

Radio Design 201 Microwave Circuits and Antennas

Episode 7, Part 2 – Antenna Analysis and Simulation

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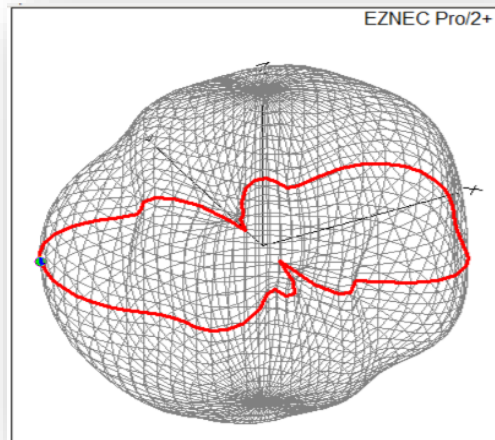
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In this second part of Episode 7, we dive deeper into solutions to the Maxwell equations relevant to antennas. We begin with a review, including the solutions in the so-called “far-field”, but then discuss how to find what is happening at the antenna interface as well. This includes the concept of antenna impedance and the mathematics needed to understand how it changes for different antenna designs. As always, the focus is on engineering rather than mathematical methods. But the presentation remains at the level of the university course on which the video is based and designed to support.

Far-field solution:

$$E_x = E_o \cos\left(2\pi f\left(t - \frac{Z}{c}\right)\right) \quad \text{and} \quad B_y = \frac{1}{c} E_x$$

$$\text{With } c = \sqrt{\frac{1}{\mu_o \epsilon_o}} = 2.998E8 \text{ meters/second}$$



Current = 1 A at 0.0 deg.

Voltage = 83.13 V at 2.64 deg.

Impedance = 83.04 + j 3.83 Ohms

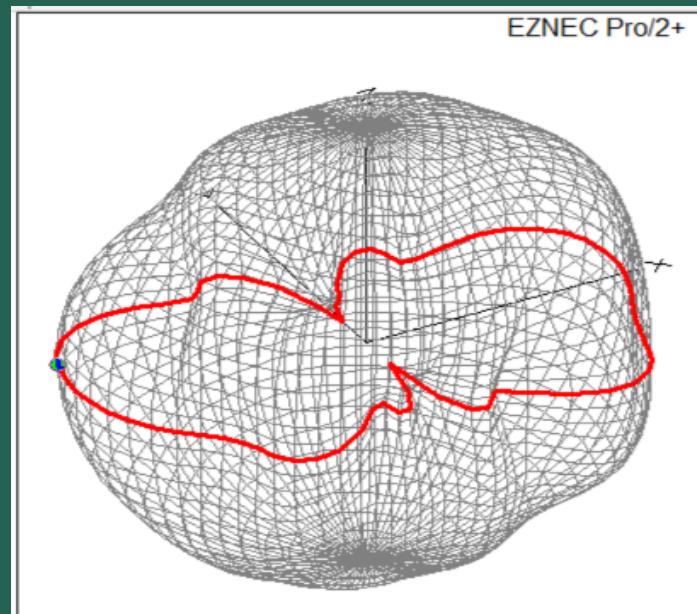
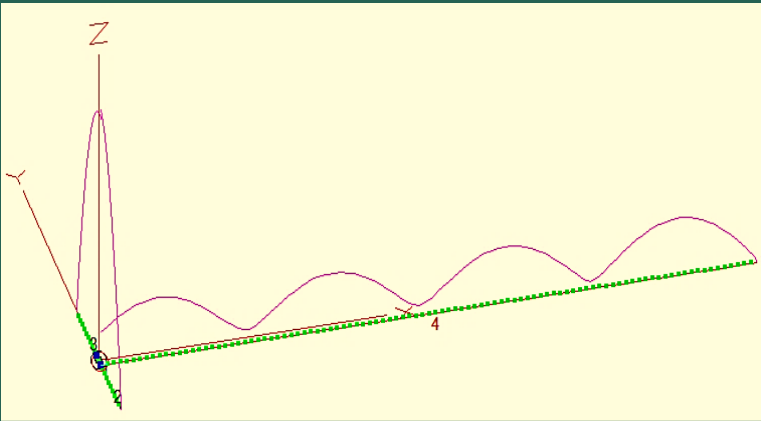
SWR (50-Ohm system) = 1.66

Microwave Circuits and Antennas

Radio Design 201 #7 Part 2

Antenna Analysis & Simulation

(Currents, Patterns, Gain, and Impedance)

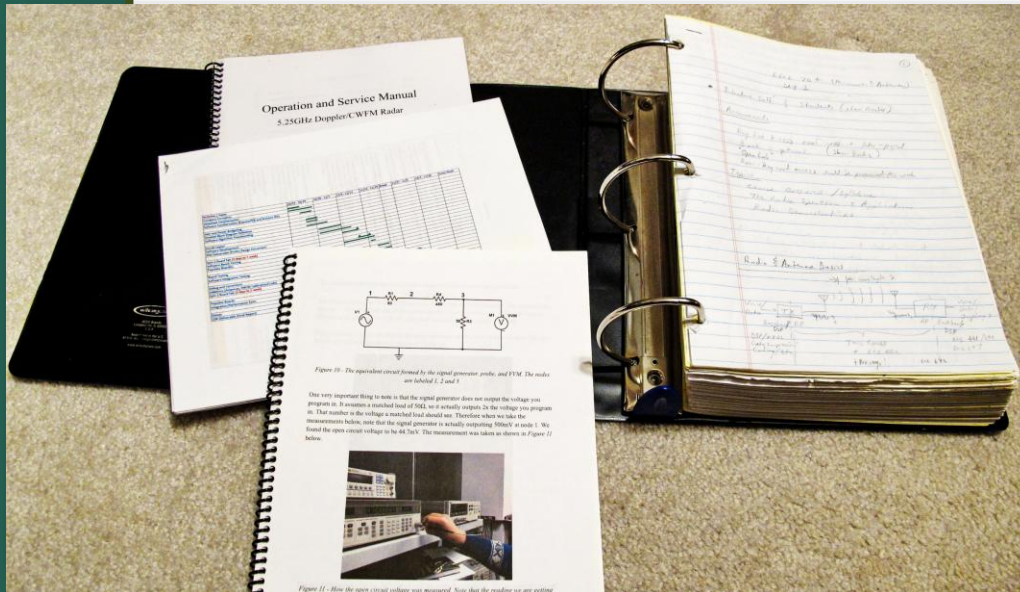


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Today's "Lecture"

Announcements

Lab 2 "assigned" in Episode 7, Part 1



Topics



Quick Review of Part 1

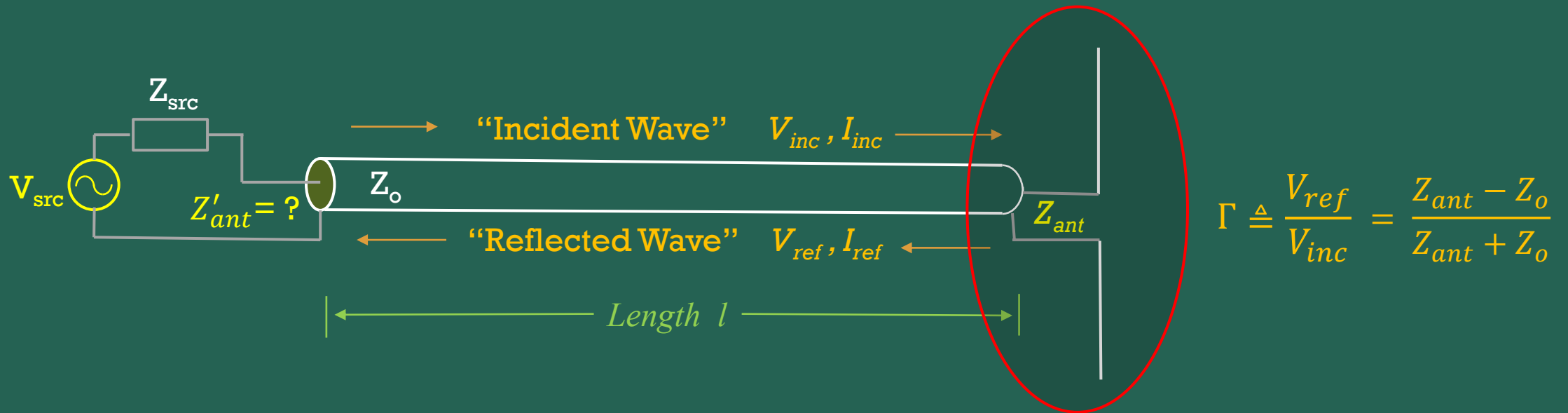
*Antenna Examples and Essential Theory
Impedance and Reflection coefficient
S11, Return loss, and VSWR - with Demo*

Solutions to Maxwell equations

Finding currents, impedance, and far-field patterns for any antenna

EM Simulators (e.g. EZ-NEC)

Antenna and Feedline System



$|\Gamma| < 0.3$ (S11 < -10 dB) is OK: (about 90% of incident Power is radiated)

$|\Gamma| < 0.1$ (S11 < -20 dB) is Excellent: (99% of incident Power is radiated and $Z'_{ant} \approx Z_{ant}$)

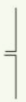
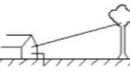
NOTE: $Z'_{ant} = Z_o \frac{1 + \Gamma'}{1 - \Gamma'}$ $\Gamma' = \Gamma e^{-j(2)2\pi \frac{l}{\lambda}}$ (To be shown in a future episode)

Antenna Designs

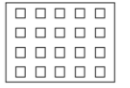
Antenna Examples

Antennas come in a nearly infinite number of shapes and sizes. Here are a few of the more common ones. Note that many commercial designs are variations or combinations of these.

"Non-directional" Types

Antenna		Impedance	Features
1) Halfwave Dipole		$73 + j0$ Ohms	Relatively isotropic, simple construction
2) Folded (halfwave) Dipole		$300 + j0$ Ohms	Similar to dipole. Higher impedance. Sometimes used in simple vertical arrays.
3) Quarterwave Monopole		$36 + j0$ Ohms	Similar to dipole. Ground-plane often abbreviated (e.g. case of cell-phone is ground plane)
4) Short Monopole		$R - jX$ $R \ll 36, X \text{ large}$	Physically shorter than quarterwave monopole, but requires resonating coil and/or matching network.
5) Loaded monopole		$R + j0$	Similar to short monopole, but resistive input impedance. Can be engineered to be nominally 50 Ohms.
6) Simple longwire		Varies Widely	Simple useful design at low freq (e.g. < 30 MHz). Often used for shortwave receivers.
7) Simple large loop or smaller resonant loop		Varies Widely	Simple, low-cost. Popular for indoor UHF TV antennas in "the old days".. Resonant loop used in KeyFobs today.
8) Small ferrite-core loop		$R + jX$	Physically small with large effective aperture. Used in portable AM broadcast receivers and other LF to HF products.
9) Microstrip patch		50 Ohms	Simple, low-cost. Useful mainly at high frequency (e.g. good for GPS).
10) Other	Inverted F, small loaded patches, etc.	50 Ohms	Simple, low-cost designs for PC boards. May use high-K dielectrics to make antenna much smaller than a wavelength.

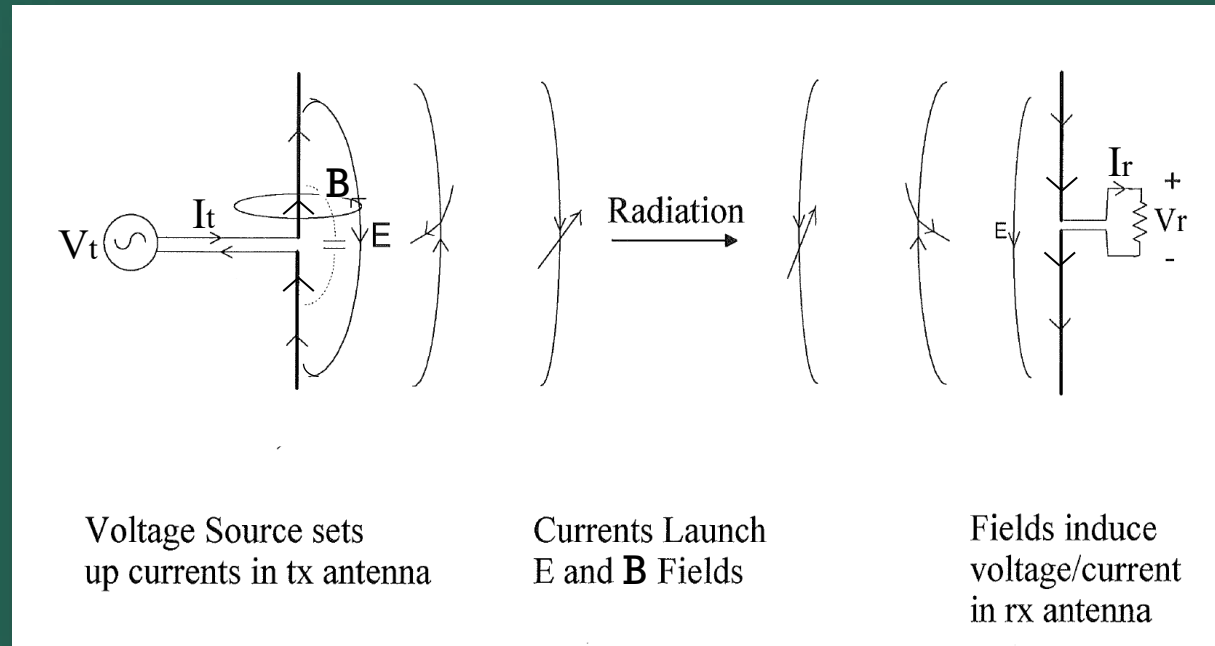
Directional Designs

1) Yagi-Uda		Moderate gain (10 dB) Good front-to-back ratio. Relatively simple construction.
2) Log-Periodic		Similar to Yagi-Uda, but broadband. Lower gain and less directivity.
3) Corner Reflector		Good "sector-coverage" (i.e. beamwidth of 90 to 120 degrees with excellent front/back ratio). Often used in cell-towers.
4) Horn		Gains to about 12 dB. Good illumination pattern for dish antennas.
5) Helix		Circular polarization. Moderate gain, and good illumination for dish antenna.
6) Linear, vertical array (tower-mounted dipoles)		Concentrates power toward horizon for max range. Used in public-safety (police/fire/etc.) Used in cell-towers when array embedded in corner reflector.
7) Parabolic dish		High-gain, narrow-beamwidth. Simple, low-cost construction.
8) 2-D Phased-array Array of microstrip patches, or waveguide slots		High-gain, narrow-beamwidth, rapid-steering. Relatively high cost.

Far-Field Calculations (The easy way)

(from previous Episodes and Antenna Briefs Episode 6)

$$P_t = \frac{V_t^2}{R_{ant}} *$$
$$= I_t^2 R_{ant}$$



$$V_r = E L_{eff}$$

$$P_r = \frac{V_r^2}{R_{in}}$$

$$P_{density} = \frac{P_t G_t}{4 \pi d^2} = \frac{|E|^2}{Z_o}$$

$$E = \sqrt{P_{density} Z_o}$$

* For Resonant Dipole (where $Z_{ant} = R_{ant} + j0$)

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*Antenna Examples and Essential Theory
Impedance and Reflection coefficient
S11, Return loss, and VSWR - with Demo*



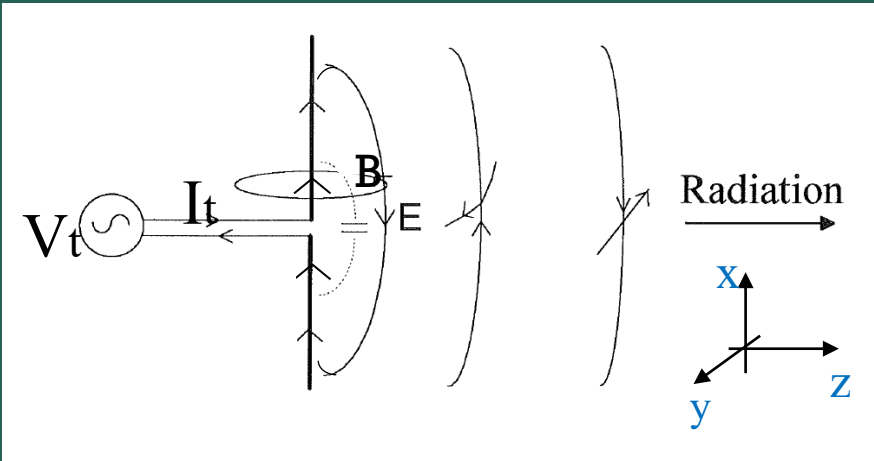
Solutions to Maxwell equations

Finding currents, impedance, and far-field patterns for any antenna

EM Simulators (e.g. EZ-NEC)

Maxwell Equations, Far-Field Solution

(from Antenna Briefs, Episode 5)



Maxwell's Equations

Differential form

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

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

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

Far from source (antenna),
Maxwell's equations
simplify to:

$$\frac{\Delta E_x}{\Delta z} = -\frac{\Delta B_y}{\Delta t}$$

$$-\frac{\Delta B_y}{\Delta z} = \mu_0 \epsilon_0 \frac{\Delta E_x}{\Delta t}$$

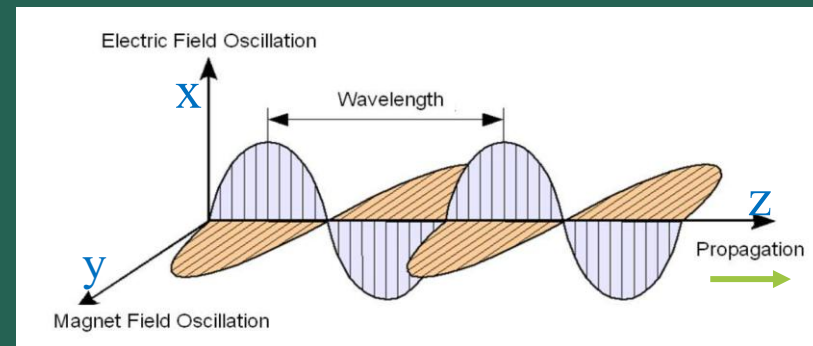
From: <https://owlcation.com/stem/maxwell-equations-displacement-current>

From: <http://cleanenergywiki.org/index.php?title=File:Emwavepropagation.jpg>

Far-field solution:

$$E_x = E_0 \cos\left(2\pi f\left(t - \frac{z}{c}\right)\right) \quad \text{and} \quad B_y = \frac{1}{c} E_x$$

With $c = \sqrt{\frac{1}{\mu_0 \epsilon_0}} = 2.998E8$ meters/second



Far-field plus Near-field Solution

Maxwell's Equations

Differential form

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

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

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

From:

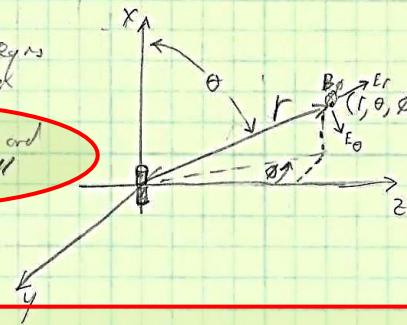
<https://owlcation.com/stem/maxwell-equations-displacement-current>

Computing Antenna
Radiation Patterns (& Hence Gain/Impedance, etc)

Approaches:

1) Solve Maxwell's Eqs for each antenna

2) Solve for 1 case and apply linearity "



Consider short segment ^{with} at origin as shown, carry current $I e^{j\omega t}$

Solving Maxwell's Eqs: (see EM text book)

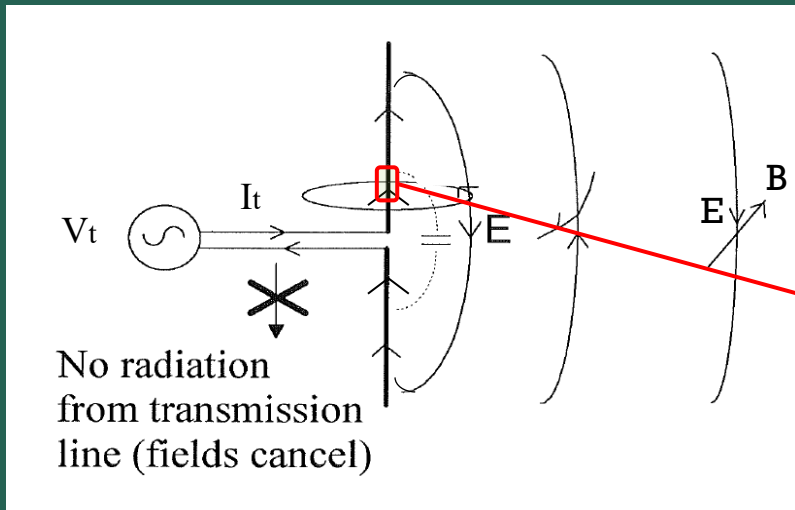
$$E_\theta = 30 I L \beta^2 \sin \theta \left[\frac{j}{\beta r} + \frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right] e^{j\omega t} e^{-j\beta r}$$

$$E_r = 60 I L \beta^2 \cos \theta \left[\frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right] e^{j\omega t} e^{-j\beta r}$$

$$B_\phi = \frac{\mu_0}{4\pi} I L \beta^2 \sin \theta \left[\frac{j}{\beta r} + \frac{1}{(\beta r)^2} \right] e^{j\omega t} e^{-j\beta r}$$

$$\text{where } \beta \triangleq \frac{\omega}{c} = \frac{2\pi}{\lambda}$$

Far Field Pattern Analysis



NOTES:

- In "Far Field" $\frac{1}{(br)^2}, \frac{1}{(br)^3} \rightarrow 0 \Rightarrow$

$$E \equiv E_\theta = 30 I L \beta^2 \sin(\theta) \frac{j}{br} e^{j\omega t - j\beta r}$$

$$B \equiv B_\phi = \frac{1}{c} E_\theta$$

Complex sinusoid where
 $\frac{j}{br}$ ← Field decreases as $1/r$
 $e^{j\omega t - j\beta r}$ ← Phase shift as r changes
 $\sin(\theta)$ ← max at $\theta = 90^\circ$ (Broadside)
 $377/4\pi$
- For Field begin at $(br \gg 1) \Rightarrow r \gg \frac{1}{\beta} = cr, r \gg \frac{\lambda}{2\pi}$ e.g. $r \gg 22\lambda$
- Fields for any wire antenna found from superposition: e.g. For $\lambda/2$ dipole:

assumed current amplitude

$$E_\theta = 30 \beta^2 \sin \theta \frac{1}{br} e^{j\omega t} \int_{-\lambda/4}^{\lambda/4} I(x) e^{-j\beta r(x)} dx$$

$\approx$ cosine shape

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S11, Return loss, and VSWR - with Demo*

Solutions to Maxwell equations



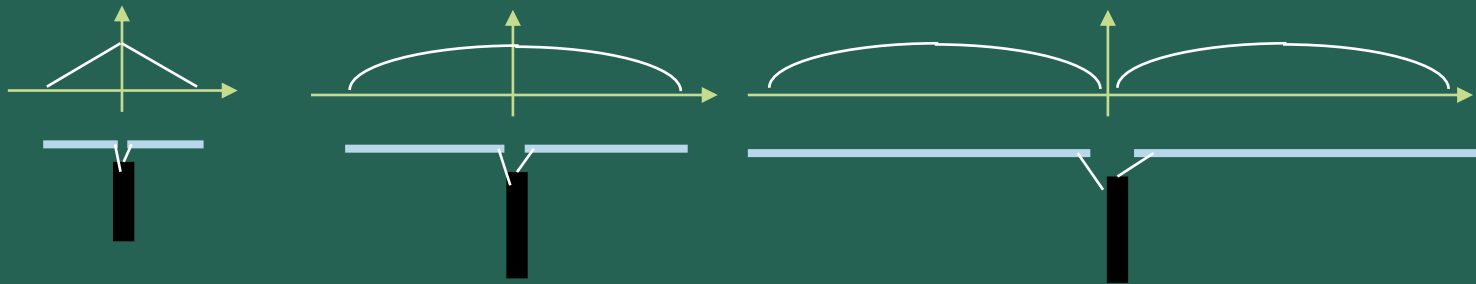
Finding currents, impedance, and far-field patterns for any antenna

EM Simulators (e.g. EZ-NEC)

Finding Currents in Antennas and Far-Field Patterns

Finding $I(x)$ Function

- *Guesstimate* based on velocity of propagation / wavelength, and boundary conditions:

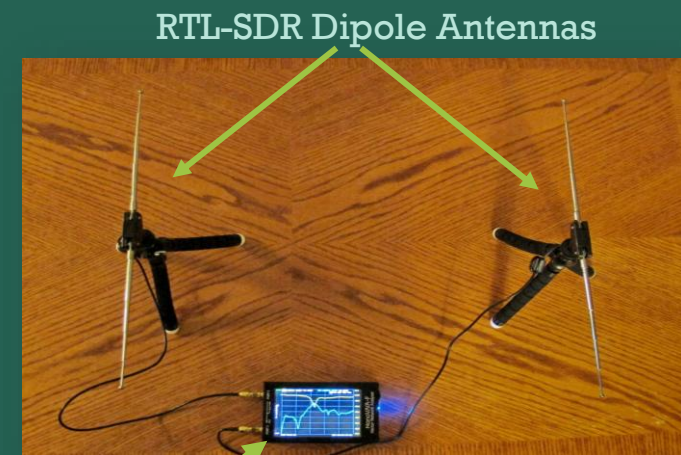


- And/or use EM simulator – e.g.:

- NEC or EZNEC
- Ansys HFSS
- Keysight ADS/Empro
- QucsStudio or uSimmics

Finding Far-Field Patterns

- Do integrals ☹
- Use simulator
- Build and measure !



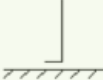
NanoVNA
(Transmitter, receiver, display ☺)

Analyzing Antenna Impedance

Antenna Examples

Antennas come in a nearly infinite number of shapes and sizes. Here are a few of the more common ones. Note that many commercial designs are variations or combinations of these.

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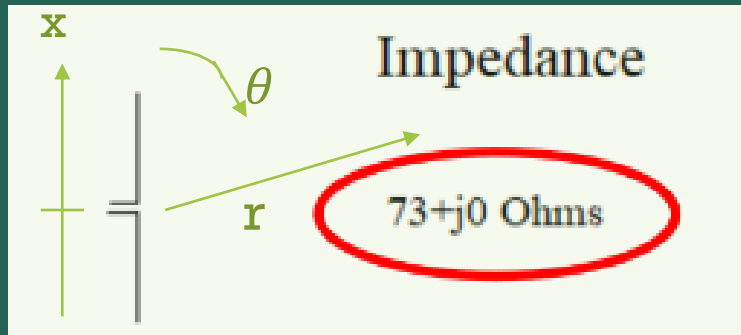
- Find *far-field* pattern and E-field strength as above
- Integrate $\frac{|E|^2}{Z_{o \text{ free-space}}}$ over full sphere around antenna to find total radiated power P_{tot}
- Set equal to $P_{tot} = I^2 R_{ant}$ and solve for R_{ant}

Doing it the Hard Way

Some of the math we're going to try to avoid ...

Problem:

Analytically prove that $R_{ant} = 73\Omega$ for a half-wave dipole at resonance



Solution Outline:

- Assume $I(x) \approx I_0 \cos(x)$ for $-\frac{\lambda}{4} < x < \frac{\lambda}{4}$
- Find E_θ in the broadside direction ($\theta = 90^\circ$) at distance r from a single segment of length dx
- Integrate (add) contributions to total E_θ from all segments along antenna (from $x = -\frac{\lambda}{4}$ to $\frac{\lambda}{4}$)
- Approximate total E_θ at other angles as scaled by $\sin(\theta)$ **CAUTION: Approx valid if length $\leq \frac{\lambda}{4}$ only !**
- Integrate $dP = \frac{|E_\theta|^2}{Z_0}$ over surface of sphere at distance r to get total radiated power
- Equate to $P = I_0^2 R_{ant}$ and solve for R_{ant}

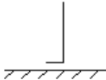
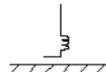
Homework/Study Questions

Antenna Examples

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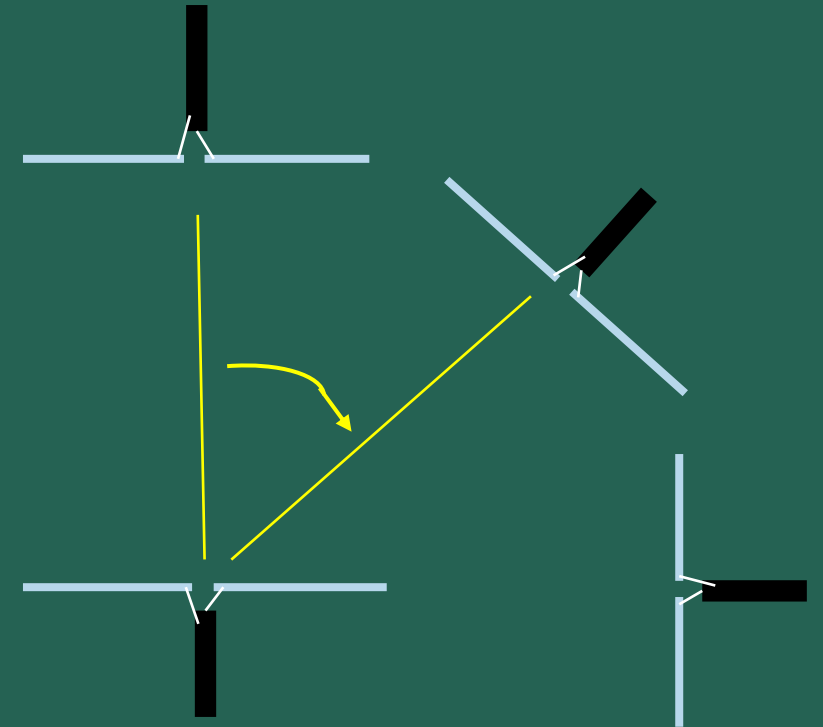
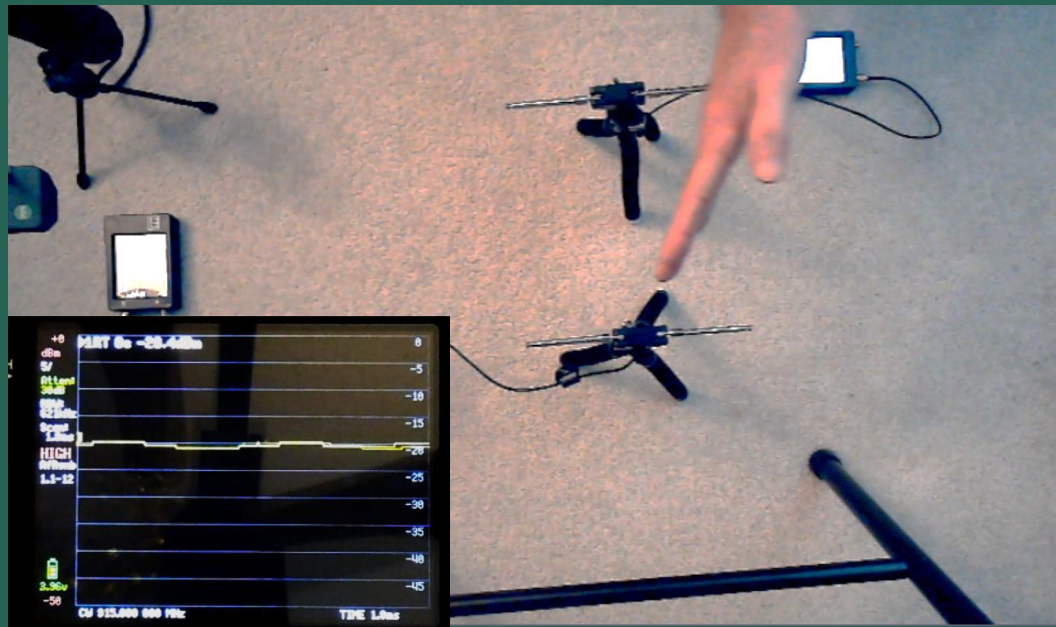
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1. Why is R_{ant} for a half-wave dipole 73 Ohms ?
2. Why is R_{ant} for folded dipole 4x that of value for basic dipole ?
3. Why is R_{ant} for a monopole above large ground-plane only $\frac{1}{2}$ of dipole ?
4. Why does R_{ant} for an electrically-short monopole decrease by $\left(\frac{length}{\lambda/4}\right)^2$ (as X becomes large and negative) ?
5. What would happen to R_{ant} of a half-wave dipole if the feed-point were moved close to one end ?

Pattern and Polarization Measurements

See Antenna Briefs, Episode 6: <https://www.youtube.com/watch?v=VFRIBtFwPiE>



Using *TinySA* instruments with *RTL-SDR antenna kits*
(in a not-so-good home “antenna range” ☺)

Fixed frequency at 915 MHz (unlicensed ISM band)

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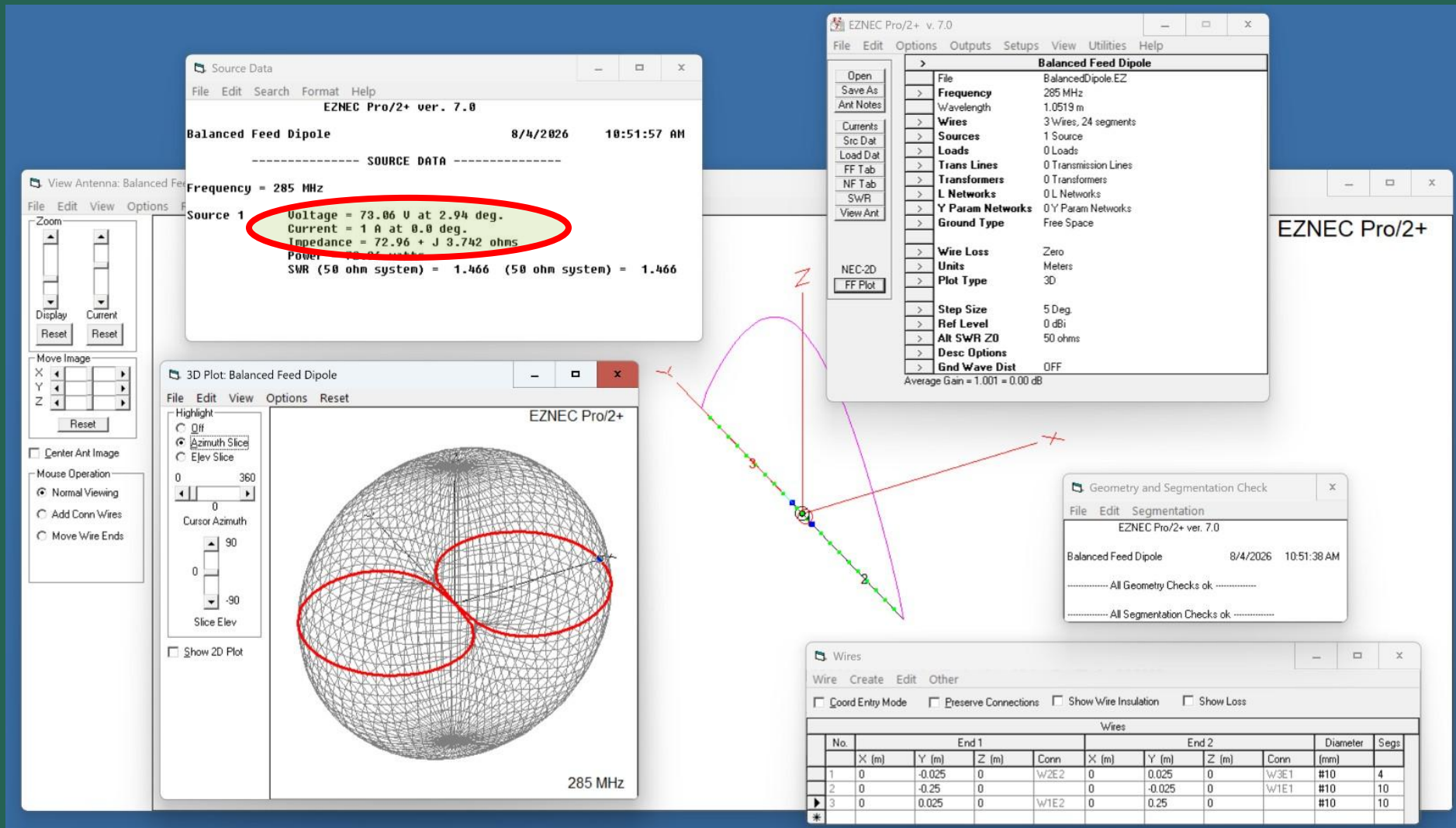
Solutions to Maxwell equations

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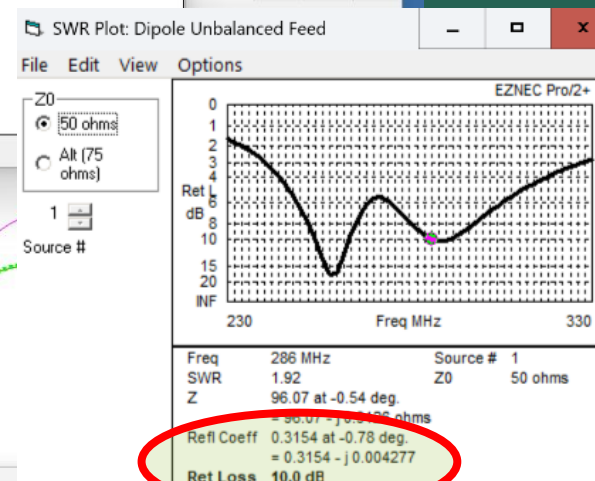
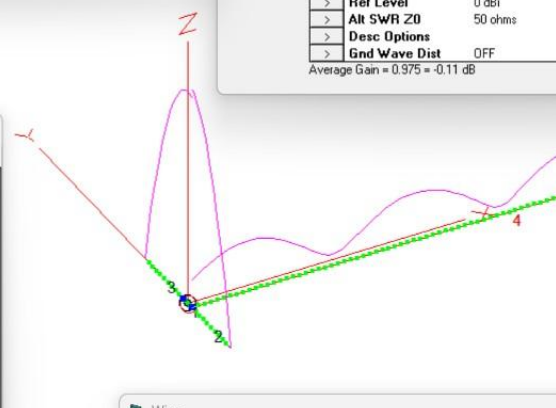
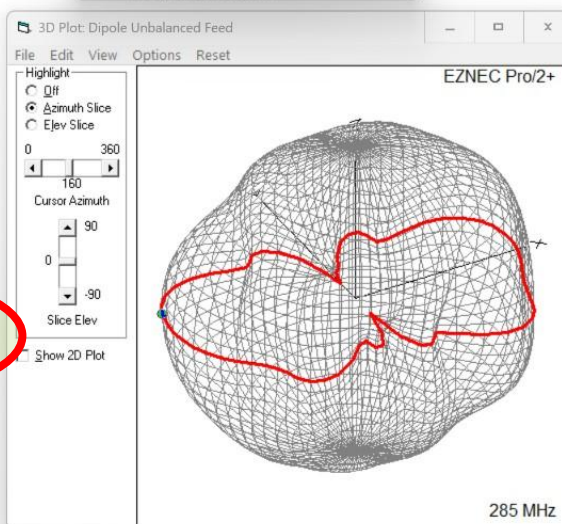
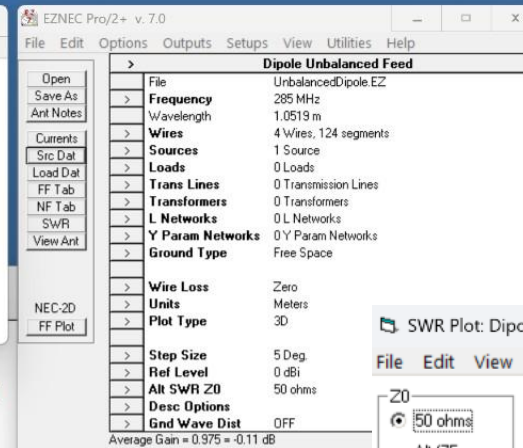


EM Simulators (e.g. EZ-NEC)

Half-wave Dipole Simulation (with EZNEC)



A long, thin, yellowish-green probe with a T-shaped handle and a coiled black cable. The handle has two white rectangular labels attached to its vertical stem. The probe is laid out horizontally against a dark background. A coiled black cable is attached to the right end of the probe.



Wires

Wire

Create

Edit

Other

☐ Coord Entry Mode
☐ Preserve Connections
☐ Show Wire Insulation
☐ Show Loss

Ret Loss

Wires										
No.	End 1				End 2				Diameter [mm]	Segs
	X [m]	Y [m]	Z [m]	Conn	X [m]	Y [m]	Z [m]	Conn		
1	0	-0.025	0	W2E2	0	0.025	0	W3E1	#10	4
2	0	-0.25	0		0	-0.025	0	W4E1	#10	10
3	0	0.025	0	W1E2	0	0.25	0		#10	10
4	0	-0.025	0	W1E1	2	-0.025	0		#10	100

The image displays five screenshots from the EZNEC Pro/2+ software interface, showing various simulation results and antenna models.

Top Left: View Antenna: Dipole Balanced Fullwave

- File Edit View Options Reset
- Zoom: Display, Current, Reset
- Move Image: X, Y, Z, Reset
- 3D Plot: Dipole Balanced Fullwave
- Highlight: Qif, Azimuth Slice, Elev Slice
- Cursor Azimuth: 0 to 360
- Slice Elev: 90 to -90
- Show 2D Plot
- 264 MHz

Top Right: EZNEC Pro/2+ v. 7.0

- File Edit Options Outputs Setups View Utilities Help
- Open, Save As, Ant Notes, Currents, Src Dat, Load Dat, FF Tab, NF Tab, SWR, View Ant, NEC-2D, FF Plot
- File: FullwaveDipole.EZ
- Frequency: 264 MHz
- Wavelength: 1.13558 m
- Wires: 3 Wires, 30 segments
- Sources: 1 Source
- Loads: 0 Loads
- Trans Lines: 0 Transmission Lines
- Transformers: 0 Transformers
- L Networks: 0 L Networks
- Y Param Networks: 0 Y Param Networks
- Ground Type: Free Space
- Wire Loss: Zero
- Units: Meters
- Plot Type: 3D
- Step Size: 5 Deg.
- Ref Level: 0 dBi
- Alt SWR Z0: 1700 ohms
- Desc Options
- Gnd Wave Dist: OFF
- Average Gain = 1.001 = 0.01 dB

Bottom Left: 3D Plot: Dipole Balanced Fullwave

- File Edit View Options Reset
- Highlight: Qif, Azimuth Slice, Elev Slice
- Cursor Azimuth: 0 to 360
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Bottom Center: 2D Plot: Dipole Balanced Fullwave

- File Edit View Options Reset
- Highlight: Qif, Azimuth Slice, Elev Slice
- Cursor Azimuth: 0 to 360
- Slice Elev: 90 to -90
- Show 2D Plot
- 264 MHz

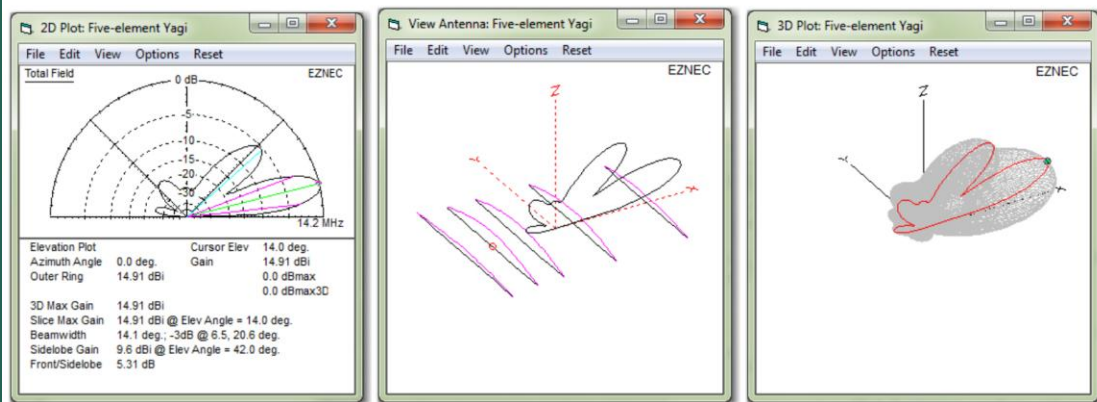
Bottom Right: Source Data

- File Edit Search Format Help
- EZNEC Pro/2+ ver. 7.0
- Dipole Balanced Fullwave
- 8/10/2026 8:44:40 PM
- Frequency = 264 MHz
- Source 1
- Voltage = 1806 V at 3.72 deg.
- Current = 1 A at 0.0 deg.
- Impedance = 1803 + J 117.2 ohms
- Power = 1800 watts
- SWR (50 ohm system) = 36.203 (1700 ohm system) = 1.093

Getting and Learning EZNEC

EZNEC Antenna Software by W7EL

FREE - EZNEC Pro+ v. 7.0 is now available! - FREE



Above: Screen shots from several **EZNEC** displays. **Right:** 3D far field pattern, with 2D elevation "slice" highlighted. Any azimuth or elevation slice can be highlighted. **Center:** View Antenna display, showing the "wires" making up the model of the five-element beam, with currents and 2D slice superimposed to show orientation. Several other items, such as currents and wire numbers, can be added to this display. **Left:** 2D display showing detailed information about the selected slice.

[Download EZNEC Pro/2+ v. 7.0](https://www.eznec.com/)

[Printable manual for EZNEC Pro+](#)

***** Support is no longer available for any type or version of EZNEC program *****

<https://www.eznec.com/>

youtube.com/watch?v=WNPghbiJFbU

YouTube ezneC pro/2+ v. 7.0

Roy, W7EL, explains antenna modelling using EZNEC

G-QRP Club 1.66K subscribers

Subscribe

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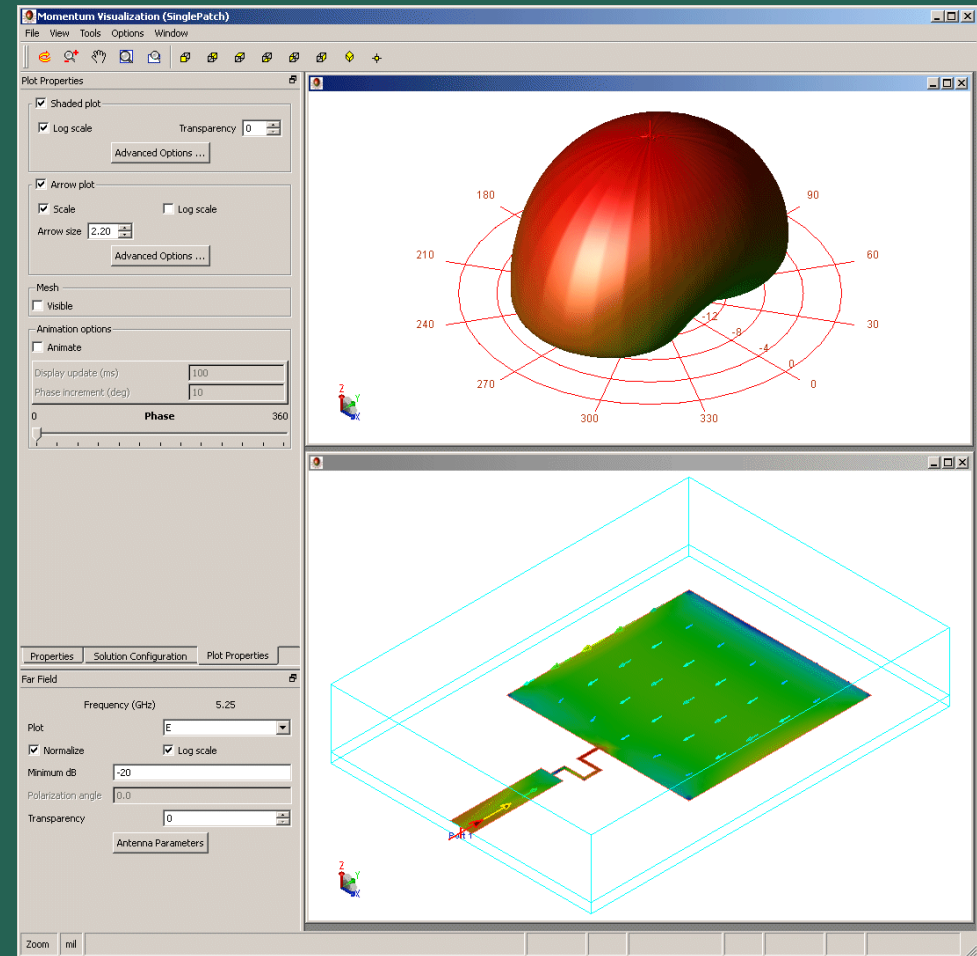
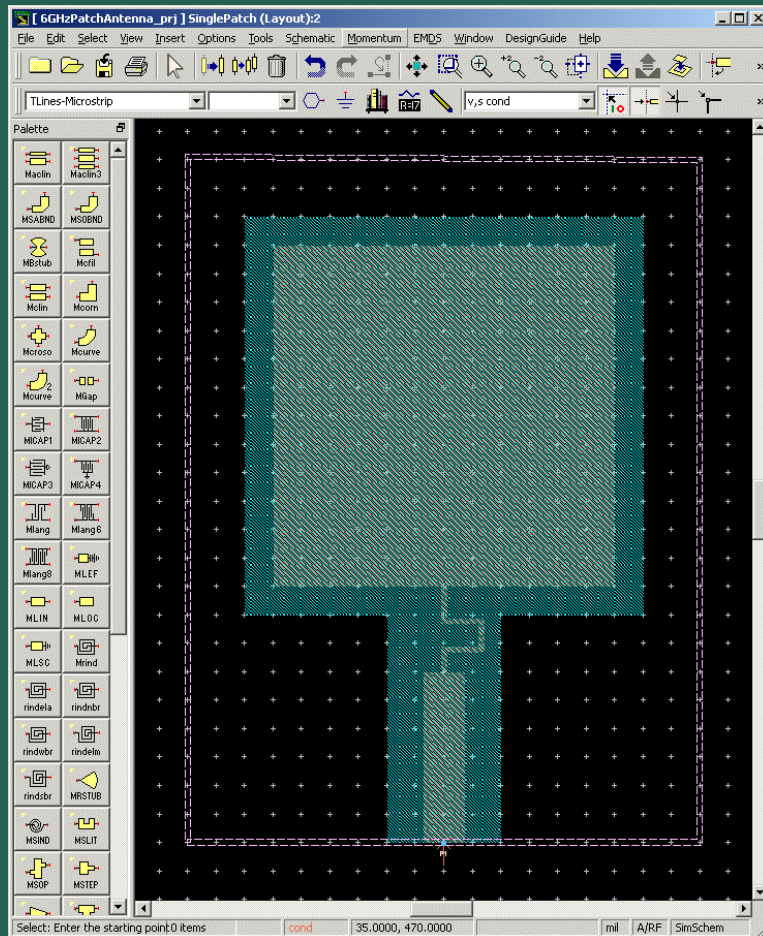
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Ask

...

<https://www.youtube.com/watch?v=WNPghbiJFbU>

Microwave Patch Antenna Simulation (with Keysight Momentum)



Upcoming Episode(s)

Directional Designs

1) Yagi-Uda



2) Log-Periodic



3) Corner Reflector



4) Horn



5) Helix



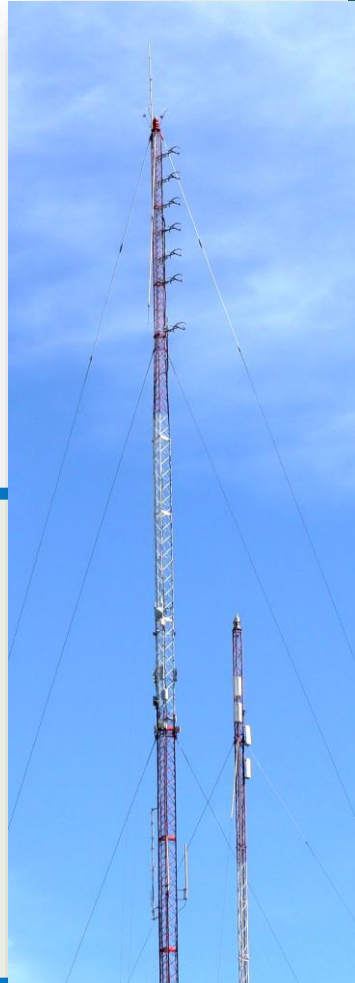
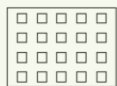
6) Linear, vertical array
(tower-mounted dipoles)



7) Parabolic dish



8) 2-D Phased-array
Array of microstrip patches,
or waveguide slots

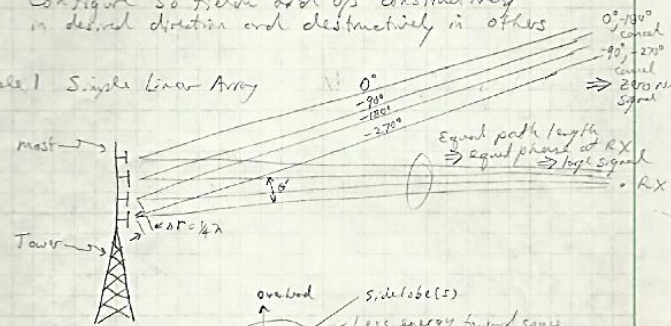


Phased Array Directional Antenna

Basic Concept:

- Use multiple (or distributed) sources
- Configure so fields add up constructively in desired direction and destructively in others

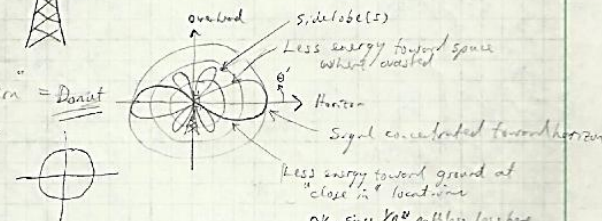
Example 1 Single Linear Array



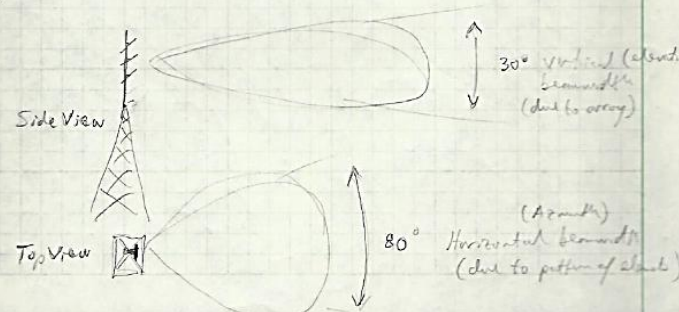
Typical
"Elevation Pattern" = Donut

"Azimuth Pattern"

Omnidirectional



Example 2 Stacked Horizontal Dipoles



Quantitative Analysis

Element #

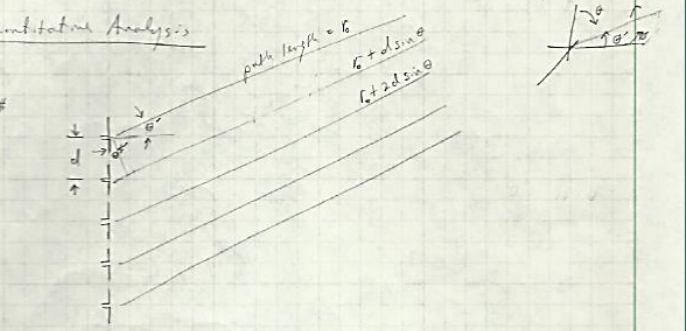
0

1

2

3

4



Field at observation point (r, θ) from element n is
(for short dipole)

$$E_n(r, \theta) \approx 30 I_n L \beta \cos \theta' \frac{1}{r_n} e^{-j\beta r_n} \quad \text{where } \beta = \frac{2\pi}{\lambda} \quad r_n = r_0 + nd \sin \theta$$

OR, in general,

$$= F(\theta) \frac{1}{r_n} I_n e^{-j\beta r_n}$$

And total field is

$$E_{\text{tot}} = \sum_{n=0}^{N-1} F(\theta) \frac{1}{r_n} I_n e^{-j\beta r_n}$$

$$= F(\theta) \sum_{n=0}^{N-1} \frac{1}{r_0 + nd \sin \theta} I_n e^{-j\beta(r_0 + nd \sin \theta)}$$

$$\approx \underbrace{F(\theta) \frac{1}{r_0} e^{-j\beta r_0}}_{\text{Field of single element}} \underbrace{\sum_{n=0}^{N-1} I_n e^{-j\beta d \sin \theta n}}_{\text{"Array Factor"}}$$



NOTE: Array Factor $\sim$ (discrete) Fourier Transform of Excitation currents I_n
if $I_n = \delta[n] = 1$
 $\Rightarrow$ Can pick I_n to give desired pattern using FT theory!

Upcoming Episode(s)

Aperture Antennas

For high gain and narrow beamwidth at low cost, use

- High Frequency (why?)
- Parabolic dish

With typical illumination
i.e. $2\psi = \text{BW}_{\text{hos of feed}}$

$$\text{BW}_{\text{dish}} \approx 70^\circ \frac{\lambda}{D}$$

Example: 2m dish @ 10 GHz

$$\Rightarrow \text{BW} = 70^\circ \frac{30\text{mm}}{2} = 1.1^\circ$$

Recall that narrow beam concentrates power
resulting in high Effective Isotropic Radiated Power

$$\text{EIRP} = P_t G_t$$

Directional gain of dish
Transmitter output power

Can be shown that

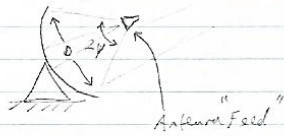
$$G_t \approx 0.5 \left(\pi \frac{D}{\lambda} \right)^2$$

Example: 2m dish, 10 GHz, $P_t = 1\text{W}$

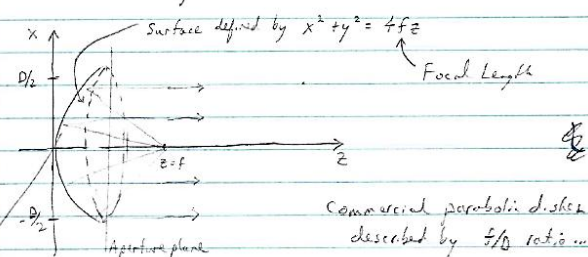
$$\Rightarrow G_t = 0.5 \left(\pi \frac{2}{30\text{mm}} \right)^2 = 44,000$$

$$\Rightarrow \text{EIRP} = 44\text{ kW}!$$

Safety concerns!



Dish Geometry

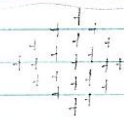


If dish "feed" antenna is at focal point ($z = f$),

- All rays leave dish parallel to z -axis
- All path lengths are equal $\Rightarrow$ equal phase

$\Rightarrow$ Field is uniform throughout aperture (if uniformly illuminated)

$\Rightarrow$ Similar to field from (2-D) discrete array



$\Rightarrow$ Similar for field pattern

$$\text{1-D Dipole array } \text{BW} = 50^\circ \frac{\lambda}{L}$$

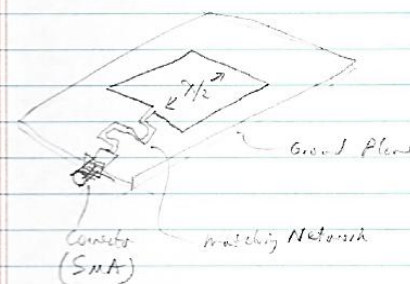
$$\text{2-D Dish } \text{BW} = 70^\circ \frac{\lambda}{D}$$

Non-uniform excitation in aperture plane

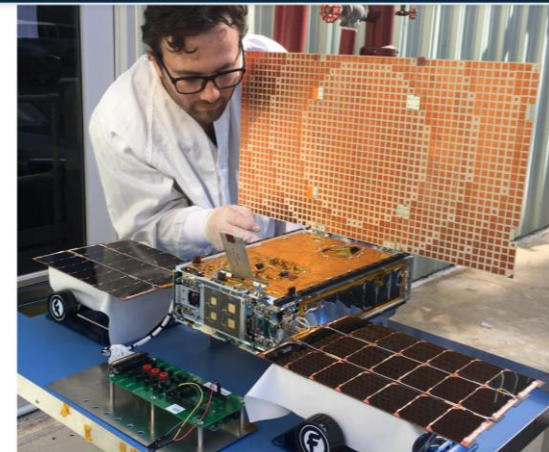
Antenna Feed Examples

- Patch
- Horn
- Helix
- Yagi-Uda
- Log Periodic
- Corner Reflector

Patch Antenna



Approx (rough) model



Engineer Joel Steinkraus uses sunlight to test the solar arrays on one of the Mars Cube One (MarCO) spacecraft.

<https://solarsystem.nasa.gov/mis-sions/mars-cube-one/in-depth/>

*Thanks For
Watching !*