

The background of the slide is a composite image. On the left, a warfighter in full combat gear, including a helmet and goggles, is shown from the chest up. In the center, a large aircraft carrier is sailing on the ocean. Above the carrier, a fighter jet is in flight. On the right, a missile is launching from a ship, with a large plume of smoke and fire behind it. The title text is overlaid on this background.

HARNESSING THE POWER OF TECHNOLOGY for the **WARFIGHTER**

Wireless Power/Energy Analysis Tool with User Interface

***Presented By: Dr. Corey A.M. Bergsrud and Mr. Alex Zellner
Date: May 25, 2017***

***CAPT JT Elder, USN
Commanding Officer
NSWC Crane***

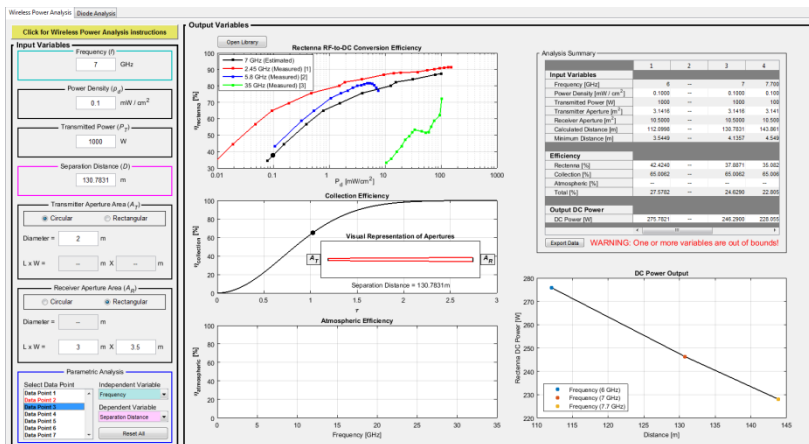
***Dr. Brett Seidle, SES
Technical Director
NSWC Crane***

Wireless Power/Energy Analysis Tool with User Interface

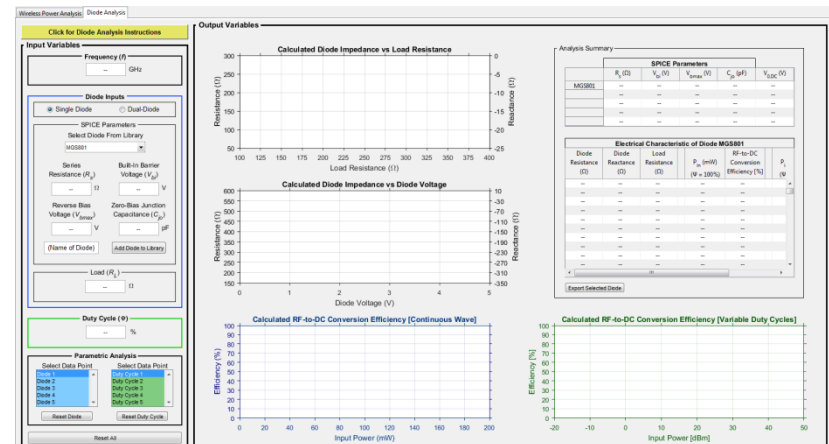
NOTE

- Naval Innovation Science and Engineering (NISE/219) funding
 - Internal Rapid Experimentation (IRE)

Wireless Power Analysis



Diode Analysis



Why Develop Tool?

- **Simplify** and **streamline** initial wireless power/energy parametric analysis
 - Saves effort, time, and money
 - Aid in teaching/learning
- **Standardize** procedure
 - Consistency amongst research community
 - Avoids ambiguity
 - Reduces possible errors
- **Base tool** allows for **evolving** multi-purpose platform
 - New measured data
 - Incorporate other relevant systems/information

How Develop Tool?

- **Formulas**

- N. Shinohara [1]; W. Brown and E. Eves [2].

- **Closed form equations**

- J. McSpadden, L. Fan, and K. Chang [4]; T.-W. Yoo and K. Chang [7]; Y.-J. Ren and K. Chang [8]; C. Valenta, M. Morys, and G Durgin [11].

- **Measured data**

- W. Brown [3]; J. McSpadden, L. Fan, and K. Chang [4]; P. Koert, J. Cha, and M. Macina [5].

- **Creativity**

Wireless Power Analysis GUI

Default GUI: Wireless Power Analysis

Tabs

Wireless Power Analysis Diode Analysis

Parametric Analysis Graphs

Link to instructions

Click here to open instructions

Input Variables

Frequency (f) GHz

Power Density (p_d) mW / cm²

Transmitted Power (P_T) W

Separation Distance (D) m

Transmitter Aperture Area (A_T)

☒ Circular ☐ Rectangular

Diameter = m

L x W = m X m

Receiver Aperture Area (A_R)

☒ Circular ☐ Rectangular

Diameter = m

L x W = m X m

Parametric Analysis

Select Data Point

- Data Point 1
- Data Point 2
- Data Point 3
- Data Point 4
- Data Point 5
- Data Point 6
- Data Point 7

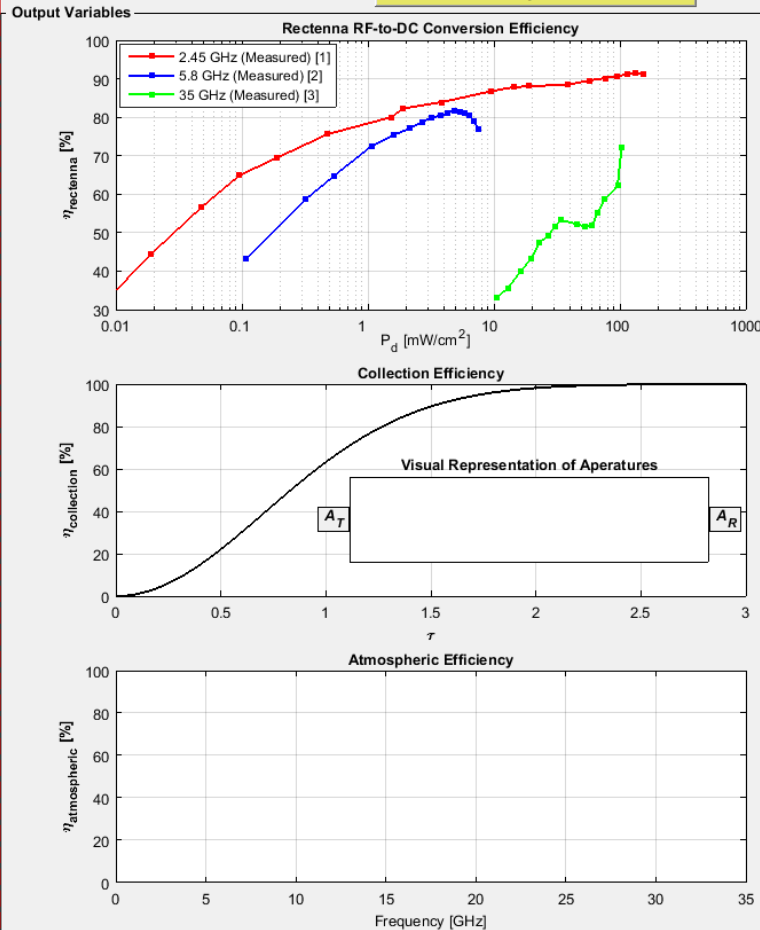
Independent Variable

Frequency

Dependent Variable

Separation Distance

Reset All



Analysis Summary

Input Variables	1	2	3	4
Frequency [GHz]	--	--	--	--
Power Density [mW / cm ²]	--	--	--	--
Transmitted Power [W]	--	--	--	--
Transmitter Aperture [m ²]	--	--	--	--
Receiver Aperture [m ²]	--	--	--	--
Calculated Distance [m]	--	--	--	--
Minimum Distance [m]	--	--	--	--
Efficiency				
Rectenna [%]	--	--	--	--
Collection [%]	--	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	--	--	--	--
Output DC Power				
DC Power [W]	--	--	--	--

Export Data

DC Power Output

Rectenna DC Power [W]

Not enough data points

Distance [m]

Input Variables

Output Variables

Distribution Statement A – Approved for public release.

WPA Features 1: Tabs & Inputs

Frequency (f)
-- GHz

Power Density (p_d)
-- mW / cm²

Transmitted Power (P_T)
-- W

Separation Distance (D)
-- m

Transmitter Aperture Area (A_T)

☒ Circular ☐ Rectangular

Diameter = -- m

L x W = -- m X -- m

Receiver Aperture Area (A_R)

☒ Circular ☐ Rectangular

Diameter = -- m

L x W = -- m X -- m

Wireless Power Analysis | Diode Analysis

Input Variables

Frequency (f)
-- GHz

Power Density (p_d)
-- mW / cm²

Transmitted Power (P_T)
-- W

Separation Distance (D)
-- m

Transmitter Aperture Area (A_T)

☒ Circular ☐ Rectangular

Diameter = -- m

L x W = -- m X -- m

Receiver Aperture Area (A_R)

☒ Circular ☐ Rectangular

Diameter = -- m

L x W = -- m X -- m

Parametric Analysis

Select Data Point: Data Point 1, Data Point 2, Data Point 3, Data Point 4, Data Point 5, Data Point 6, Data Point 7

Independent Variable: Frequency

Dependent Variable: Separation Distance

Reset All

Wireless Power Analysis | Diode Analysis

Input Variables

Frequency (f)
-- GHz

Power Density (p_d)
-- mW / cm²

Transmitted Power (P_T)
-- W

Separation Distance (D)
-- m

Click here to open instructions

Output Variables

Rectenna RF-to-DC Conversion Efficiency

Collection Efficiency

Atmospheric Efficiency

Analysis Summary

Input Variables	1	2	3	4
Frequency [GHz]	--	--	--	--
Power Density [mW / cm ²]	--	--	--	--
Transmitted Power [W]	--	--	--	--
Transmitter Aperture [m ²]	--	--	--	--
Receiver Aperture [m ²]	--	--	--	--
Calculated Distance [m]	--	--	--	--
Minimum Distance [m]	--	--	--	--

Efficiency

	1	2	3	4
Rectenna [%]	--	--	--	--
Collection [%]	--	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	--	--	--	--

Output DC Power

	1	2	3	4
DC Power [W]	--	--	--	--

Export Data

DC Power Output

Not enough data points

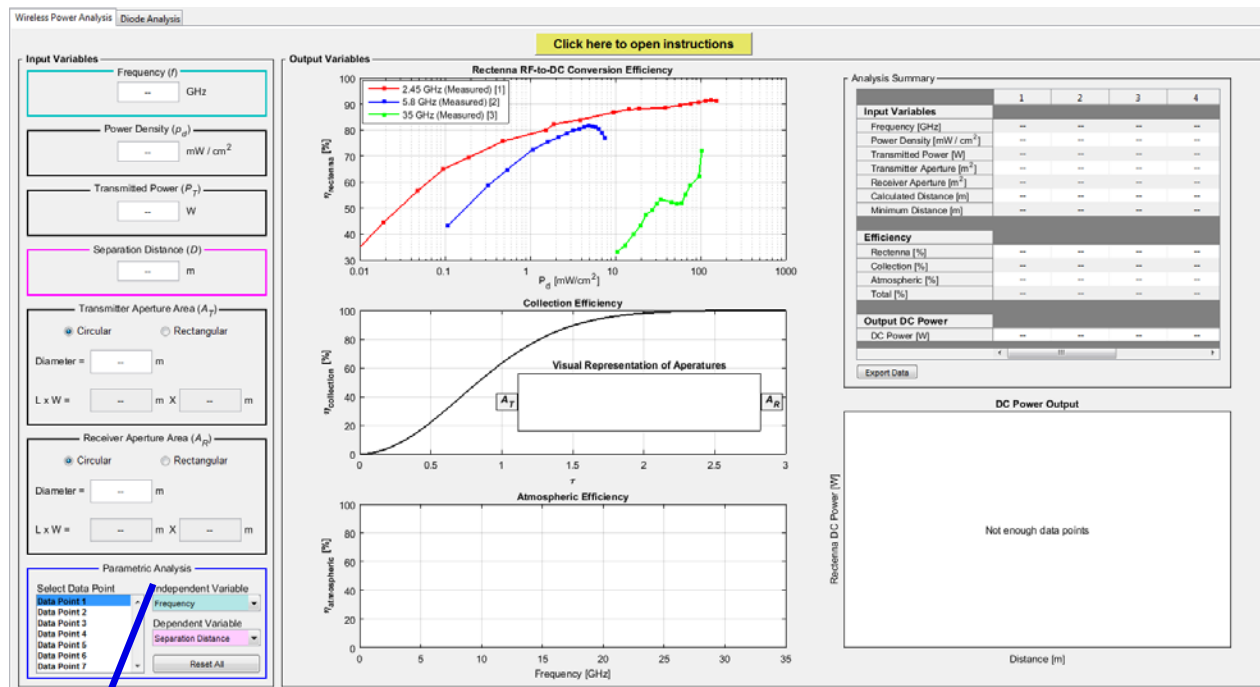
Distance [m]

Distribution Statement A – Approved for public release.

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HARNESSING THE POWER OF TECHNOLOGY FOR THE WARFIGHTER

WPA Features 2: Inputs



Parametric Analysis

Select Data Point

- Data Point 1
- Data Point 2
- Data Point 3
- Data Point 4
- Data Point 5
- Data Point 6
- Data Point 7

Independent Variable

Frequency

Dependent Variable

Separation Distance

Dependent Variable

Power Density

Frequency

Power Density

Transmitted Power

Transmitter Aperture Area

Separation Distance

WPA Parametric Analysis

$$p_d = \frac{A_t P_t}{\lambda^2 D^2}$$

$$P_t = \frac{p_d \lambda^2 D^2}{A_t}$$

Dependent Variables

$$f = \sqrt{\frac{p_d D^2 c^2}{A_t P_t}}$$

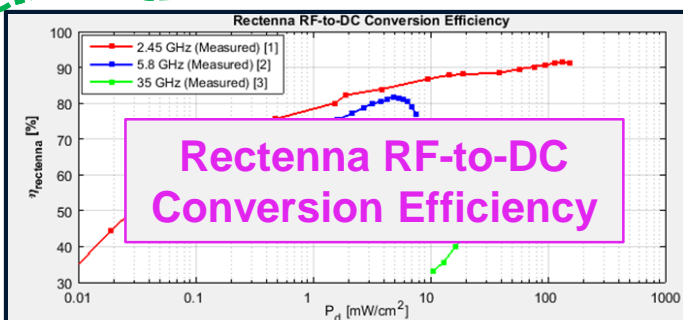
$$d = \sqrt{\frac{A_t P_t}{p_d \lambda^2}}$$

$$A_t = \frac{p_d \lambda^2 D^2}{P_t}$$

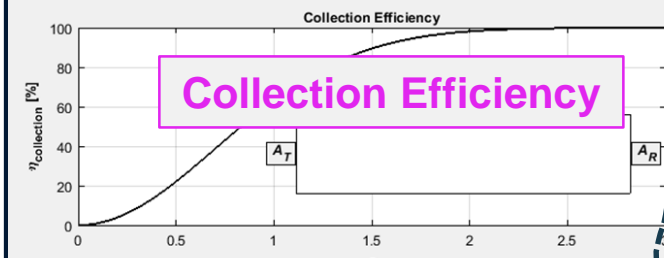
**Aperture-to-aperture
transmission
efficiency**

$$\tau = \frac{\sqrt{A_t A_r}}{\lambda D}$$

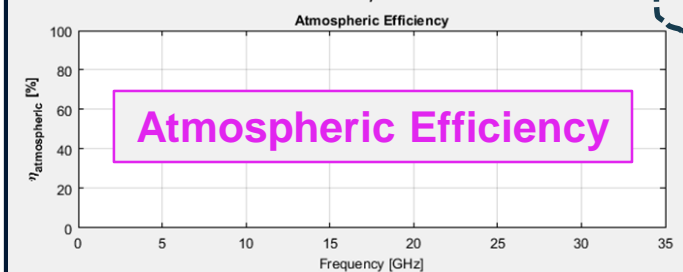
WPA Features 3: Outputs



Rectenna RF-to-DC Conversion Efficiency



Collection Efficiency



Atmospheric Efficiency

Receiver Aperture Area (A_R)

☒ Circular ☐ Rectangular

Diameter: m

L x W: m x m

Parametric Analysis

Select Data Point:

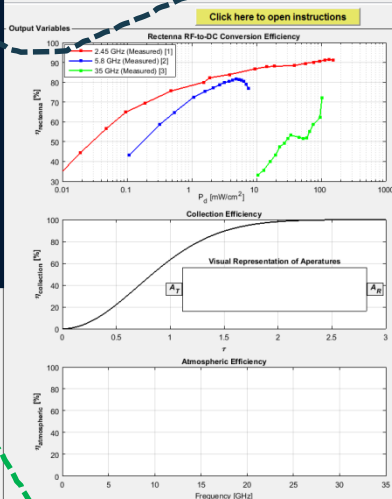
Independent Variable:

Dependent Variable:

Separation Distance:

Reset All

Output Variables



Analysis Summary

	1	2	3	4
Input Variables				
Frequency [GHz]				
Power Density [mW / cm ²]				
Transmitted Power [W]				
Transmitter Aperture [m ²]				
Receiver Aperture [m ²]				
Calculated Distance [m]				
Minimum Distance [m]				
Efficiency				
Rectenna [%]	--	--	--	--
Collection [%]	--	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	--	--	--	--
Output DC Power				
DC Power [W]	--	--	--	--

Export Data

Analysis Summary

DC Power Output

DC Power Output

Analysis Summary

	1	2	3	4
Input Variables				
Frequency [GHz]	--	--	--	--
Power Density [mW / cm ²]	--	--	--	--
Transmitted Power [W]	--	--	--	--
Transmitter Aperture [m ²]	--	--	--	--
Receiver Aperture [m ²]	--	--	--	--
Calculated Distance [m]	--	--	--	--
Minimum Distance [m]	--	--	--	--
Efficiency				
Rectenna [%]	--	--	--	--
Collection [%]	--	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	--	--	--	--
Output DC Power				
DC Power [W]	--	--	--	--

Export Data

Not enough data points

Distance [m]

WPA Example 1

EX: 1.1

Instructions Wireless Power Analysis Diode Analysis

Input Variables

Frequency (f)
5.45 GHz

Power Density (p_d)
5 mW / cm²

Transmitted Power (P_T)
5000 W

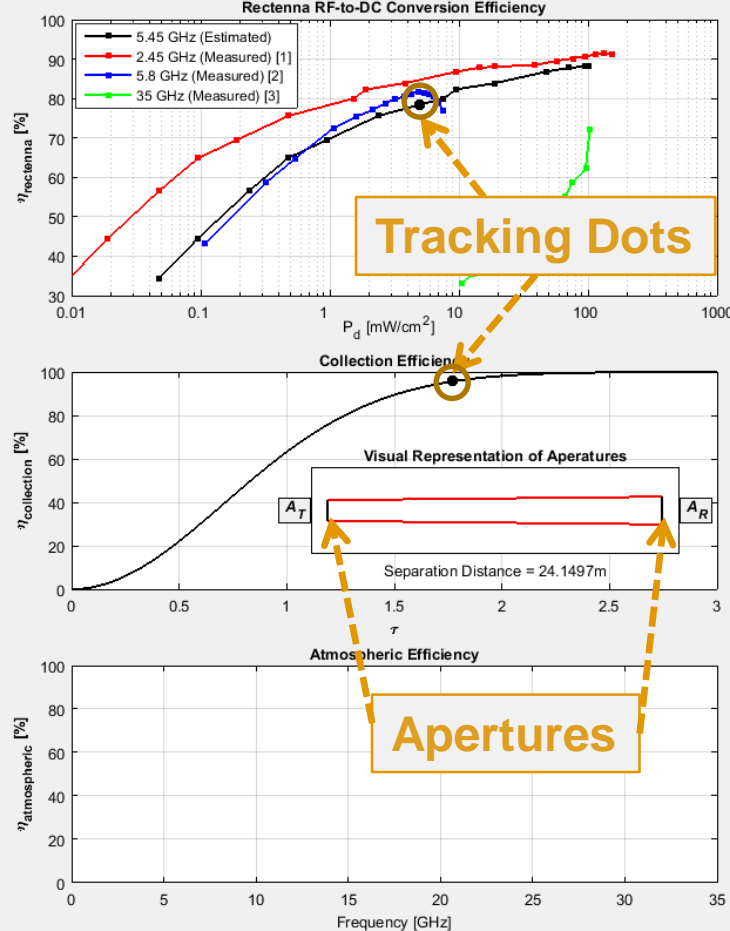
Transmitter Aperture Area (A_T)
☒ Circular ☐ Rectangular
Diameter = 1.5 m
L x W = -- m X -- m

Receiver Aperture Area (A_R)
☒ Circular ☐ Rectangular
Diameter = 2 m
L x W = -- m X -- m

Separation Distance (D)
24.1497 m

Parametric Analysis
Select Data Point: Data Point 1
Independent Variable: Frequency
Dependent Variable: Separation Distance
Reset All

Output Variables



Analysis Summary

	1	2	3	4
Input Variables				
Frequency [GHz]	5.4500	--	--	--
Power Density [mW / cm ²]	5	--	--	--
Transmitted Power [W]	5000	--	--	--
Transmitter Aperture [m ²]	1.7671	--	--	--
Receiver Aperture [m ²]	3.1416	--	--	--
Calculated Distance [m]	24.1497	--	--	--
Minimum Distance [m]	5.4000	--	--	--
Efficiency				
Rectenna [%]	78.4158	--	--	--
Collection [%]	95.6786	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	75.0271	--	--	--
Output DC Power				
DC Power [W]	3.7514e+03	--	--	--
Export Data				

DC Power Output

Rectenna DC Power [W]

Populating

Not enough data points

Distance [m]

EX: 1.2

Instructions Wireless Power Analysis Diode Analysis

Input Variables

Frequency (f) GHz

Power Density (p_d) mW/cm²

Transmitted Power (P_T) W

Transmitter Aperture Area (A_T)

☒ Circular ☐ Rectangular

Diameter = m

L x W = m X m

Receiver Aperture Area (A_R)

☒ Circular ☐ Rectangular

Diameter = m

L x W = m X m

Separation Distance (D) m

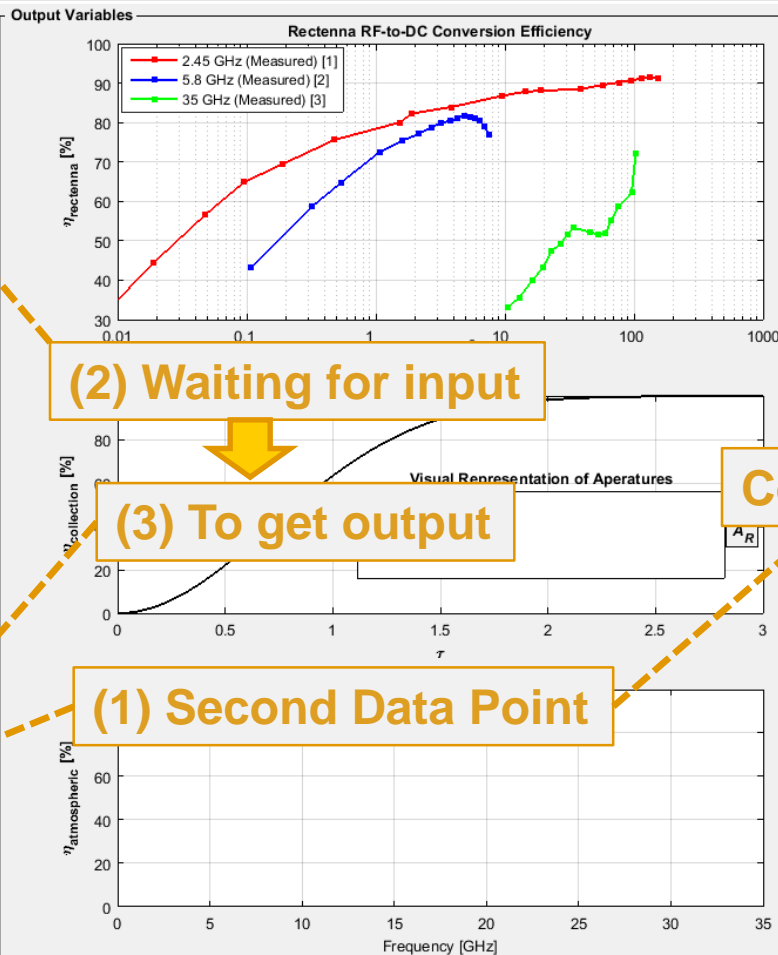
Parametric Analysis

Select Data Point

- Data Point 1
- Data Point 2**
- Data Point 3
- Data Point 4
- Data Point 5
- Data Point 6
- Data Point 7

Independent Variable

Dependent Variable



(2) Waiting for input

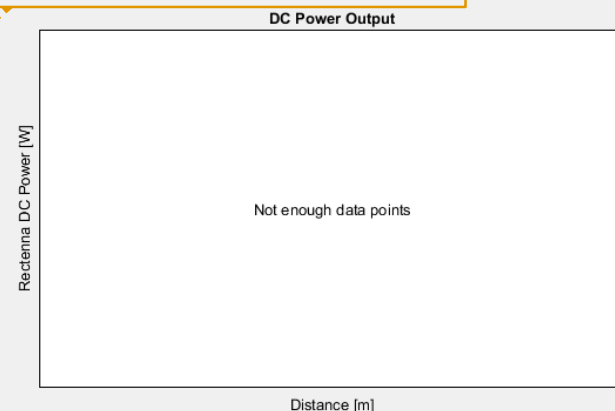
(3) To get output

(1) Second Data Point

Analysis Summary

	1	2	3	4
Input Variables				
Frequency [GHz]	5.4500	--	--	--
Power Density [mW / cm ²]	5	5	--	--
Transmitted Power [W]	5000	5000	--	--
Transmitter Aperture [m ²]	1.7671	1.7671	--	--
Receiver Aperture [m ²]	3.1416	3.1416	--	--
Calculated Distance [m]	24.145	--	--	--
Minimum Distance [m]	5.4000	--	--	--
Efficiency				
Rectenna [%]	78.4158	--	--	--
Collection [%]	95.6786	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	75.0271	--	--	--
Output DC Power				
DC Power [W]	3.7514e+03	--	--	--

Copies over fixed data



EX: 1.3

Instructions Wireless Power Analysis Diode Analysis

Input Variables

Frequency (f)
35 GHz

Power Density (p_d)
5 mW / cm²

Transmitted Power (P_T)
5000 W

Transmitter Aperture Area (A_T)
☒ Circular ☐ Rectangular
Diameter = 1.5 m
L x W = -- m X -- m

Receiver Aperture Area (A_R)
☒ Circular ☐ Rectangular
Diameter = 2 m
L x W = -- m X -- m

Separation Distance (D)
155.0897 m

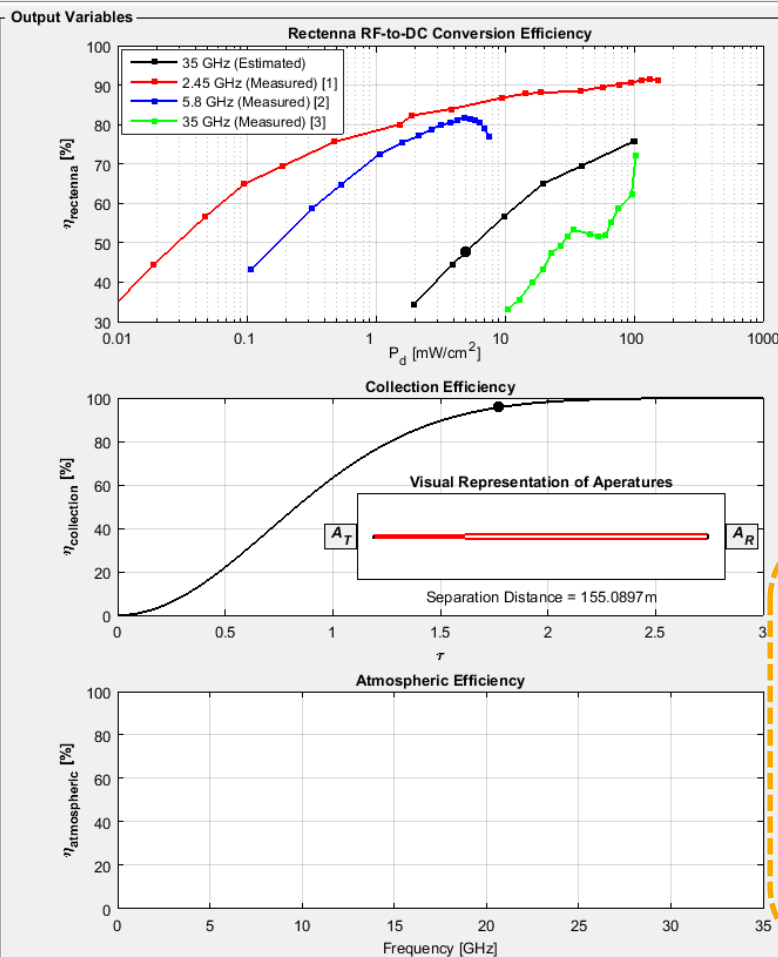
Parametric Analysis

Select Data Point
Data Point 1
Data Point 2
Data Point 3
Data Point 4
Data Point 5
Data Point 6
Data Point 7

Independent Variable
Frequency

Dependent Variable
Separation Distance

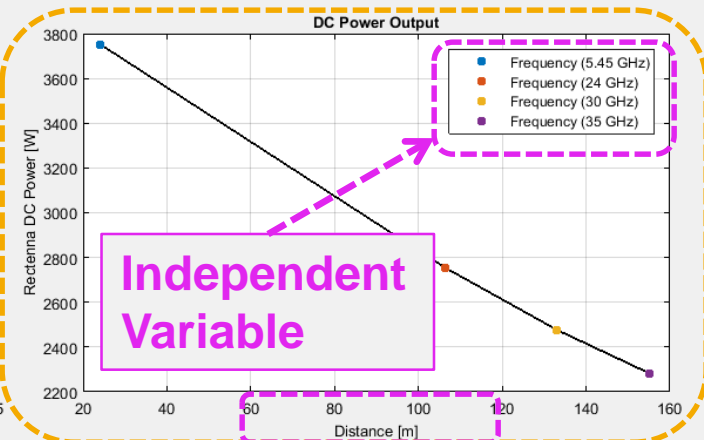
Reset All



Analysis Summary

	1	2	3	4
Input Variables				
Frequency [GHz]	5.4500	24	30	3
Power Density [mW / cm ²]	5	5	5	5
Transmitted Power [W]	5000	5000	5000	500
Transmitter Aperture [m ²]	1.7671	1.7671	1.7671	1.767
Receiver Aperture [m ²]	3.1416	3.1416	3.1416	3.141
Calculated Distance [m]	24.1497	106.3472	132.9340	155.089
Minimum Distance [m]	5.4000	23.7800	29.7250	34.679
Efficiency				
Rectenna [%]	78.4158	57.5827	51.7903	47.719
Collection [%]	95.6786	95.6786	95.6786	95.678
Atmospheric [%]	--	--	--	--
Total [%]	75.0271	55.0943	49.5522	45.656
Output DC Power				
DC Power [W]	3.7514e+03	2.7547e+03	2.4776e+03	2.2828e+03

Export Data



Generates Plot Graph

Dependent Variable

WPA Example 2

EX: 2.1

Instructions Wireless Power Analysis Diode Analysis

Input Variables

Frequency (f)
-- GHz

Power Density (p_d)
-- mW / cm²

Transmitted Power (P_T)
-- W

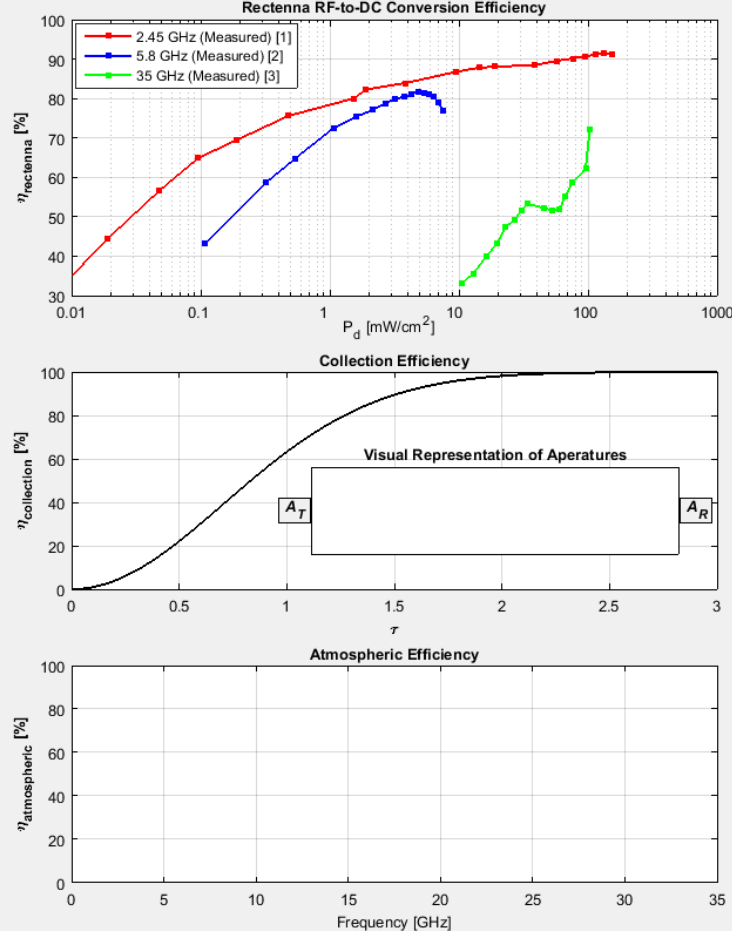
Transmitter Aperture Area (A_T)
☒ Circular ☐ Rectangular
Diameter = -- m
L x W = -- m X -- m

Receiver Aperture Area (A_R)
☒ Circular ☐ Rectangular
Diameter = -- m
L x W = -- m X -- m

Separation Distance (D)
-- m

Parametric Analysis
Select Data Point
Data Point 1
Data Point 2
Data Point 3
Data Point 4
Data Point 5
Data Point 6
Data Point 7
Independent Variable
Separation Distance
Dependent Variable
Power Density
Reset All

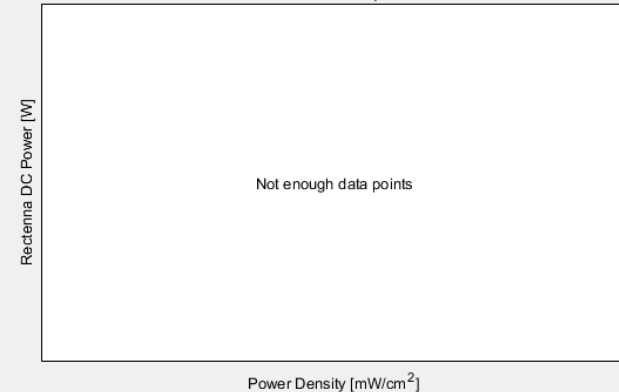
Output Variables



Analysis Summary

	1	2	3	4
Input Variables				
Frequency [GHz]	--	--	--	--
Power Density [mW / cm ²]	--	--	--	--
Transmitted Power [W]	--	--	--	--
Transmitter Aperture [m ²]	--	--	--	--
Receiver Aperture [m ²]	--	--	--	--
Calculated Distance [m]	--	--	--	--
Minimum Distance [m]	--	--	--	--
Efficiency				
Rectenna [%]	--	--	--	--
Collection [%]	--	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	--	--	--	--
Output DC Power				
DC Power [W]	--	--	--	--
Export Data				

DC Power Output



Reset All

EX: 2.2

Instructions Wireless Power Analysis Diode Analysis

Input Variables

Frequency (f)
5.45 GHz

Power Density (p_d)
0.16501 mW / cm²

Transmitted Power (P_T)
5000 W

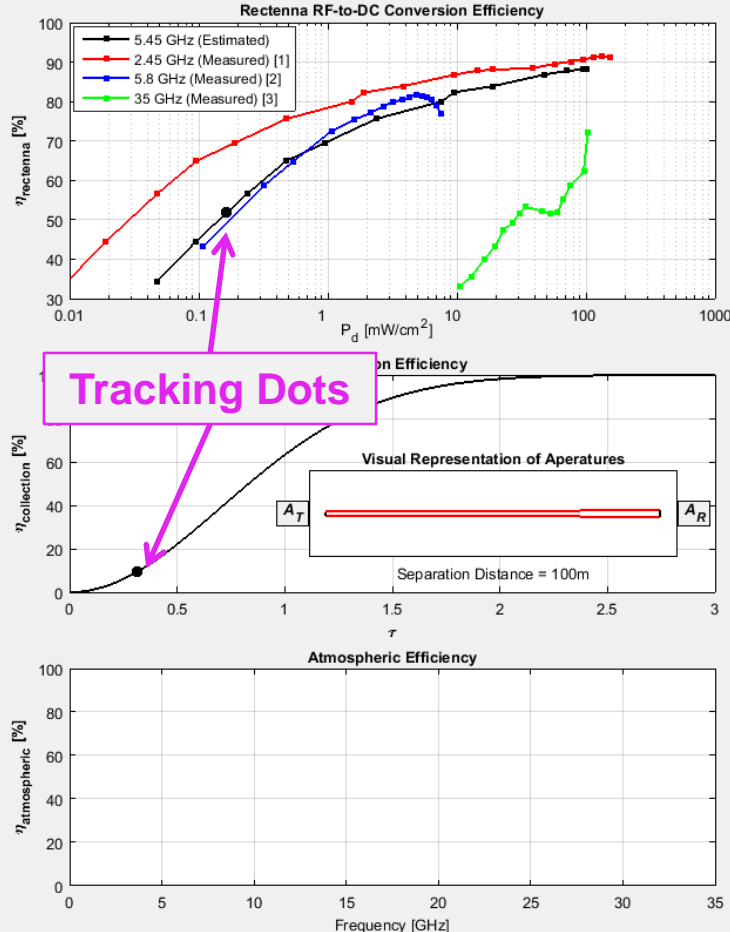
Transmitter Aperture Area (A_T)
☐ Circular ☒ Rectangular
Diameter = -- m
L x W = 1 m X 1 m

Receiver Aperture Area (A_R)
☐ Circular ☒ Rectangular
Diameter = -- m
L x W = 1.5 m X 2 m

Separation Distance (D)
100 m

Parametric Analysis
Select Data Point: Data Point 1
Independent Variable: Separation Distance
Dependent Variable: Power Density
Reset All

Output Variables



Analysis Summary

	1	2	3	4
Input Variables				
Frequency [GHz]	5.4500	--	--	--
Power Density [mW / cm ²]	0.1650	--	--	--
Transmitted Power [W]	5000	--	--	--
Transmitter Aperture [m ²]	1	--	--	--
Receiver Aperture [m ²]	3	--	--	--
Calculated Distance [m]	100	--	--	--
Minimum Distance [m]	4.0622	--	--	--
Efficiency				
Rectenna [%]	51.7903	--	--	--
Collection [%]	9.4265	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	4.8820	--	--	--
Output DC Power				
DC Power [W]	244.1002	--	--	--

Export Data

DC Power Output

Rectenna DC Power [W]

Not enough data points

Power Density [mW/cm²]

EX: 2.3

Instructions Wireless Power Analysis Diode Analysis

Input Variables

Frequency (f)
5.45 GHz

Power Density (p_d)
0.041253 mW / cm²

Transmitted Power (P_T)
5000 W

Transmitter Aperture Area (A_T)
☐ Circular ☒ Rectangular
Diameter = -- m
L x W = 1 m X 1 m

Receiver Aperture Area (A_R)
☐ Circular ☒ Rectangular
Diameter = -- m
L x W = 1.5 m X 2 m

Separation Distance (D)
200 m

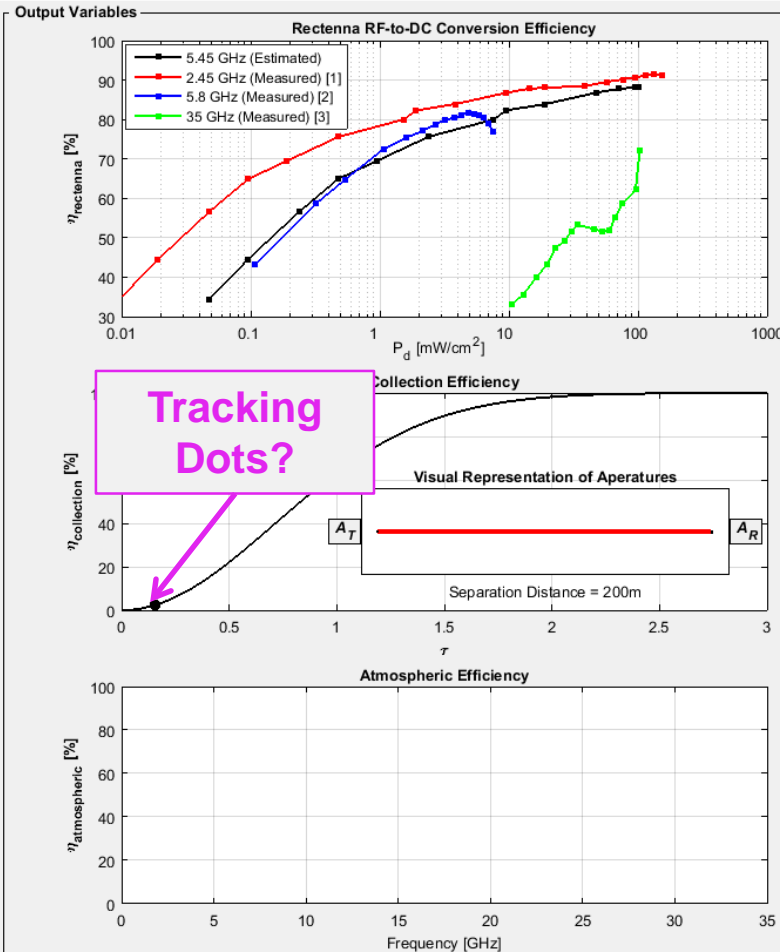
Parametric Analysis

Select Data Point
Data Point 1
Data Point 2
Data Point 3
Data Point 4
Data Point 5
Data Point 6
Data Point 7

Independent Variable
Separation Distance

Dependent Variable
Power Density

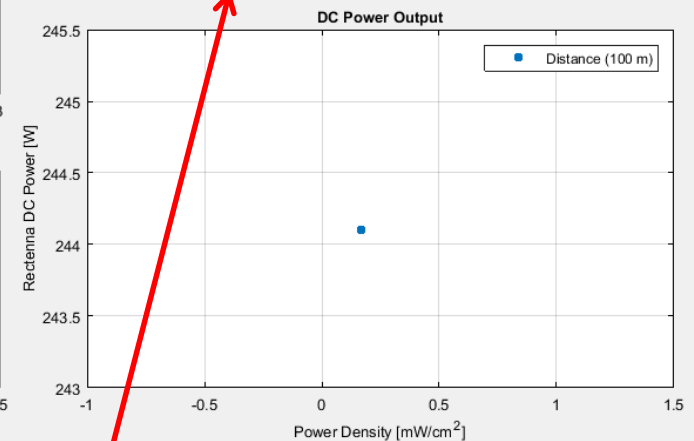
Reset All



Analysis Summary

	1	2	3	4
Input Variables				
Frequency [GHz]	5.4500	--	--	--
Power Density [mW / cm ²]	0.1650	--	--	--
Transmitted Power [W]	5000	--	--	--
Transmitter Aperture [m ²]	1	--	--	--
Receiver Aperture [m ²]	3	--	--	--
Calculated Distance [m]	100	--	--	--
Minimum Distance [m]	4.0622	--	--	--
Efficiency				
Rectenna [%]	51.7903	--	--	--
Collection [%]	9.4285	--	--	--
Atmospheric [%]	--	--	--	--
Total [%]	4.8820	--	--	--
Output DC Power				
DC Power [W]	244.1002	--	--	--

Export Data



WARNING: One or more variables are out of bounds!

Diode Analysis GUI

“The first component to consider is the nonlinear Schottky diode since the design of the other Rectenna parts depends directly upon the diode’s performance [6].”

Default GUI: Diode Analysis

Wireless Power Analysis Diode Analysis

[Click here to open instructions](#)

Input Variables

Frequency (f)

-- GHz

Diode Inputs

☒ Single Diode

☐ Dual-Diode

SPICE Parameters

Select Diode From Library

MGS801

Series Resistance (R_s)

-- Ω

Built-In Barrier Voltage (V_{bi})

-- V

Reverse Bias Voltage
(V_{bmax})

-- V

Zero-Bias Junction
Capacitance (C_{jo})

-- pF

(Input Name of Diode)

Add Diode to Library

Load (R_L)

-- Ohms

Duty Cycle (Ψ)

-- %

Parametric Analysis

Select Data Point

Diode 1
Diode 2
Diode 3
Diode 4
Diode 5

Reset Diode

Select Data Point

Duty Cycle 1
Duty Cycle 2
Duty Cycle 3
Duty Cycle 4
Duty Cycle 5

Reset Duty Cycle

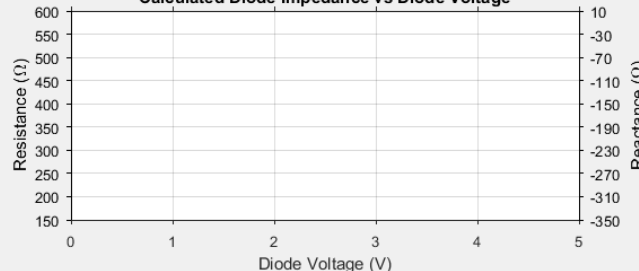
Reset All

Output Variables

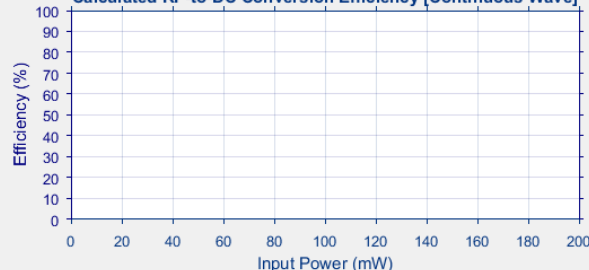
Calculated Diode Impedance vs Load Resistance



Calculated Diode Impedance vs Diode Voltage



Calculated RF-to-DC Conversion Efficiency [Continuous Wave]



Analysis Summary

SPICE Parameters

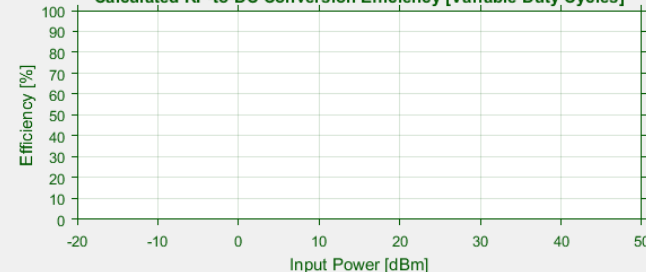
	R_s (Ω)	V_{bi} (V)	V_{bmax} (V)	C_{jo} (pF)	$V_{0,DC}$ (V)
MGS801	--	--	--	--	--
	--	--	--	--	--
	--	--	--	--	--
	--	--	--	--	--
	--	--	--	--	--

Electrical Characteristic of Diode MGS801

Diode Resistance (Ω)	Diode Reactance (Ω)	Load Resistance (Ω)	P_{in} (mW) ($\Psi = 100\%$)	RF-to-DC Conversion Efficiency [%]	P_i (Ψ)
--	--	--	--	--	--
--	--	--	--	--	--
--	--	--	--	--	--
--	--	--	--	--	--
--	--	--	--	--	--
--	--	--	--	--	--
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--	--	--	--	--	--
--	--	--	--	--	--
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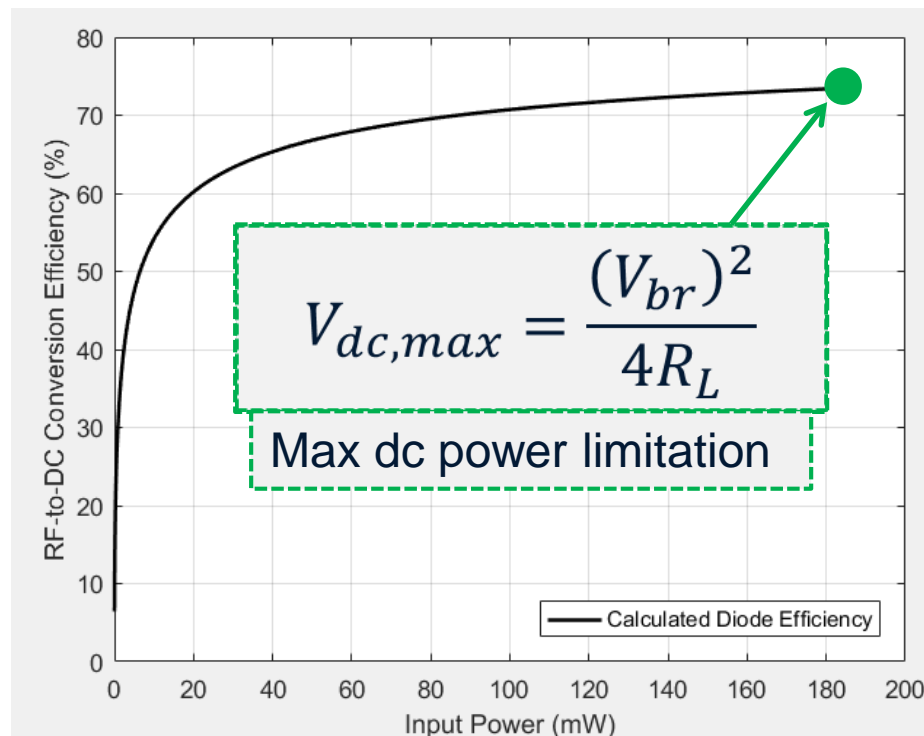
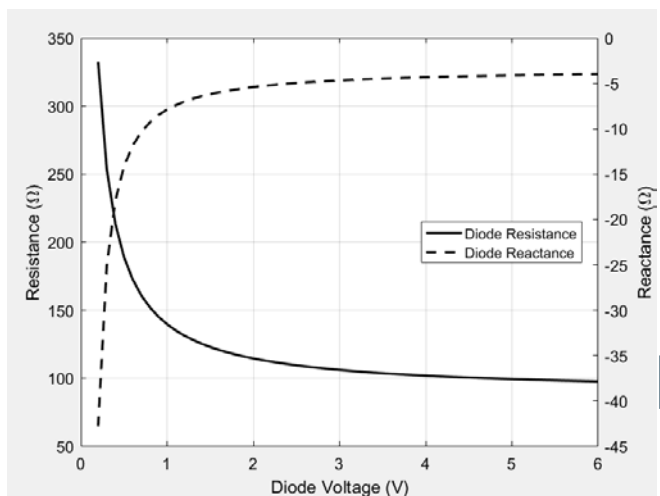
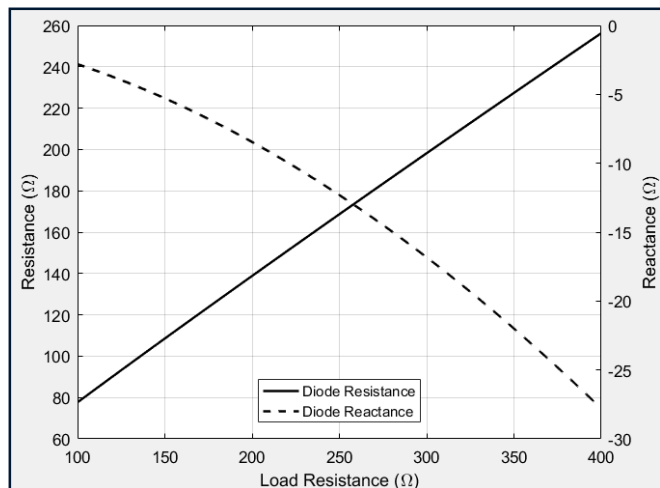
Export Selected Diode

Calculated RF-to-DC Conversion Efficiency [Variable Duty Cycles]



Example Diode Component

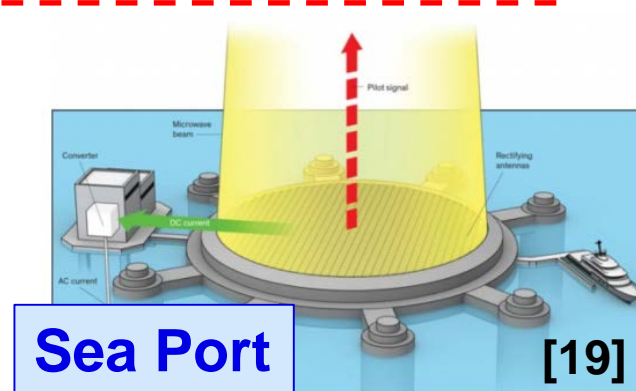
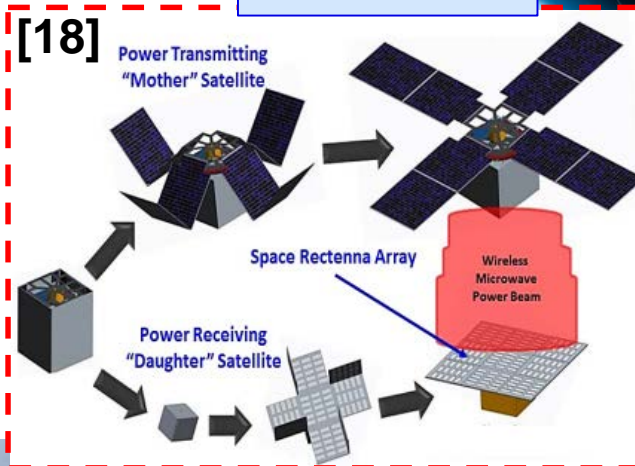
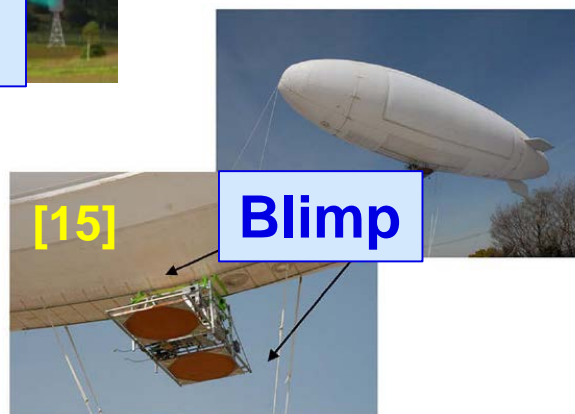
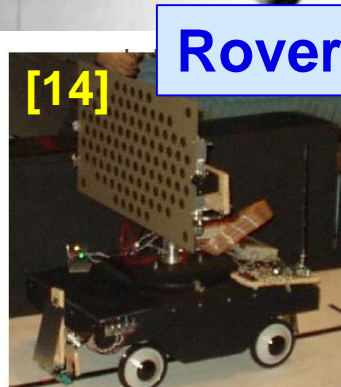
Enter Diode SPICE parameters



$$V_{O,dc} = \frac{V_{br}}{2}$$

Voltage across the diode limitation

THANK YOU FOR YOUR TIME & ATTENTION



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