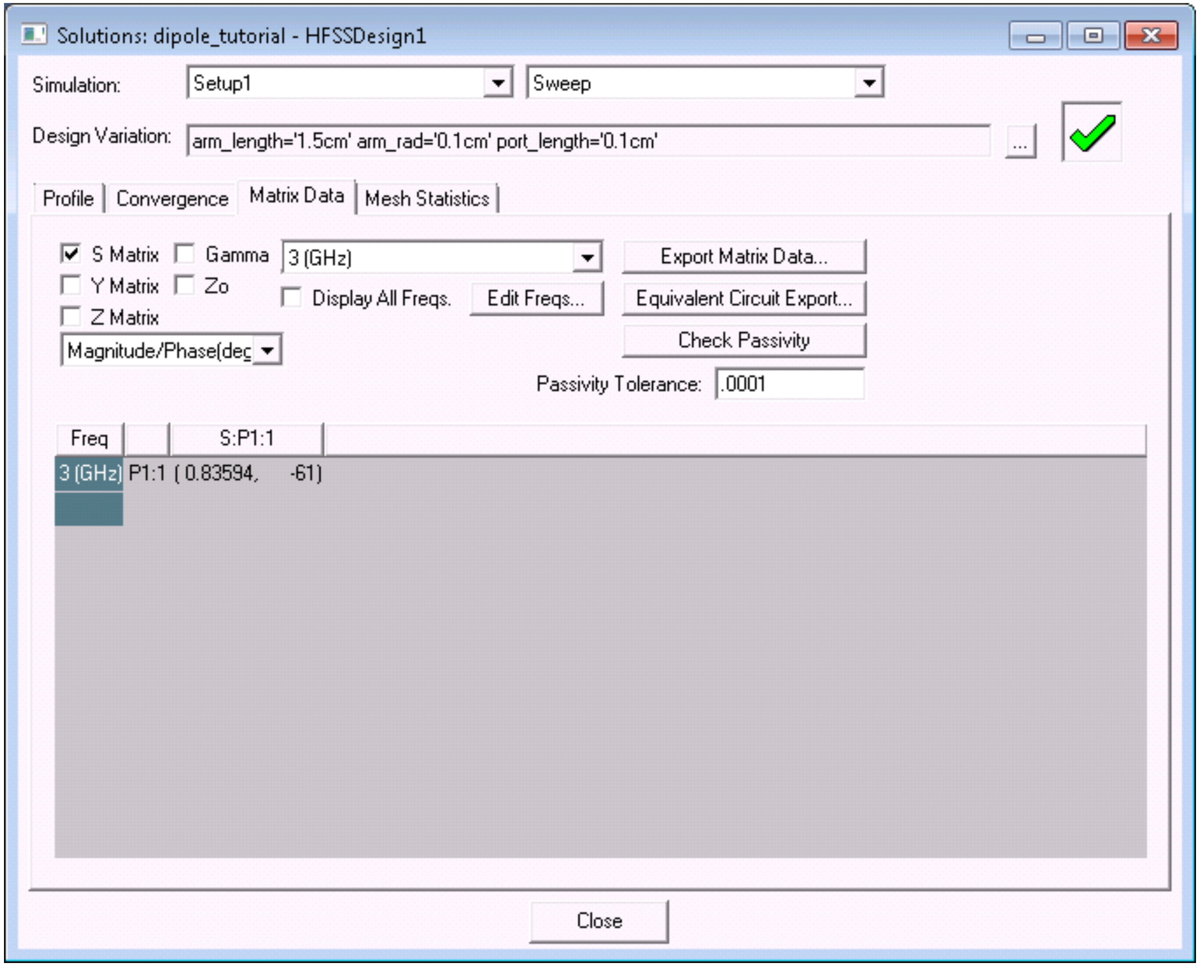
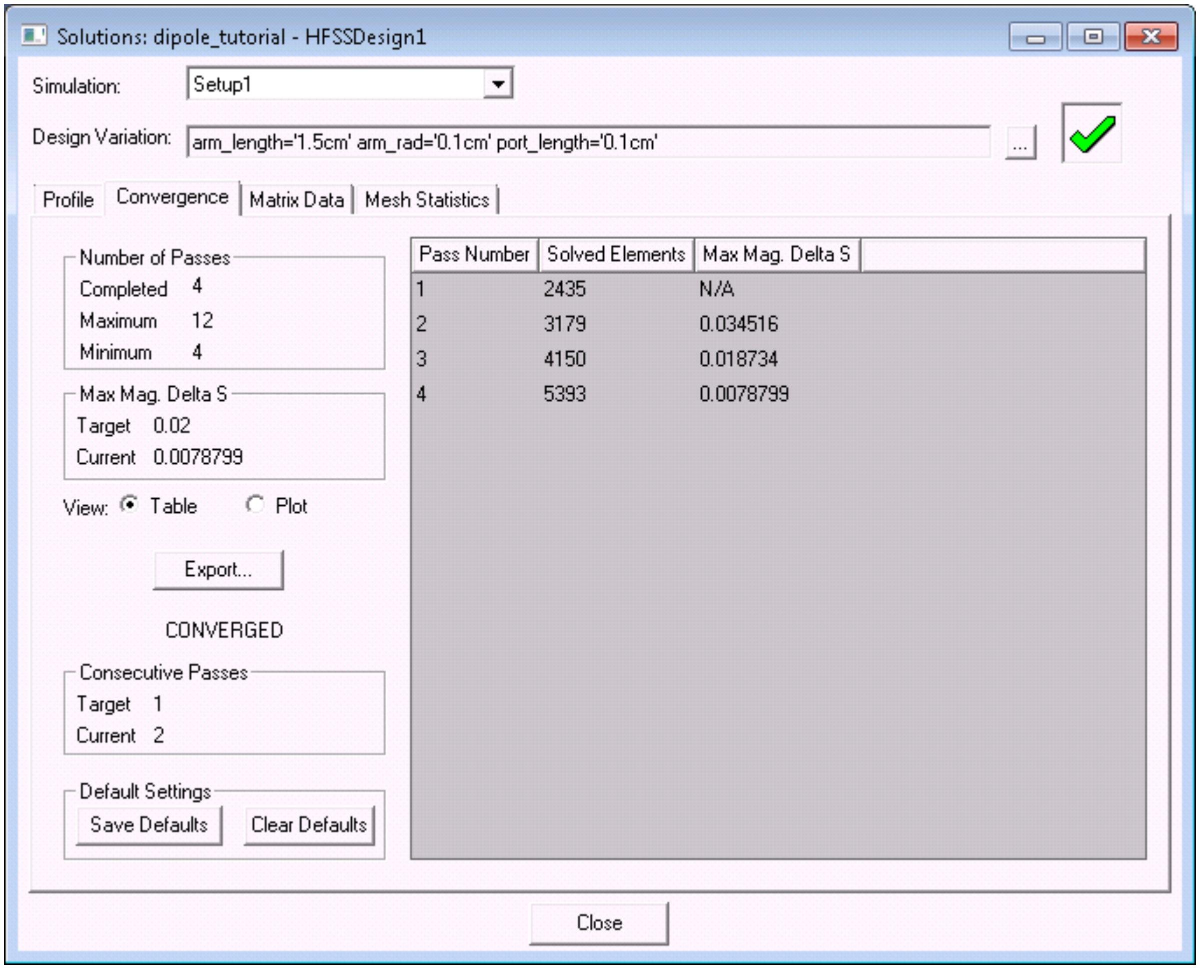
- Select ***Matrix Data*** tab to view network parameters



15: View Solution Data

- Select ***Convergence*** tab to view adaptive pass information



15: View Solution Data

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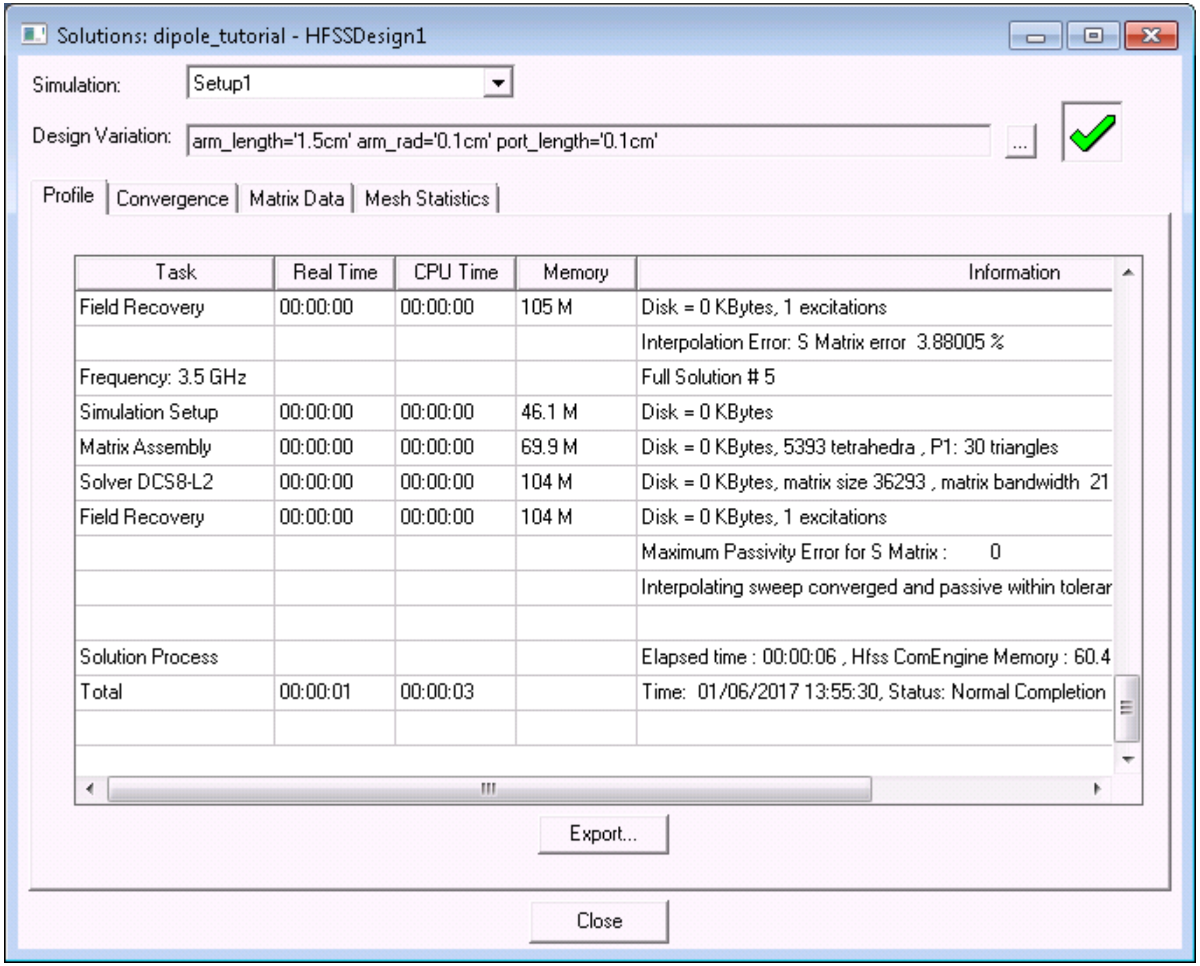
- Select ***Profile*** tab to view run log file (20 sec runtime)



Task	Real Time	CPU Time	Memory	Information
Field Recovery	00:00:00	00:00:00	105 M	Disk = 0 KBytes, 1 excitations
				Interpolation Error: S Matrix error 3.88005 %
Frequency: 3.5 GHz				Full Solution # 5
Simulation Setup	00:00:00	00:00:00	46.1 M	Disk = 0 KBytes
Matrix Assembly	00:00:00	00:00:00	69.9 M	Disk = 0 KBytes, 5393 tetrahedra , P1: 30 triangles
Solver DCS8-L2	00:00:00	00:00:00	104 M	Disk = 0 KBytes, matrix size 36293 , matrix bandwidth 21
Field Recovery	00:00:00	00:00:00	104 M	Disk = 0 KBytes, 1 excitations
				Maximum Passivity Error for S Matrix : 0
				Interpolating sweep converged and passive within tolerar
Solution Process				Elapsed time : 00:00:06 , Hfss ComEngine Memory : 60.4
Total	00:00:01	00:00:03		Time: 01/06/2017 13:55:30, Status: Normal Completion

16: Create Plot of Return Loss

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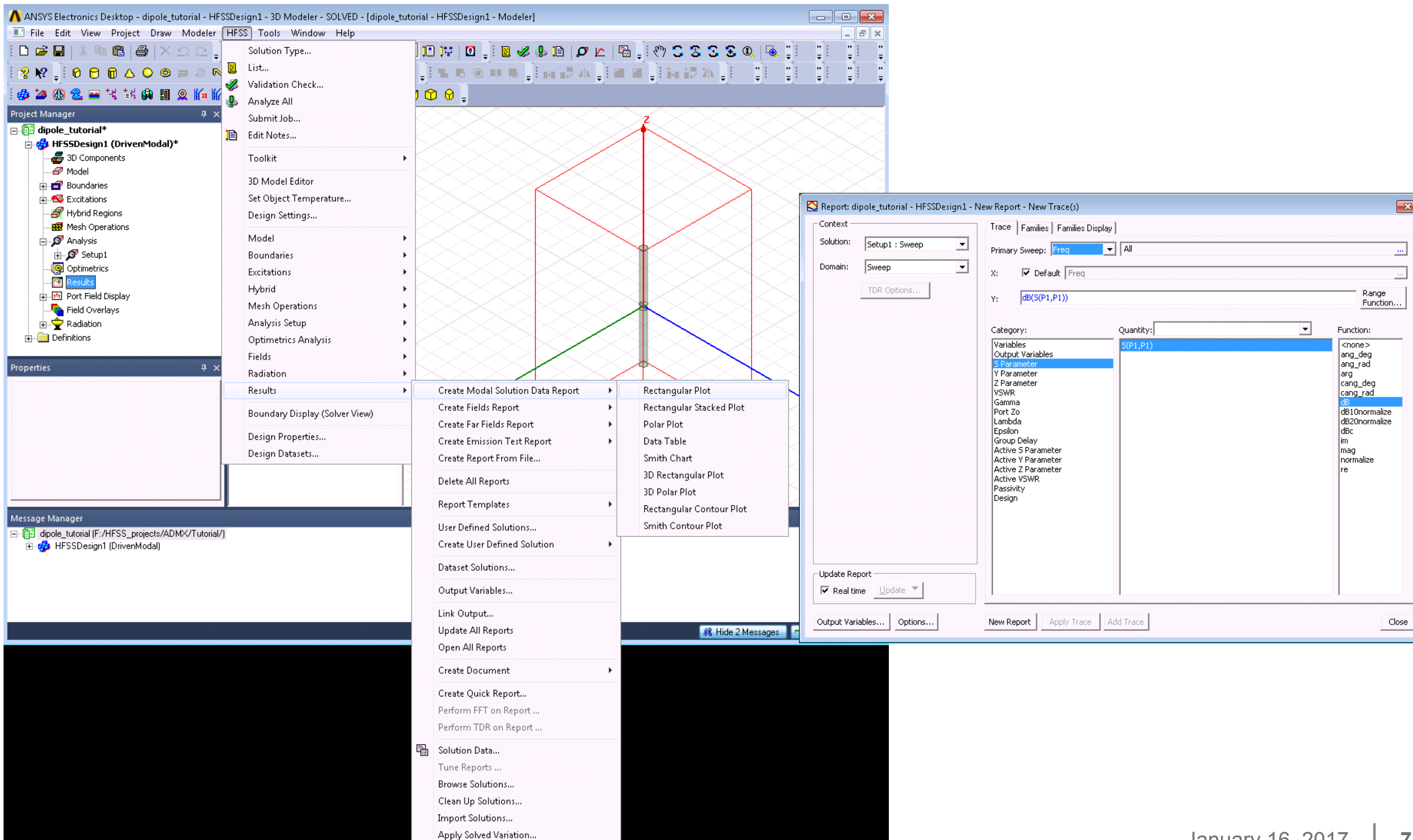
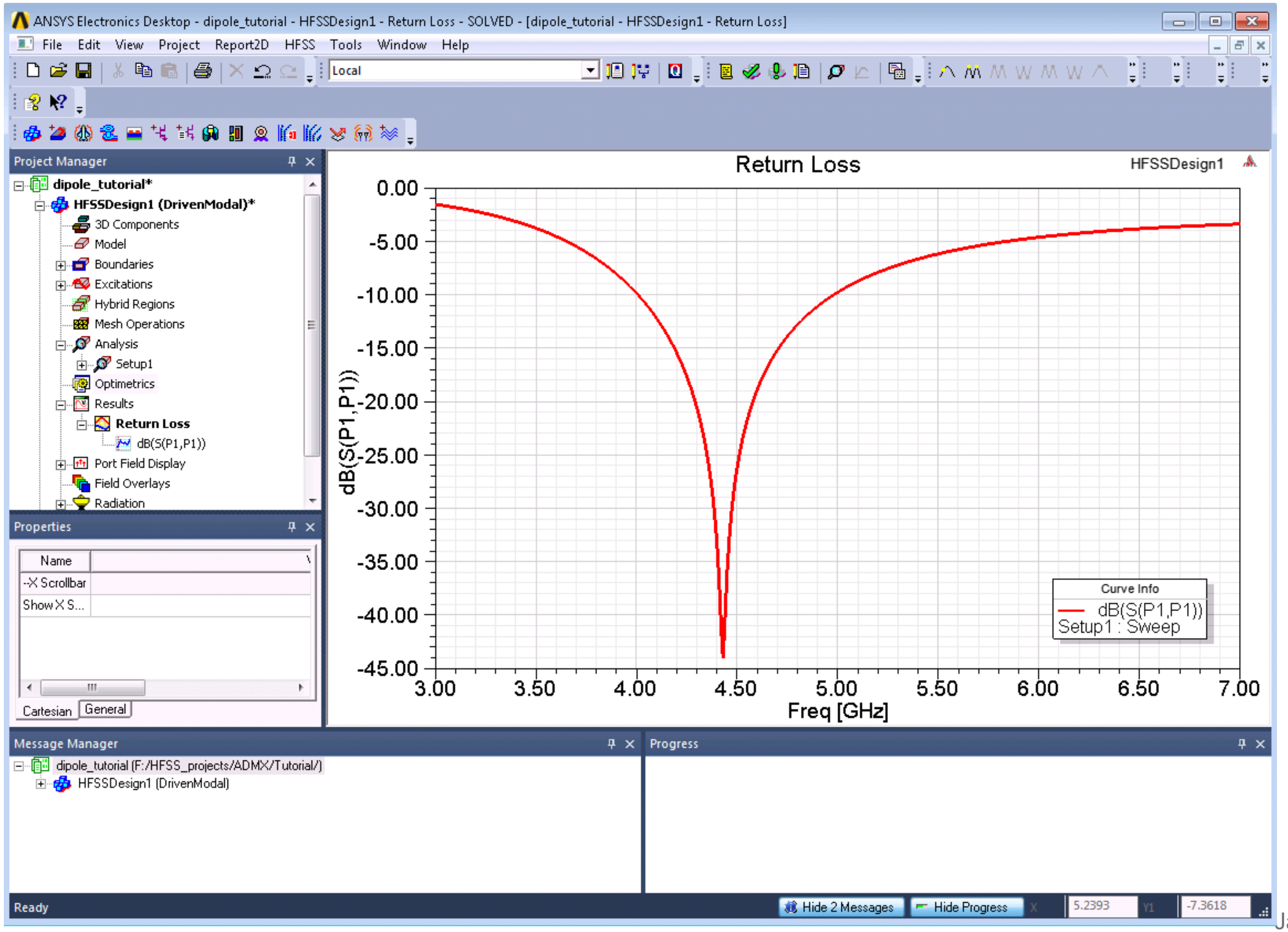
- Select **HFSS > Results > Create Modal Solution Data Report > Rectangular Plot**



16: Create Plot of Return Loss

- Antenna resonates near 4.4 GHz



17: Create Plot of Input Impedance

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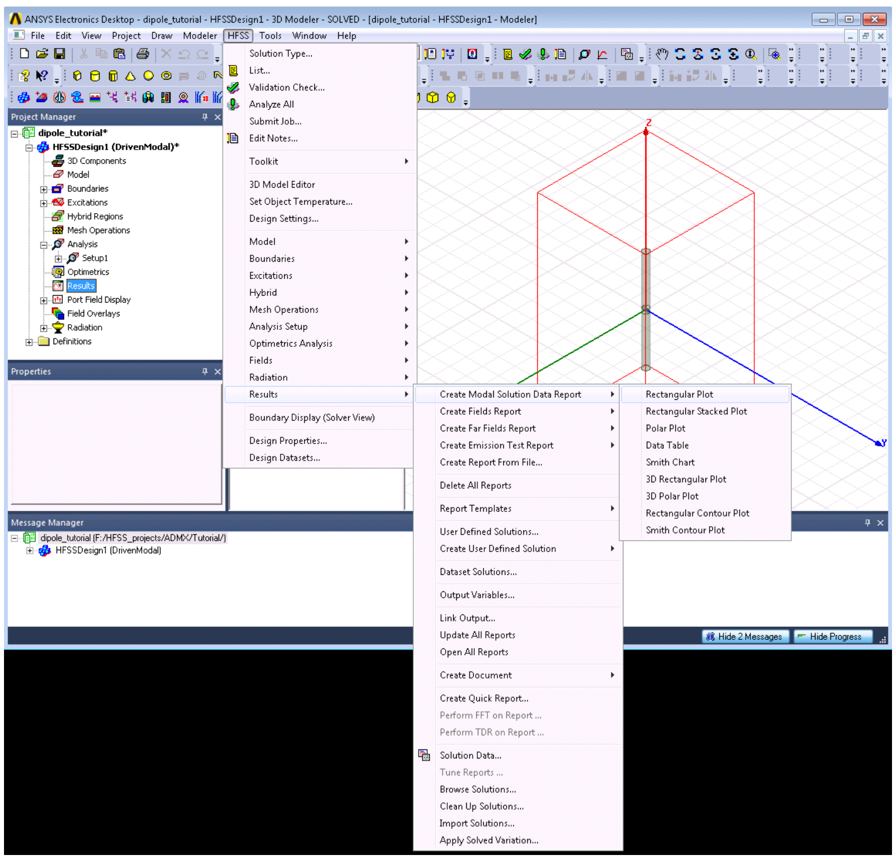
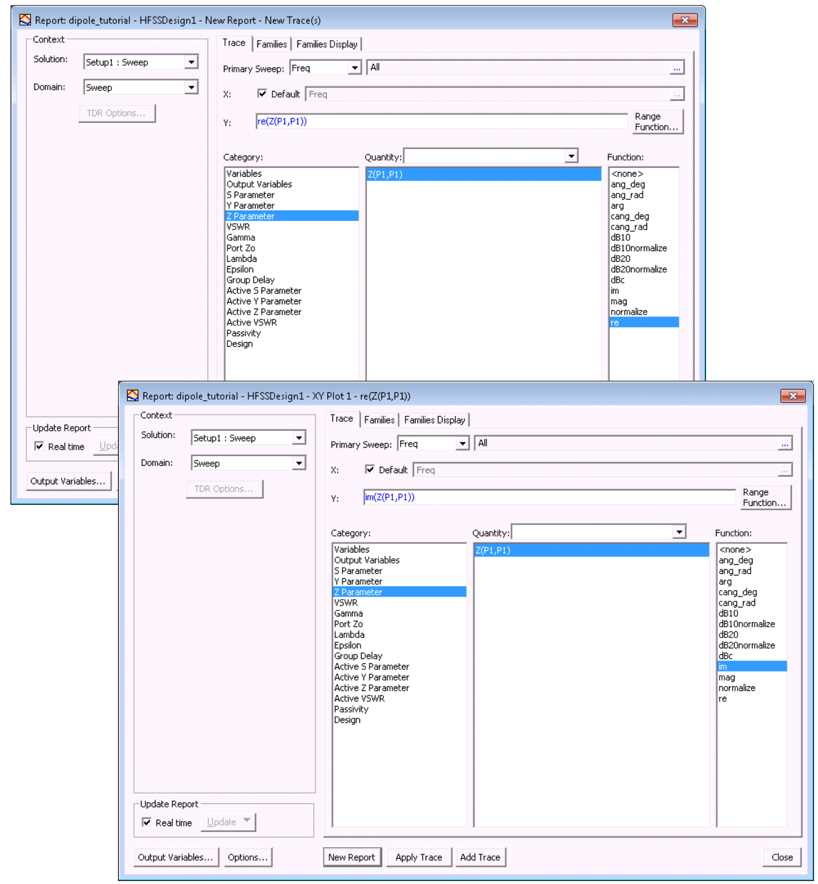
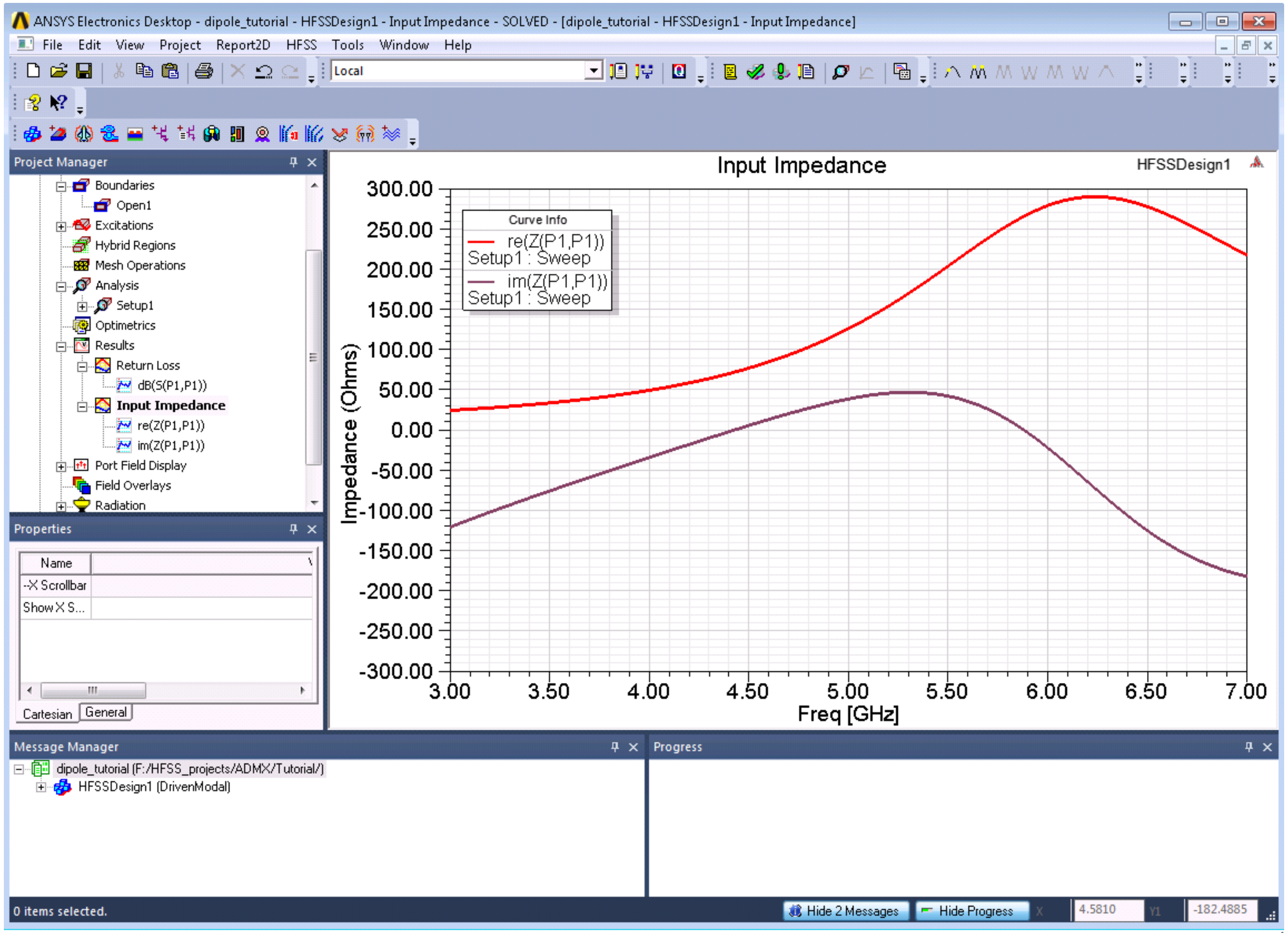
- Select **HFSS > Results > Create Modal Solution Data Report > Rectangular Plot**





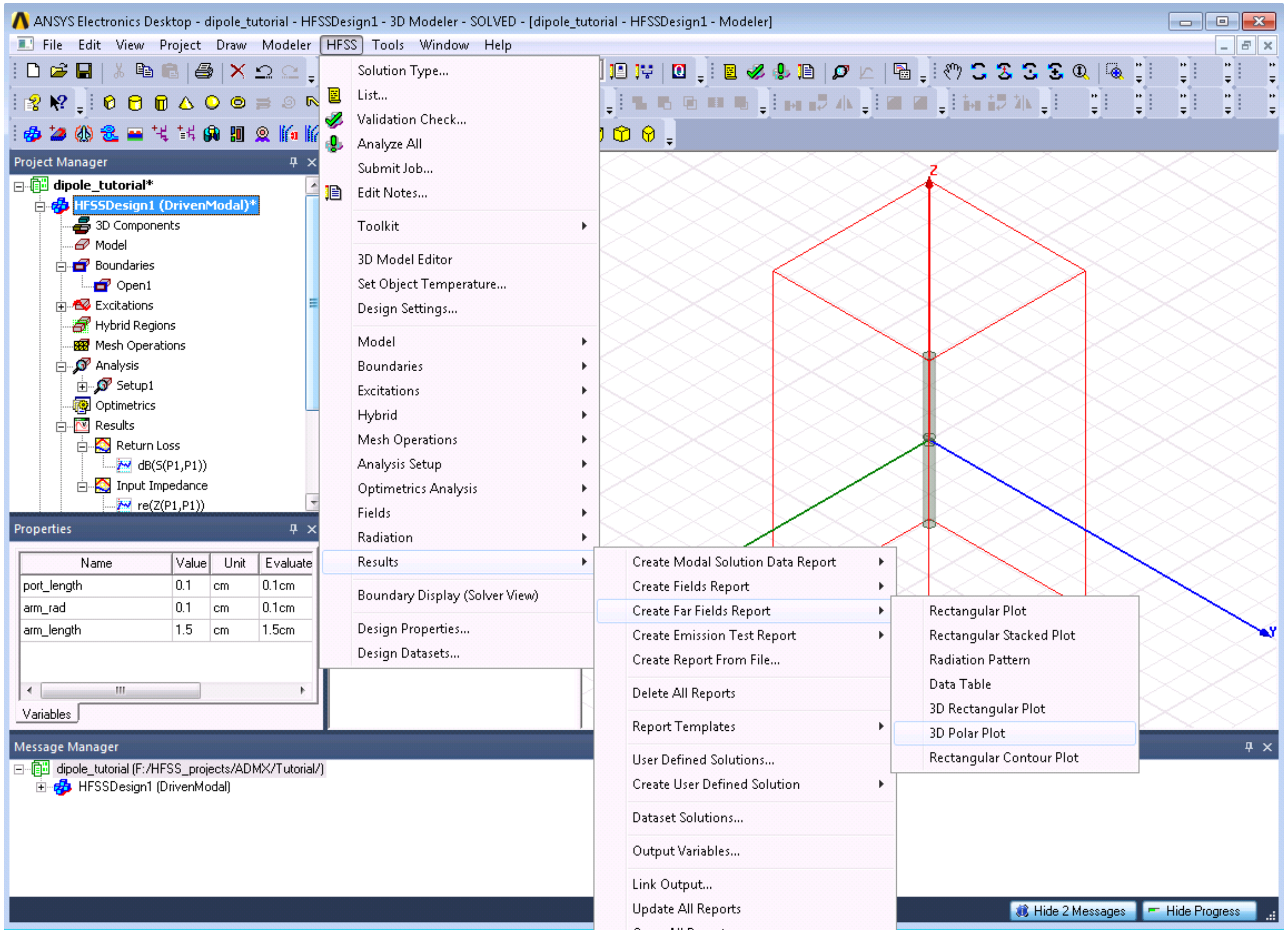
17: Create Plot of Input Impedance

- Antenna resonates near 4.4 GHz



18: Create Plot of Far-field Pattern

- Select ***HFSS > Results > Create Far Fields Report > 3D Polar Plot***



18: Create Plot of Far-field Pattern

- Select ***Gain* > *GainTotal* > *dB***