# Radio Design 201 Microwave Circuits and Antennas

# Episode 7, Part 2 – Antenna Analysis and Simulation

Slides downloaded from: https://ecefiles.org/

Companion videos at: https://www.youtube.com/playlist?list=PL9Ox3wpnB0kpOb7NdpHAK-jDpsZm3Xedx

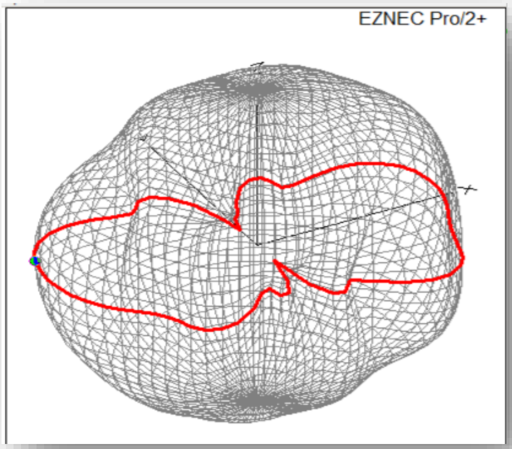


In this second part of Episode 7, we dive deeper into solutions to the Maxwell equations relevant to antennas. We begin with a review, including the solutions in the so-called "far-field", but then discuss how to find what is happening at the antenna interface as well. This includes the concept of antenna 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:

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

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



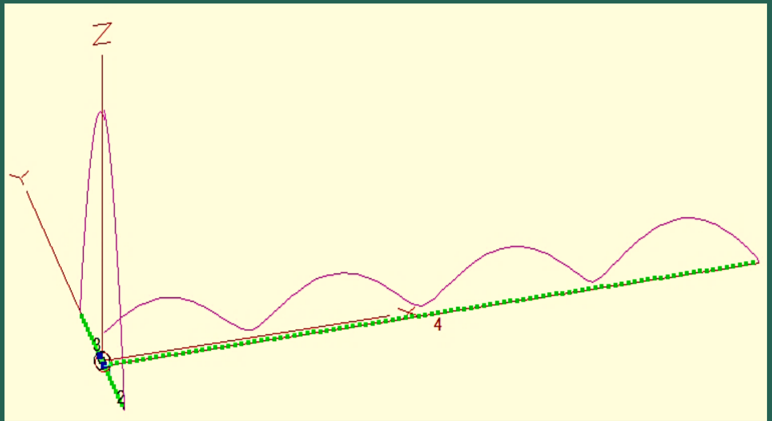

Current = 1 A at 0.0 deg.
Voltage = 83.13 V at 2.64 deg.
Impedance = 83.04 + j 3.83 Ohms
SWR (50-Ohm system) = 1.66

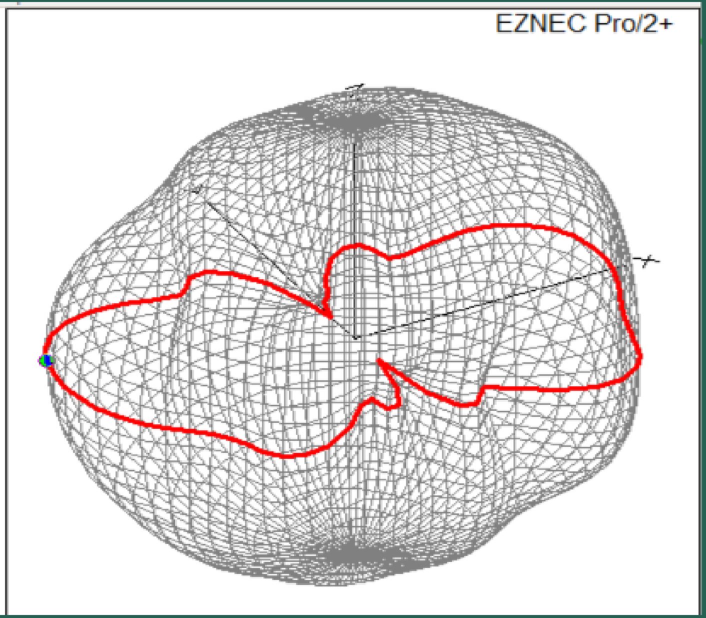
*Microwave Circuits and Antennas*

***Radio Design 201   #7  Part 2***

# Antenna Analysis & Simulation

(Currents,  Patterns, Gain, and  Impedance)

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**SWR (50-Ohm system) =  1.66**

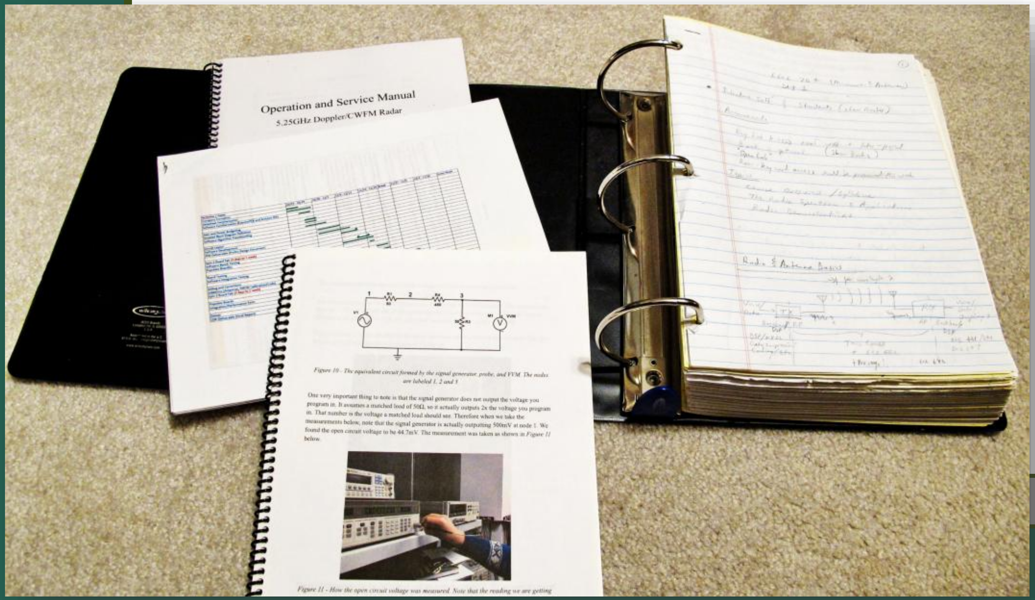
MegawattKS - YouTube

https://ecefiles.org

# Today's "Lecture"

## *Announcements*

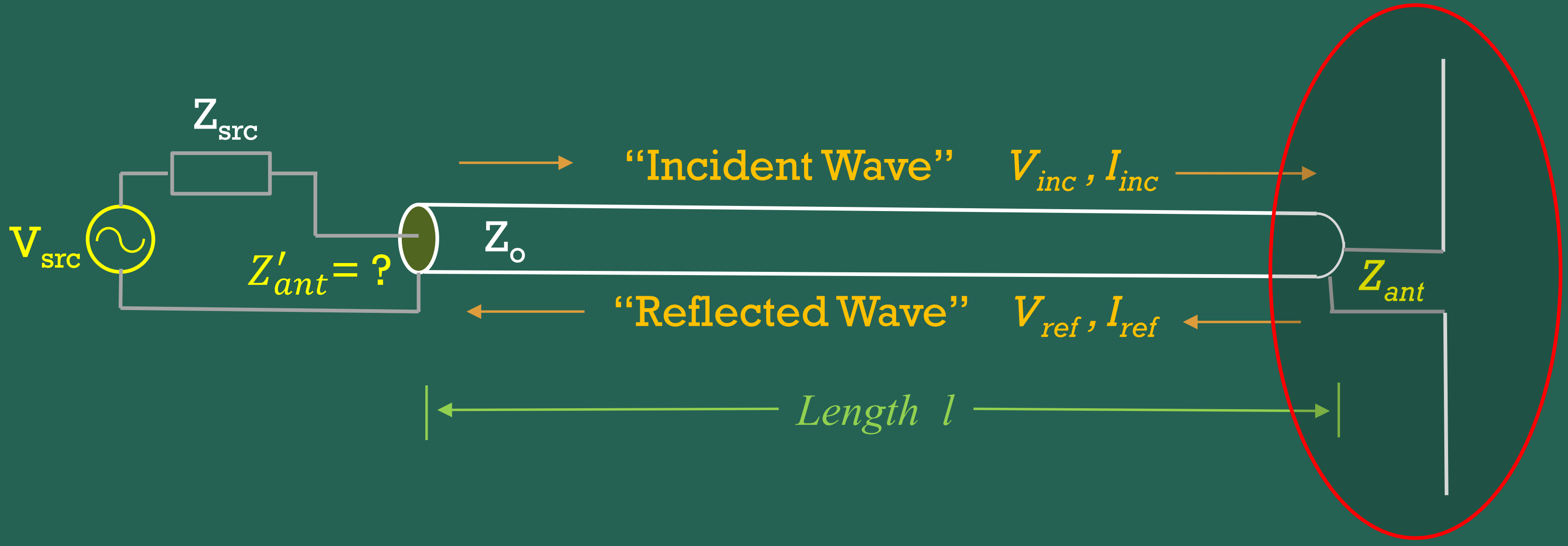
*Lab 2 "assigned" in Episode 7, Part 1*




## *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



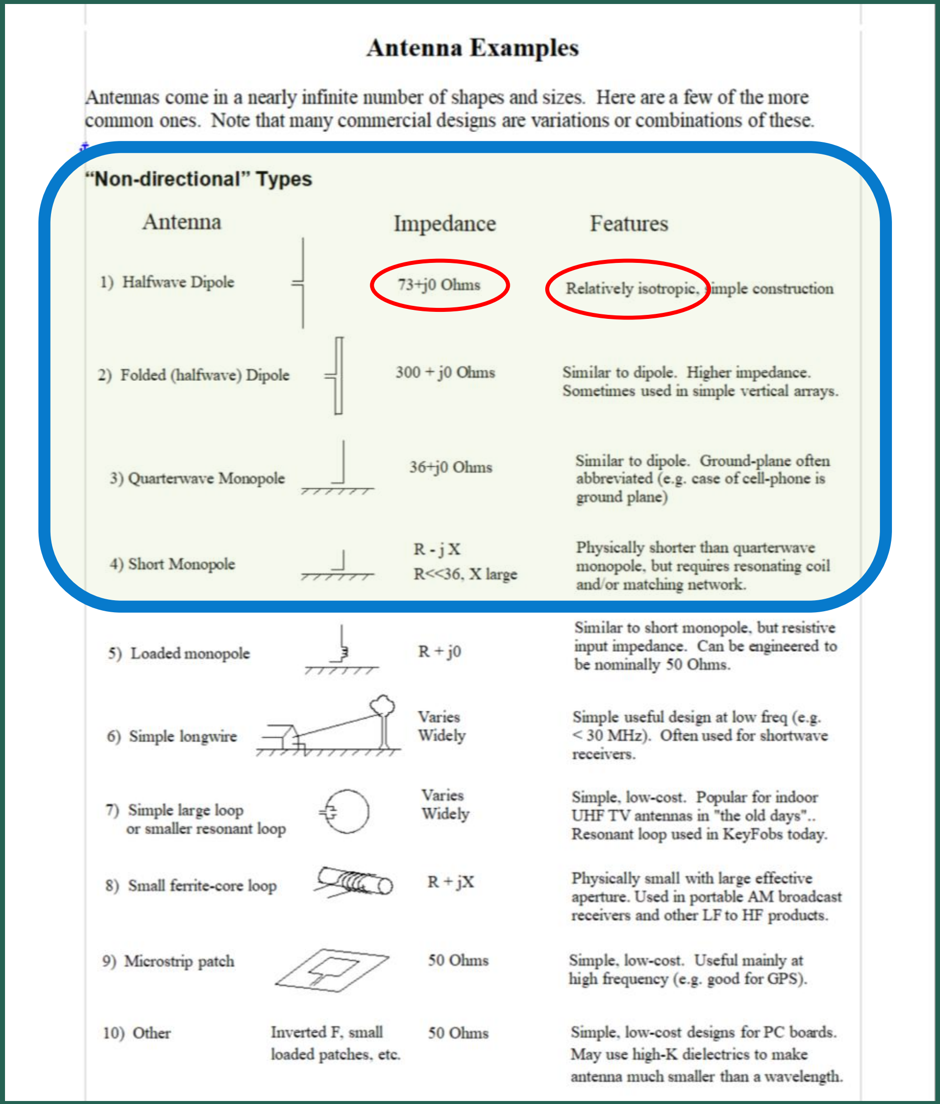

$$\Gamma \triangleq \frac{V_{ref}}{V_{inc}} = \frac{Z_{ant} - Z_o}{Z_{ant} + Z_o}$$

$|\Gamma| < 0.3$ (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

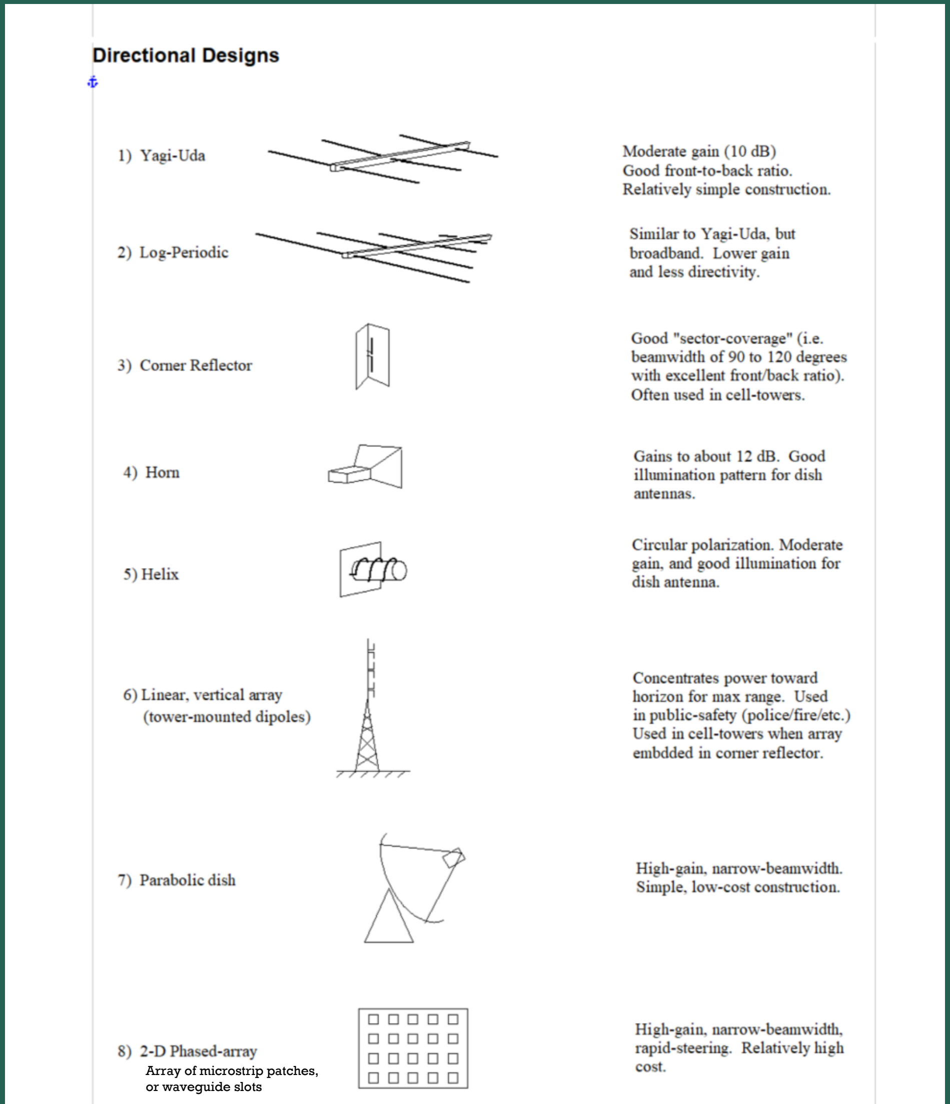


## Antenna Examples

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 - j X<br>R<<36, X 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

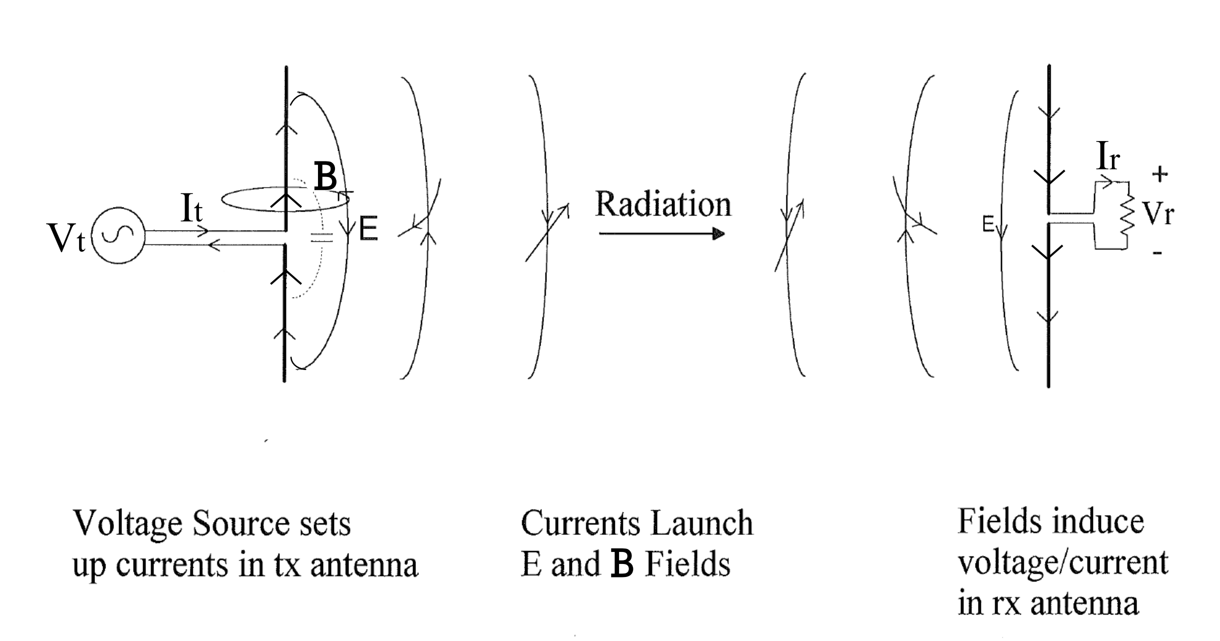
| | |
|---|---|
| 1) Yagi-Uda | Moderate gain (10 dB) Good front-to-back ratio. Relatively simple construction. |
| 2) Log-Periodic | Similar to Yagi-Uda, but broadband. Lower gain and less directivity. |
| 3) Corner Reflector | Good "sector-coverage" (i.e. beamwidth of 90 to 120 degrees with excellent 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 embdded in corner reflector. |
| 7) Parabolic dish | High-gain, narrow-beamwidth. Simple, low-cost construction. |
| 8) 2-D Phased-array<br>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)

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

$$= I_t^{\,2} R_{ant}$$




$$V_r = \mathbf{E}\, L_{eff}$$

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

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

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

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- *Impedance and Reflection coefficient*
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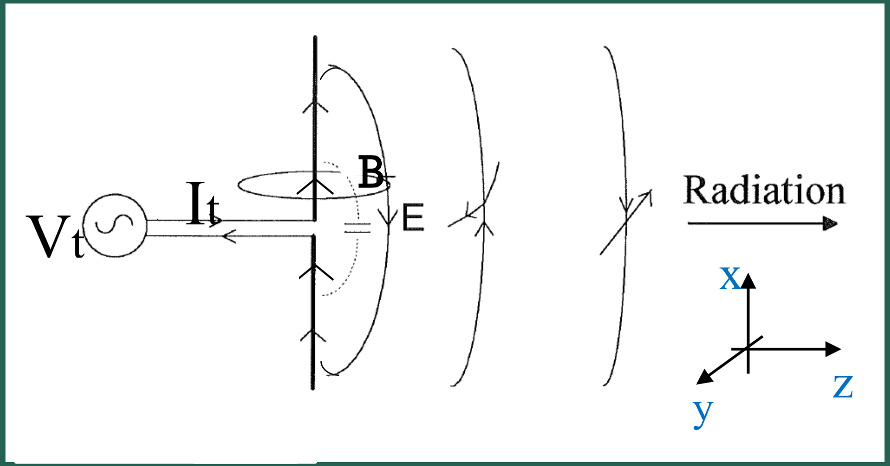
➡ *Solutions to Maxwell equations*

*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

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

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

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

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

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

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

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

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

Far-field solution:

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

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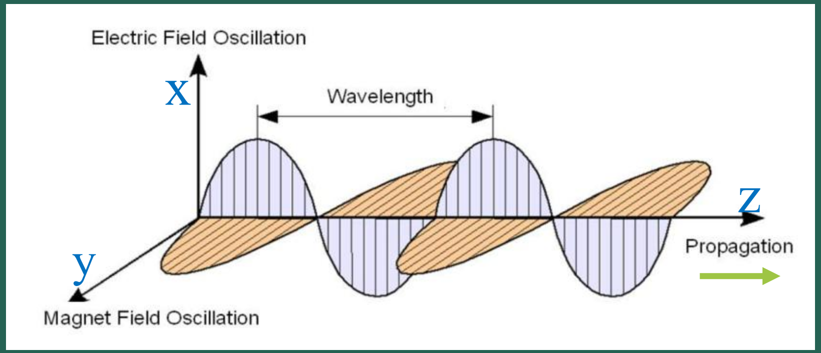
From: http://cleanenergywiki.org/index.php?title=File:Emwavepropagation.jpg



# Far-field *plus* Near-field Solution

## Maxwell's Equations

Differential form

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

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$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

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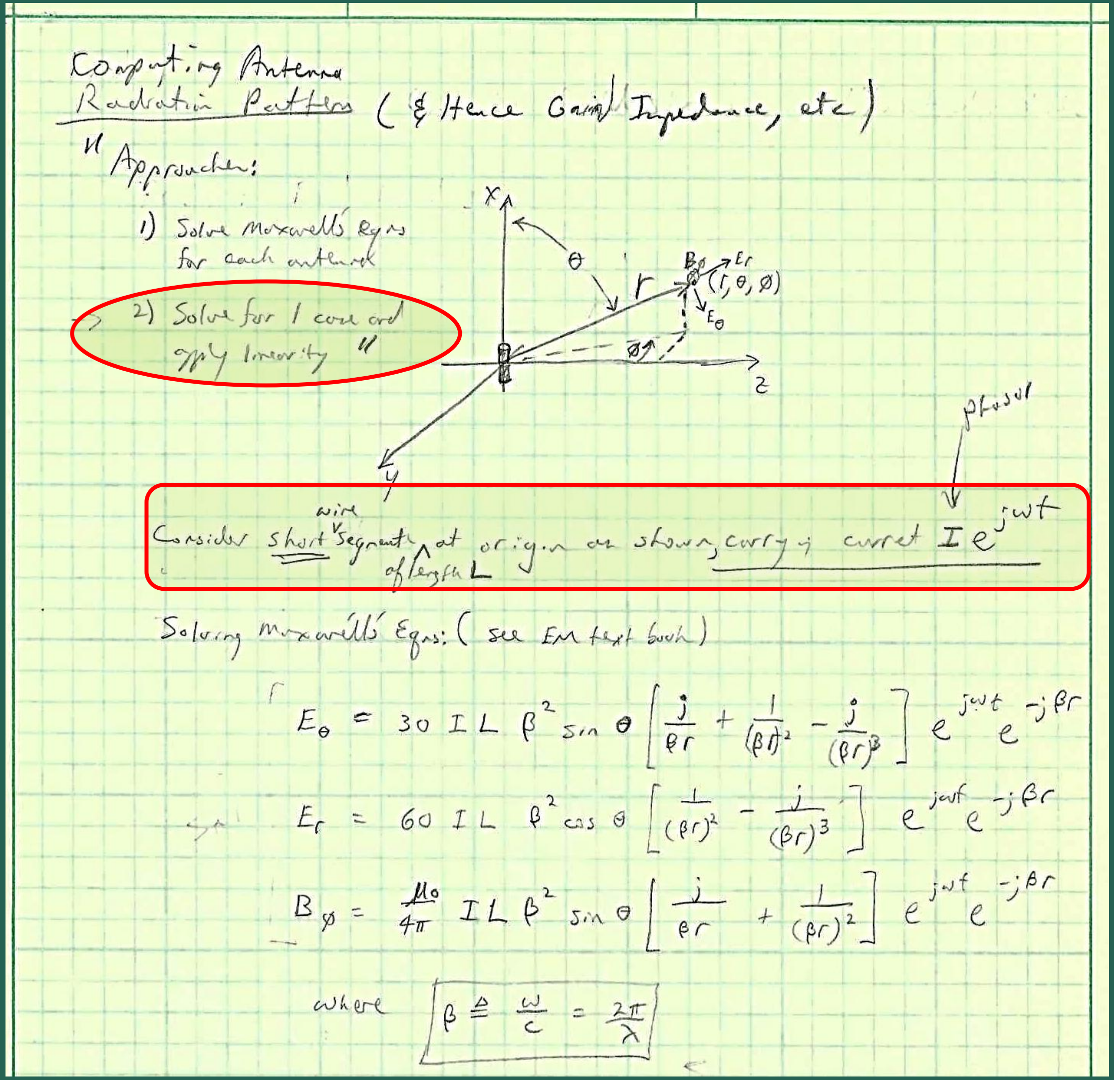
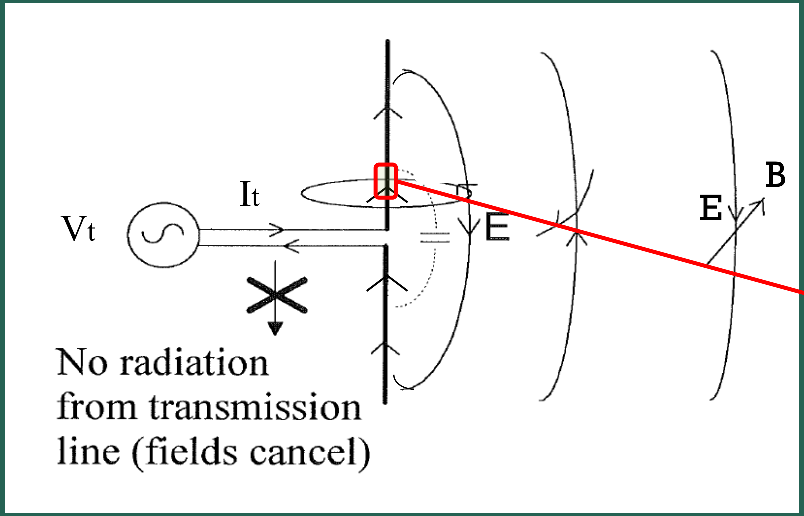
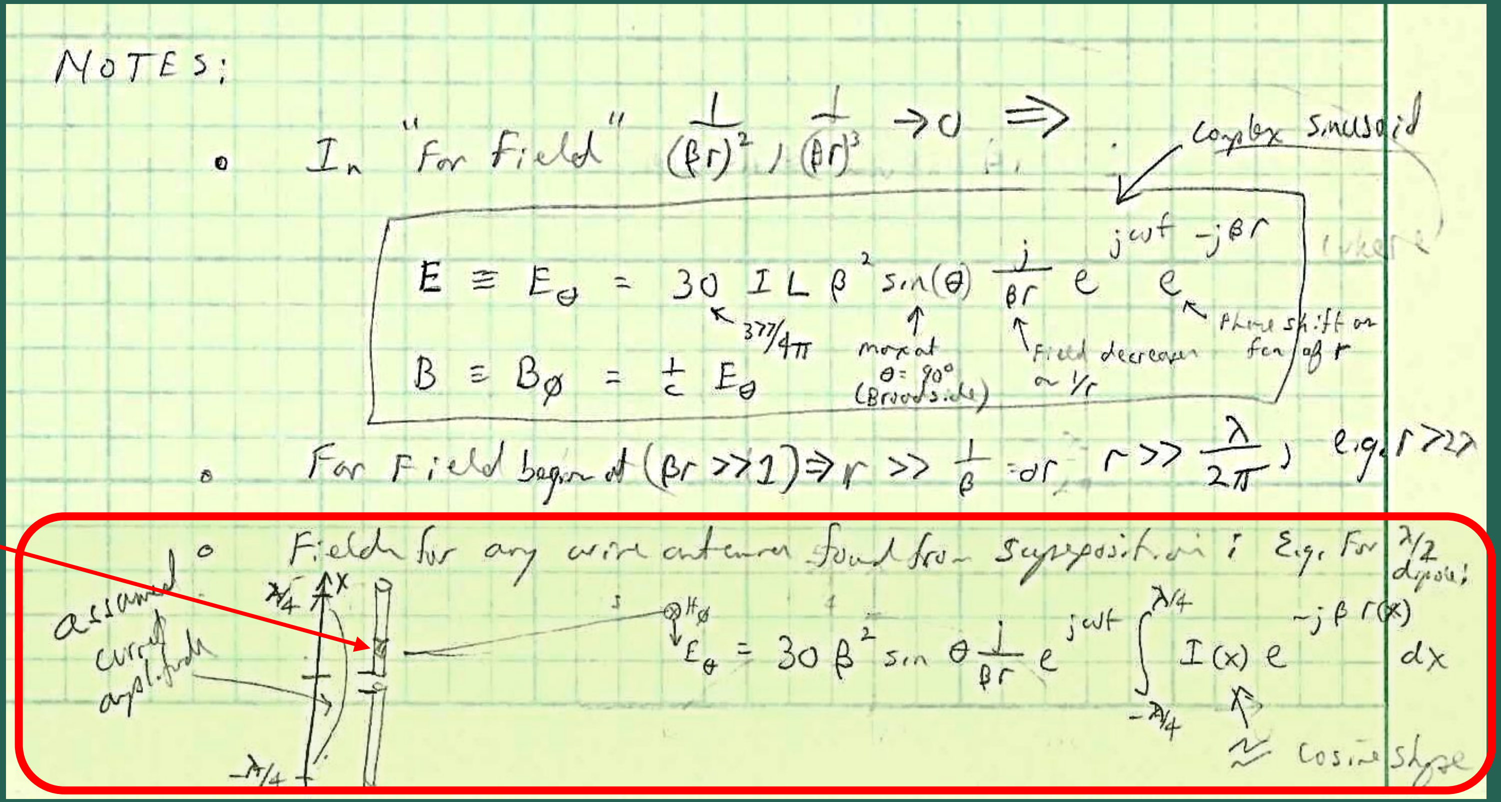


# Far Field Pattern Analysis



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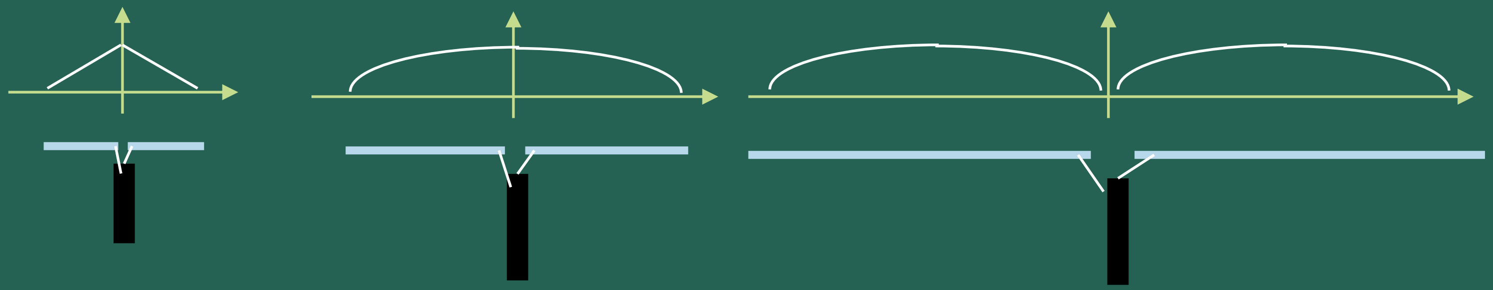
# Finding Currents in Antennas and Far-Field Patterns

## Finding I(x) Function

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

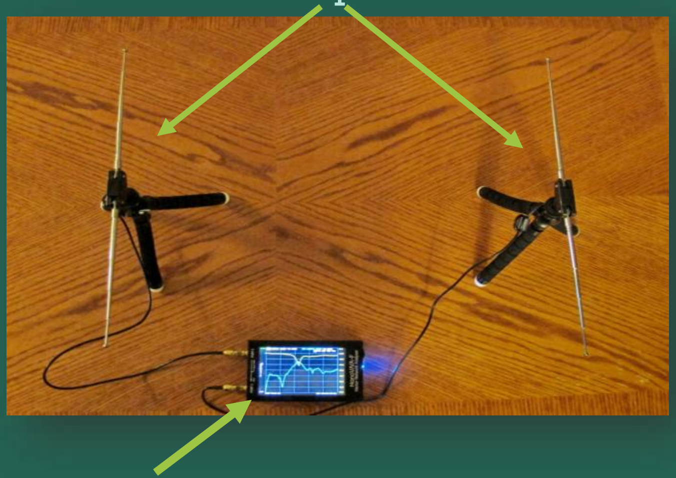


- And/or use EM simulator – e.g.:
  - NEC or EZNEC
  - Ansys HFSS
  - Keysight ADS/Empro
  - QucsStudio or uSimmics

## Finding Far-Field Patterns

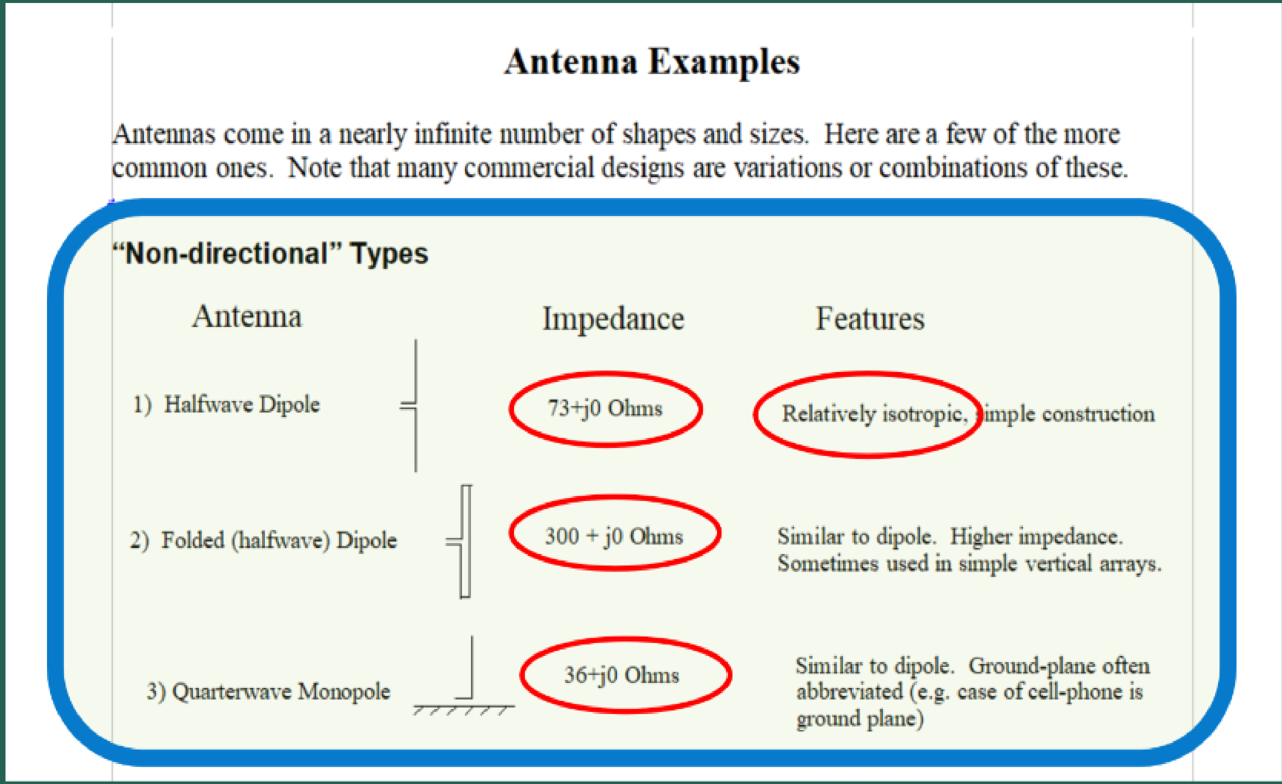
- Do integrals ☹
- Use simulator
- Build and measure !

RTL-SDR Dipole Antennas



NanoVNA
(Transmitter, receiver, display ☺ )

# Analyzing Antenna Impedance



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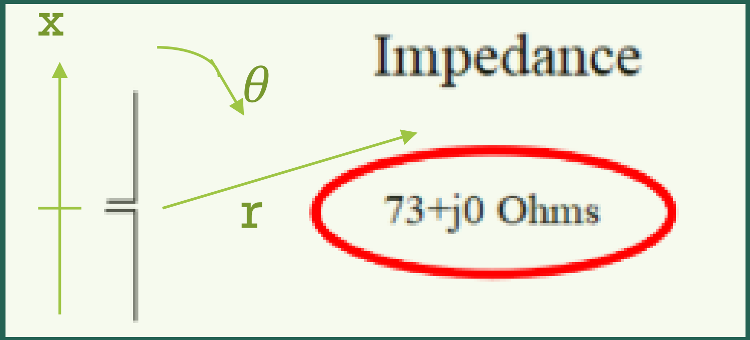
- Find *far-field* pattern and E-field strength as above
- Integrate $\frac{|E|^2}{Z_{o\ free-space}}$ over full sphere around antenna to find total radiated power $P_{tot}$
- Set equal to $P_{tot} = I^2 R_{ant}$ and solve for $R_{ant}$

# Doing it the Hard Way

## Some of the math we're going to try to avoid …

### Problem:

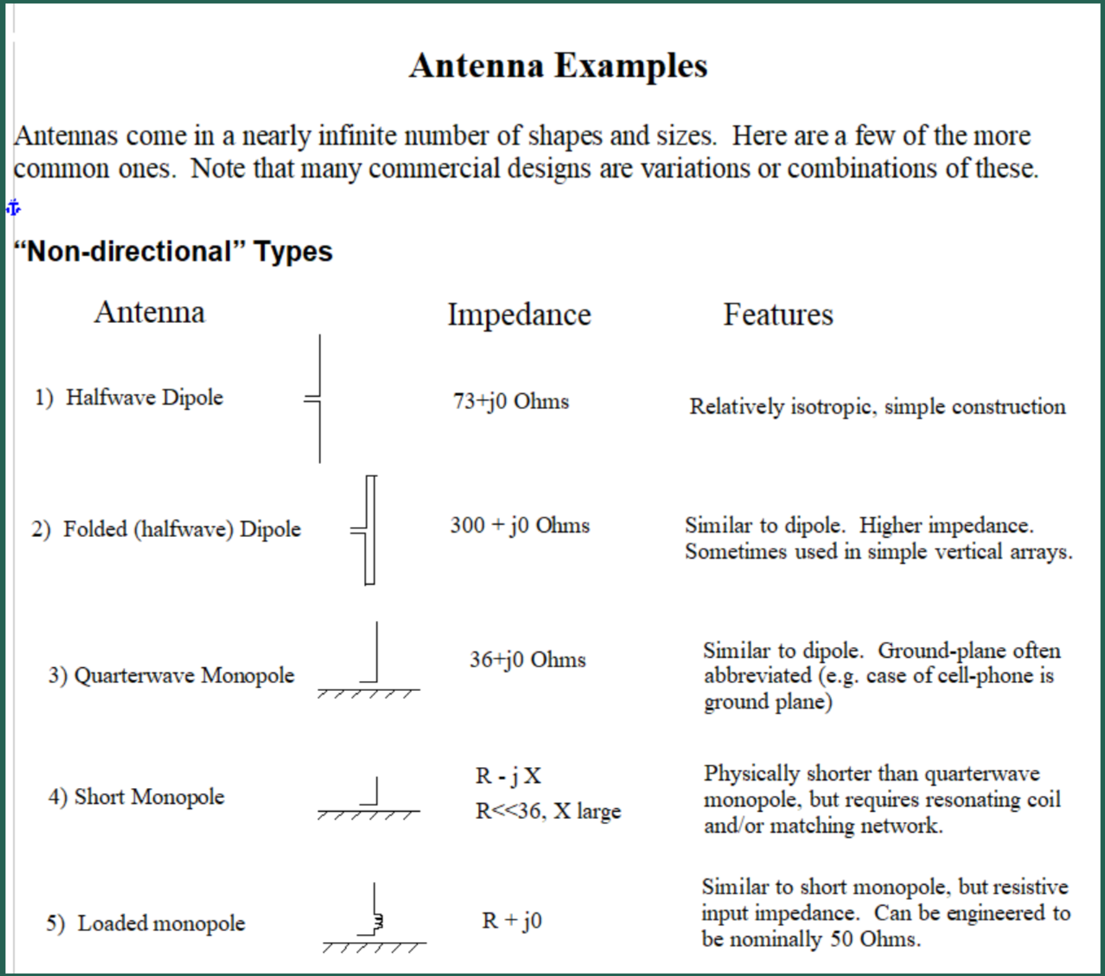
Analytically prove that $R_{ant} = 73\Omega$ for a half-wave dipole at resonance




### Solution Outline:

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

# Homework/Study Questions



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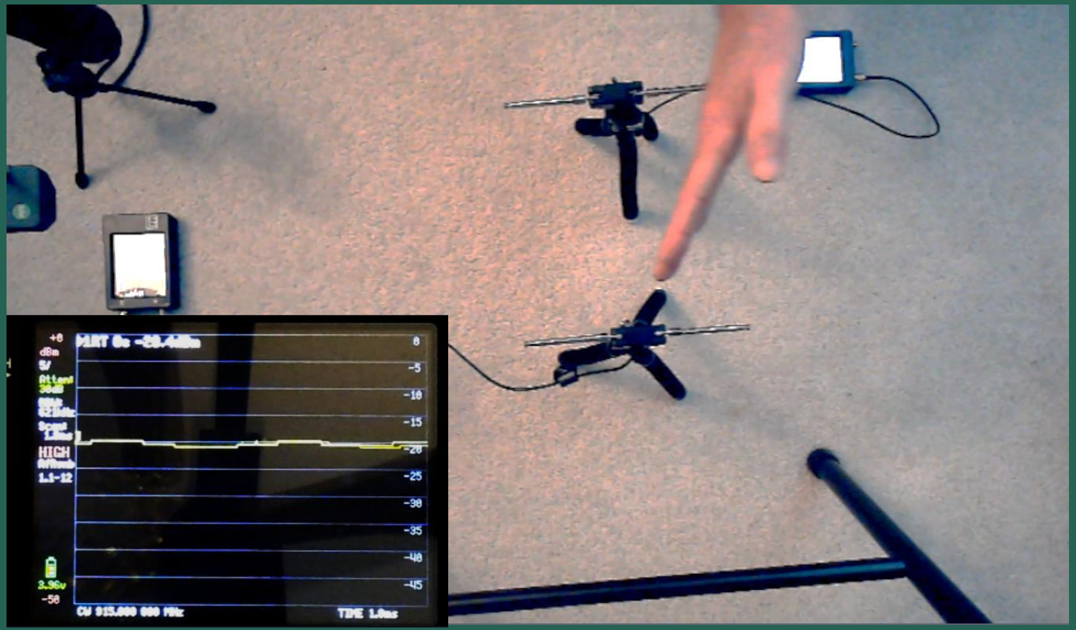
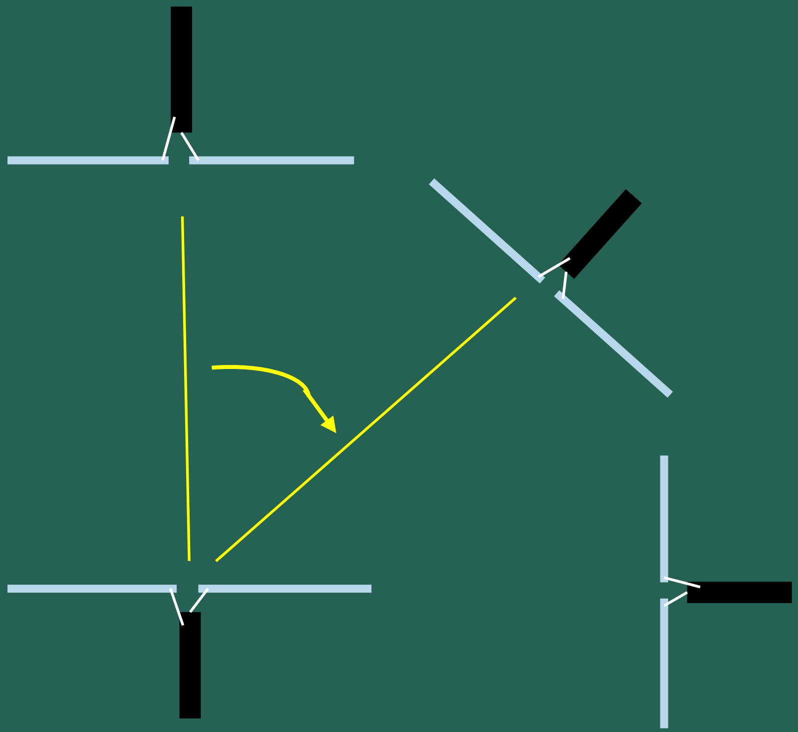
1. Why is $R_{ant}$ for a half-wave dipole 73 Ohms ?
2. Why is $R_{ant}$ for <u>*folded*</u> dipole 4x that of value for basic dipole ?
3. Why is $R_{ant}$ for a monopole above large ground-plane only ½ of dipole ?
4. Why does $R_{ant}$ for an electrically-short monopole decrease by $\left(\frac{length}{\lambda/4}\right)^2$ (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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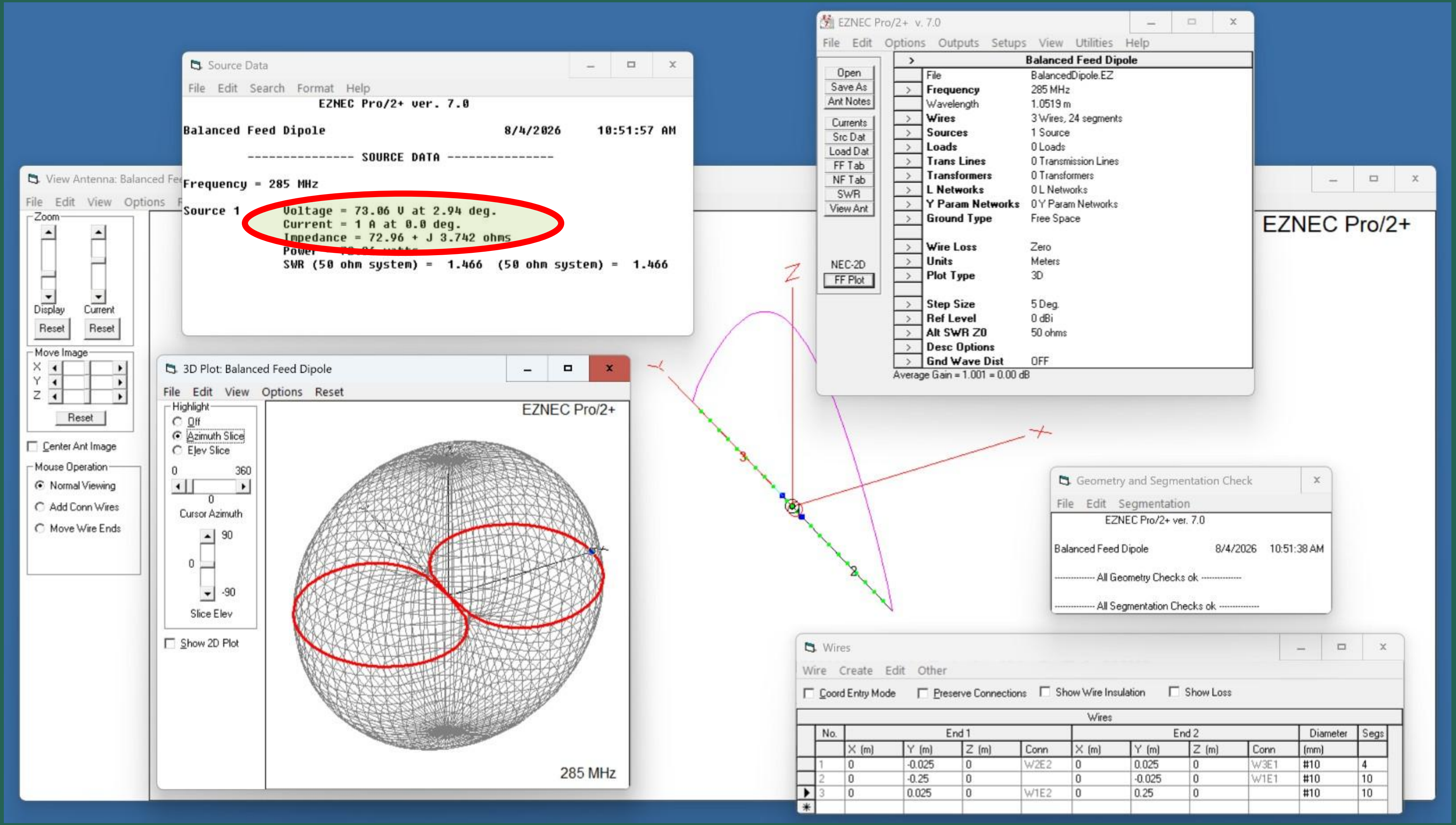
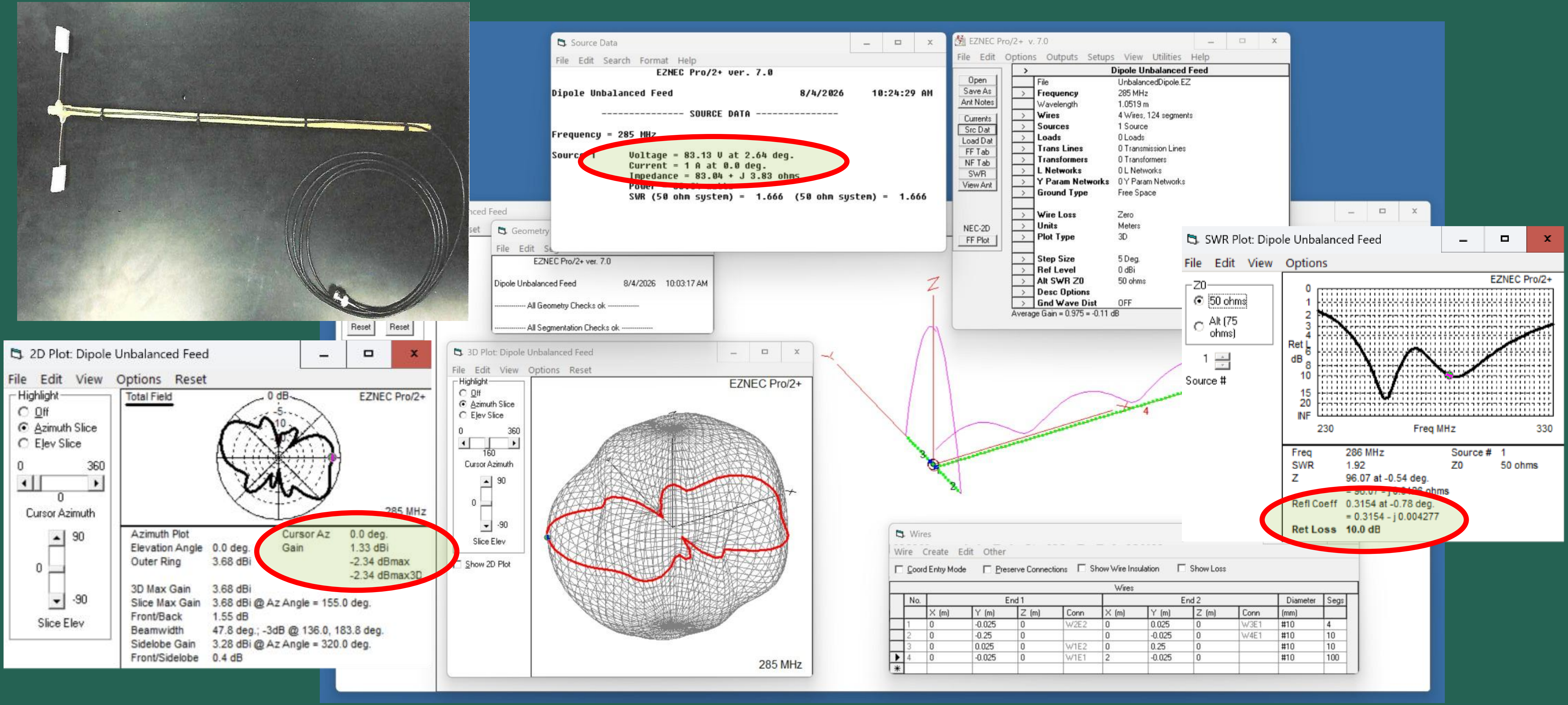
# Half-wave Dipole Simulation (with EZNEC)

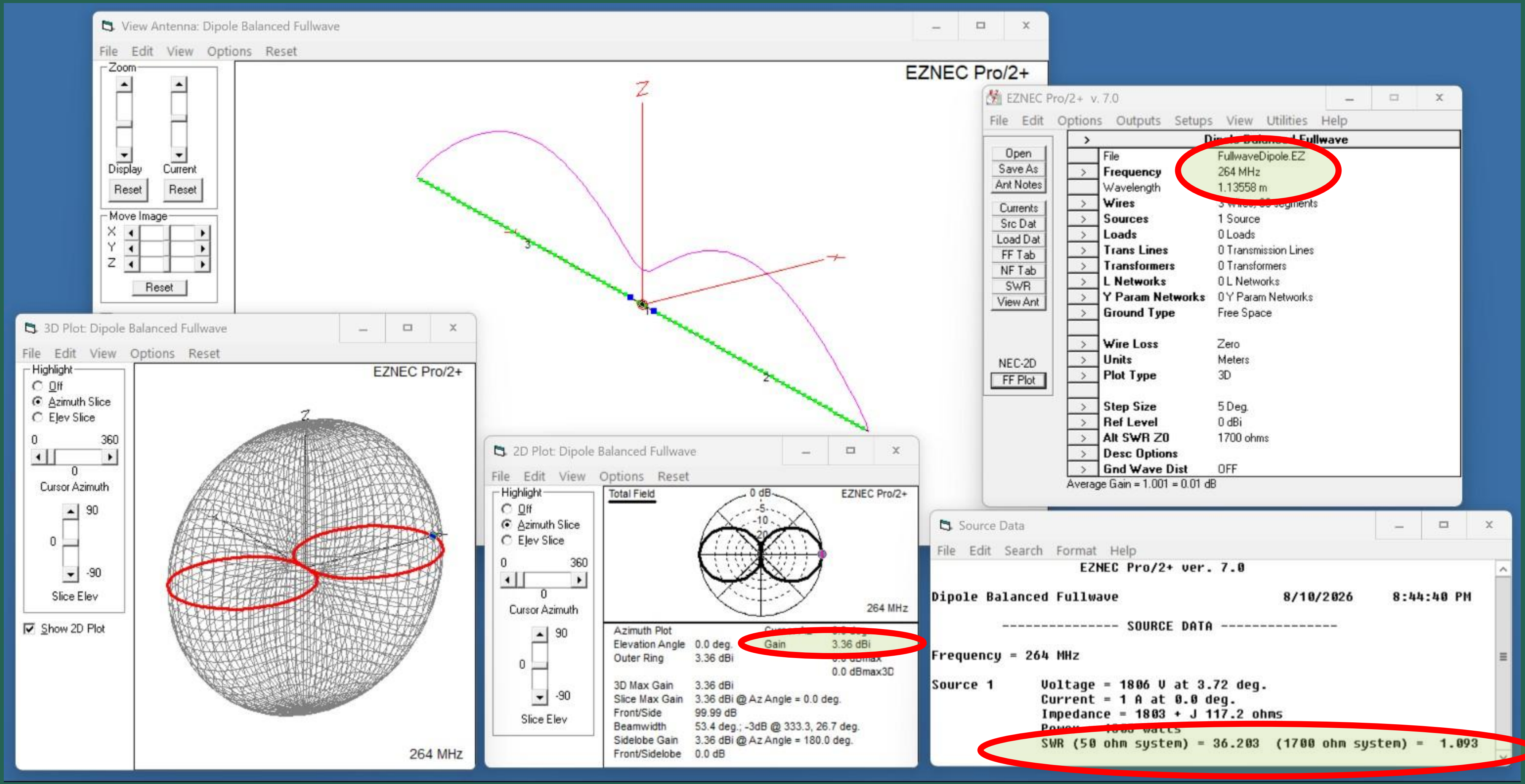


# Dipole Fed with Coax (no balun)

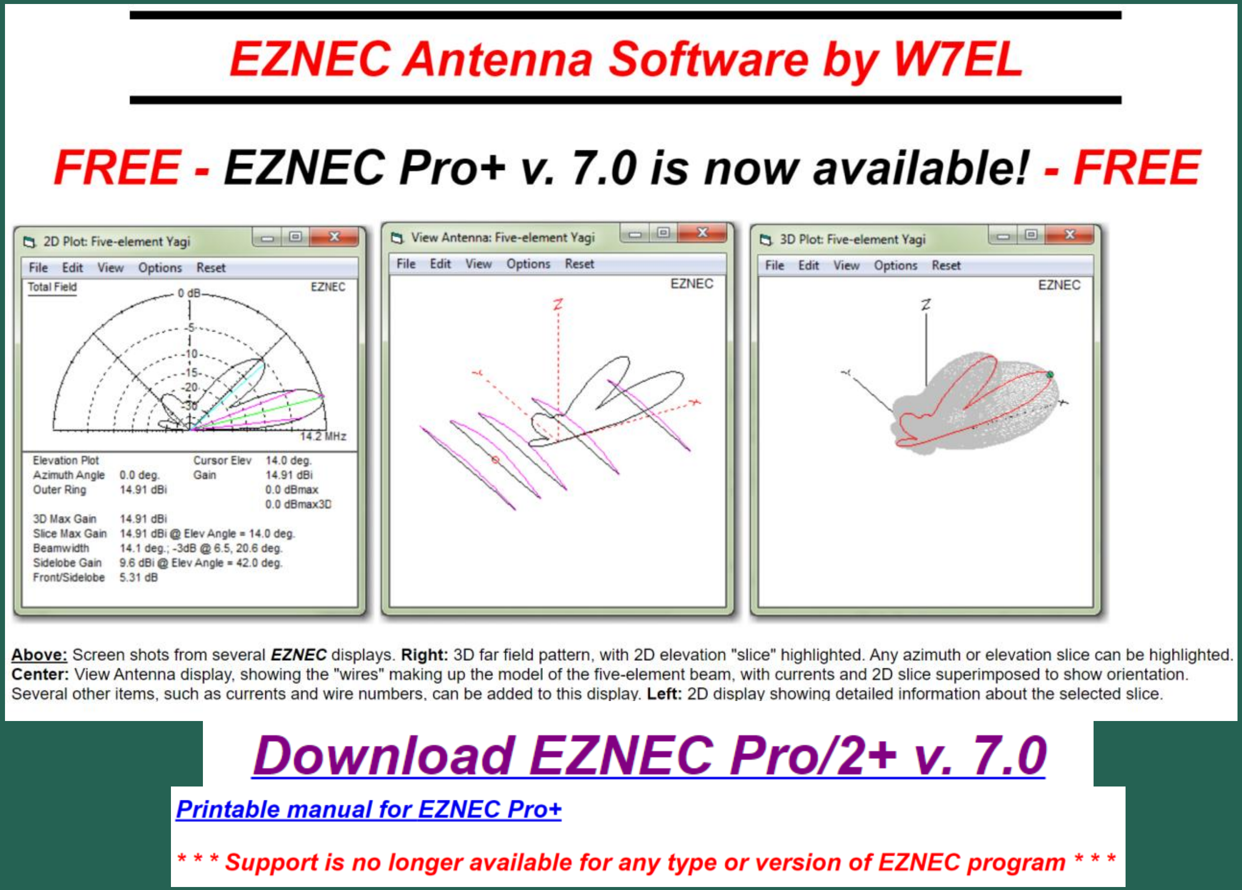


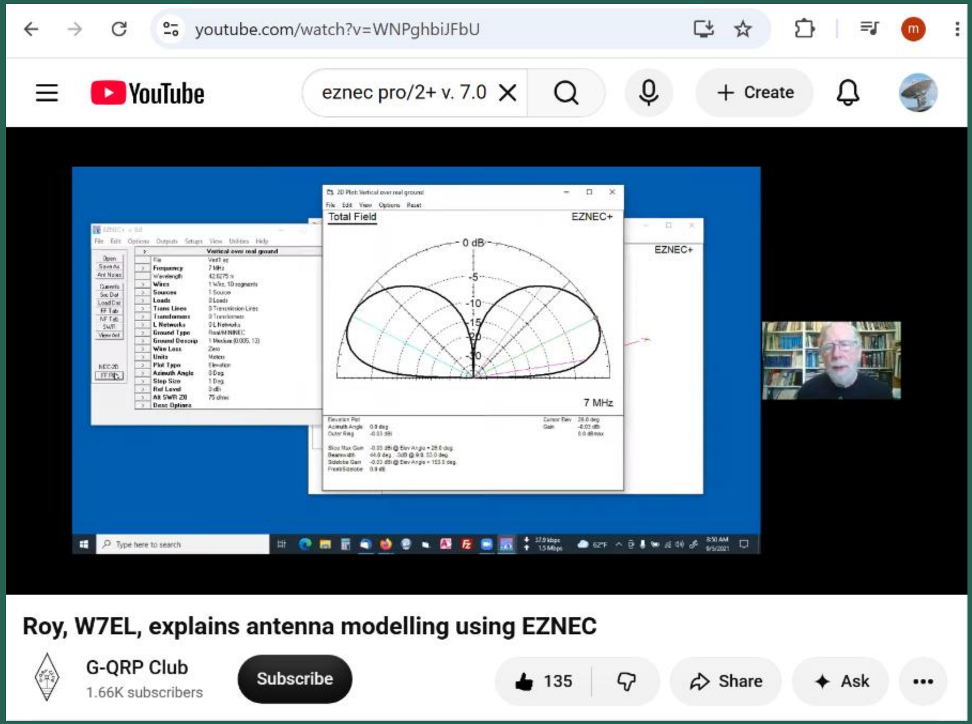

| No. | End 1 X (m) | End 1 Y (m) | End 1 Z (m) | End 1 Conn | End 2 X (m) | End 2 Y (m) | End 2 Z (m) | End 2 Conn | Diameter (mm) | Segs |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | -0.025 | 0 | W2E2 | 0 | 0.025 | 0 | W3E1 | #10 | 4 |
| 2 | 0 | -0.25 | 0 | | 0 | -0.025 | 0 | W4E1 | #10 | 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 |

# Resonant Full-wave Dipole (L=1m)



# Getting and Learning EZNEC

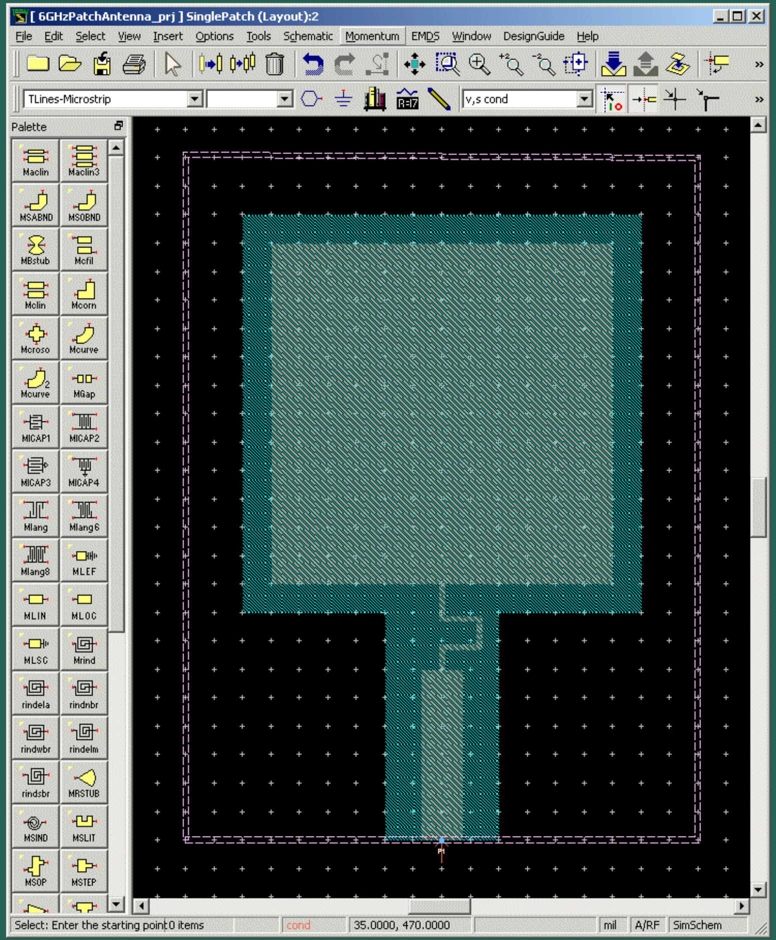


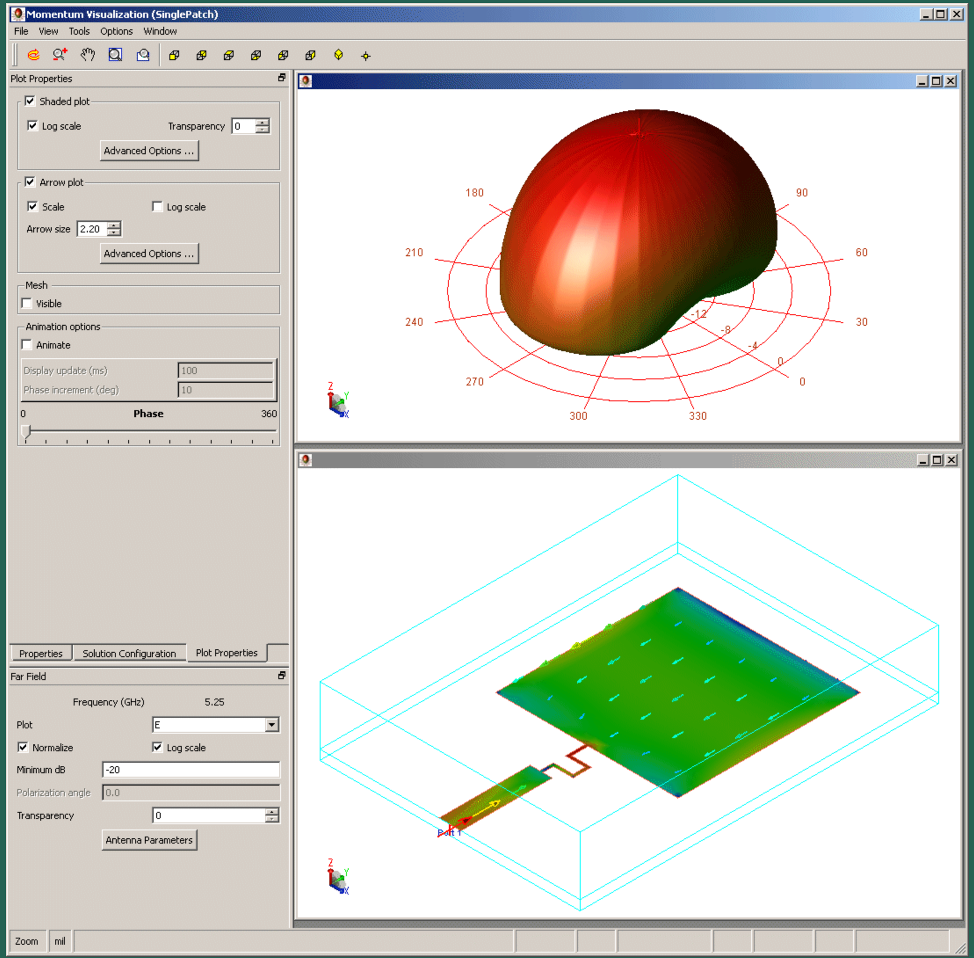




https://www.youtube.com/watch?v=WNPghbiJFbU

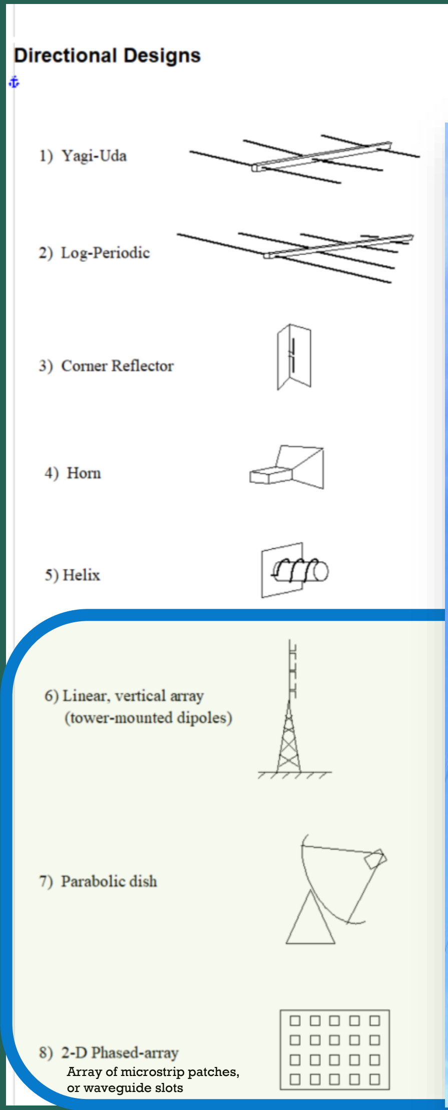
https://www.eznec.com/

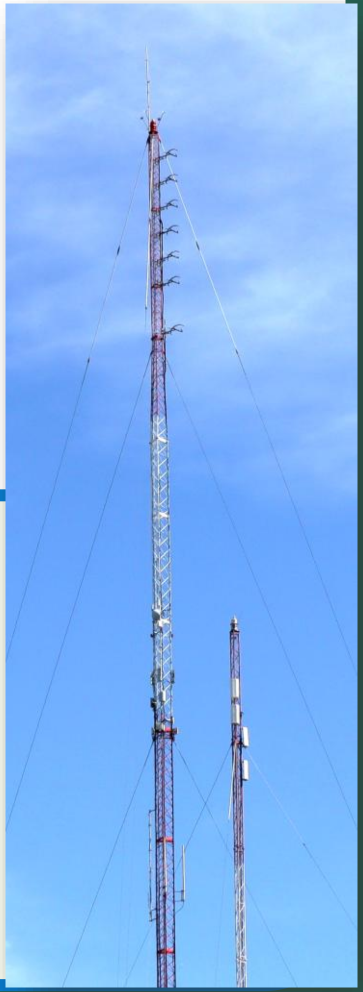
# Microwave Patch Antenna Simulation (with Keysight Momentum)

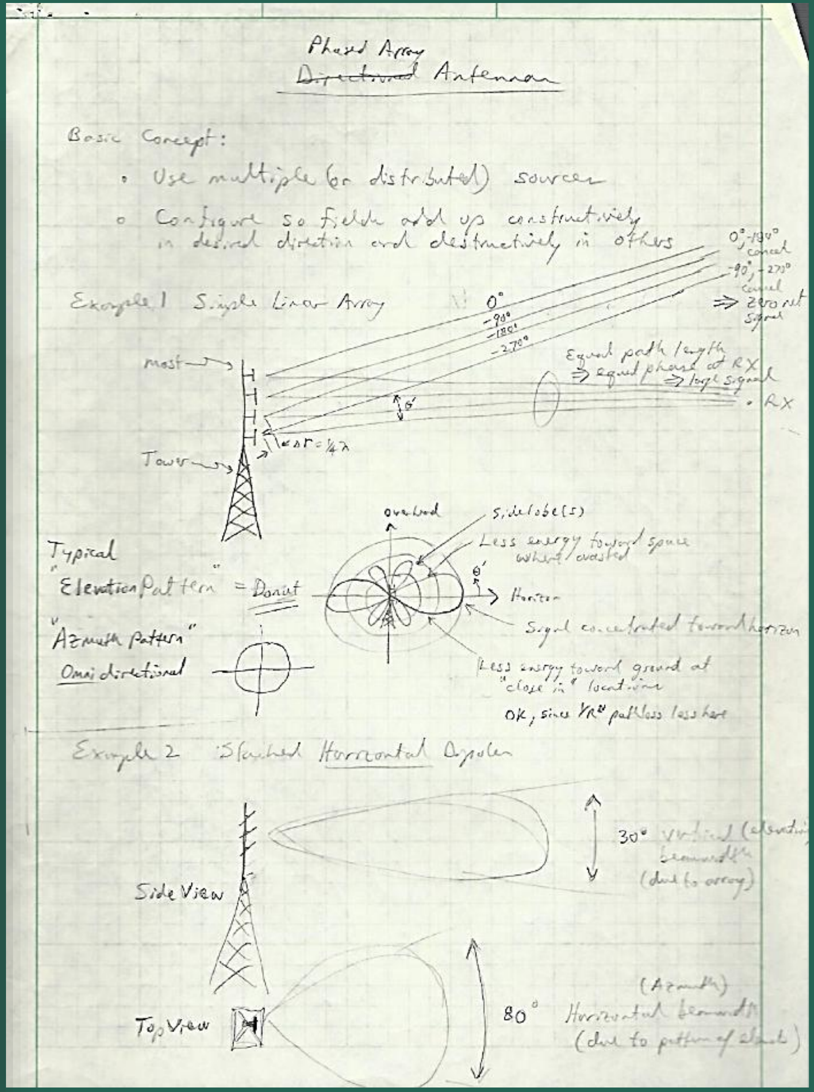


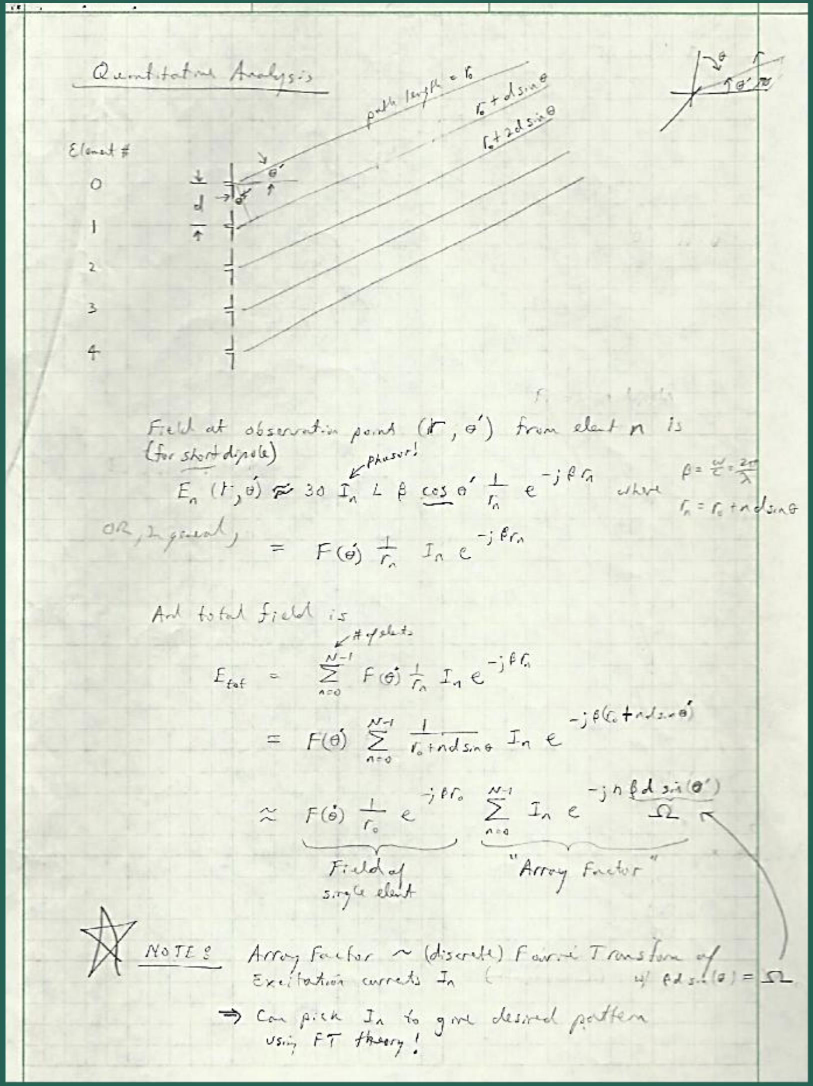



# Upcoming Episode(s)





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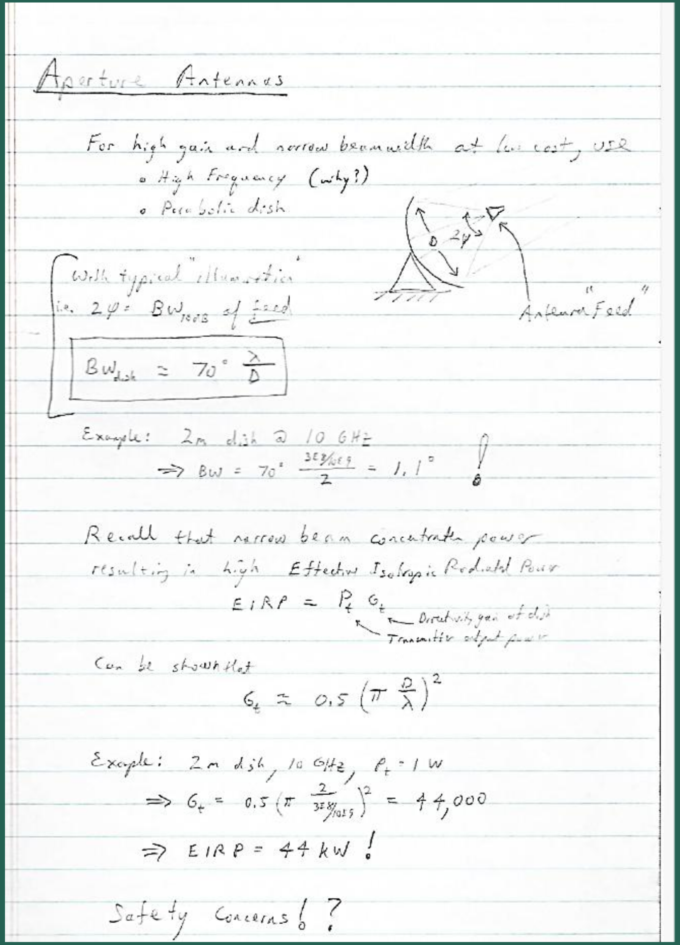

Aperture Antennas

For high gain and narrow beamwidth at low cost, use
- High Frequency (why?)
- Parabolic dish

With typical "illumination"
i.e. $2\psi = BW_{10dB}$ of feed

$BW_{dish} \approx 70° \frac{\lambda}{D}$

Antenna "Feed"

Example: 2m dish @ 10 GHz
$\Rightarrow BW = 70° \frac{3E8/1E10}{2} = 1.1°$ !

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

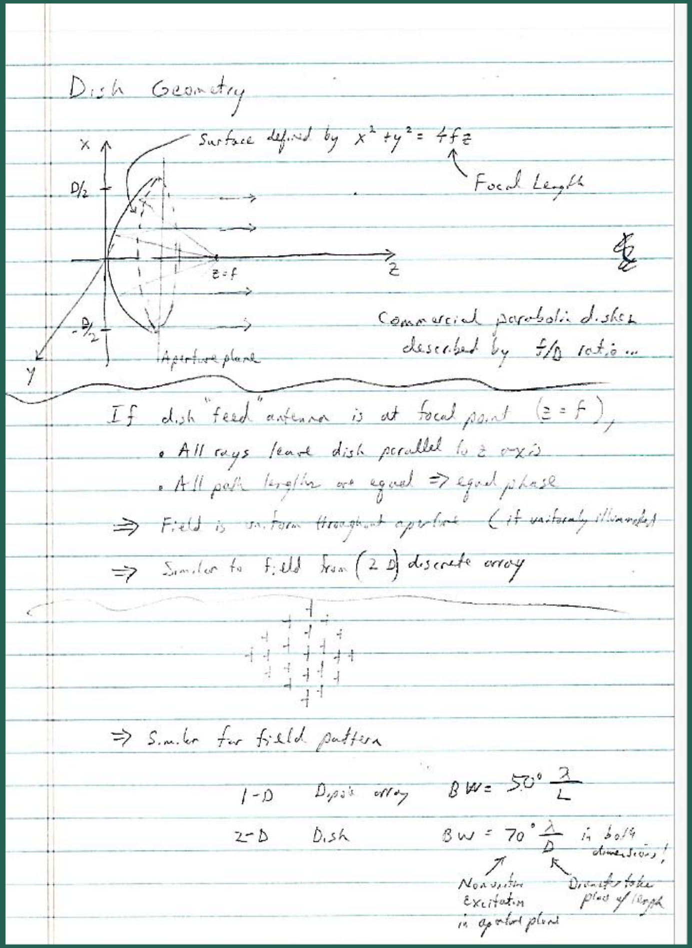
$EIRP = P_t G_t$
(Directivity gain of dish; Transmitter output power)

Can be shown that

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

Example: 2m dish, 10 GHz, $P_t = 1$ W
$\Rightarrow G_t = 0.5\left(\pi \frac{2}{3E8/1E10}\right)^2 = 44{,}000$
$\Rightarrow EIRP = 44$ kW !

Safety Concerns!?


Dish Geometry

Surface defined by $x^2 + y^2 = 4fz$

Focal Length

Aperture plane

Commercial parabolic dishes described by f/D ratio...

If dish "feed" antenna is at focal point ($z = f$),
- All rays leave dish parallel to z-axis
- All path lengths are equal ⇒ equal phase

⇒ Field is uniform throughout aperture (if uniformly illuminated)

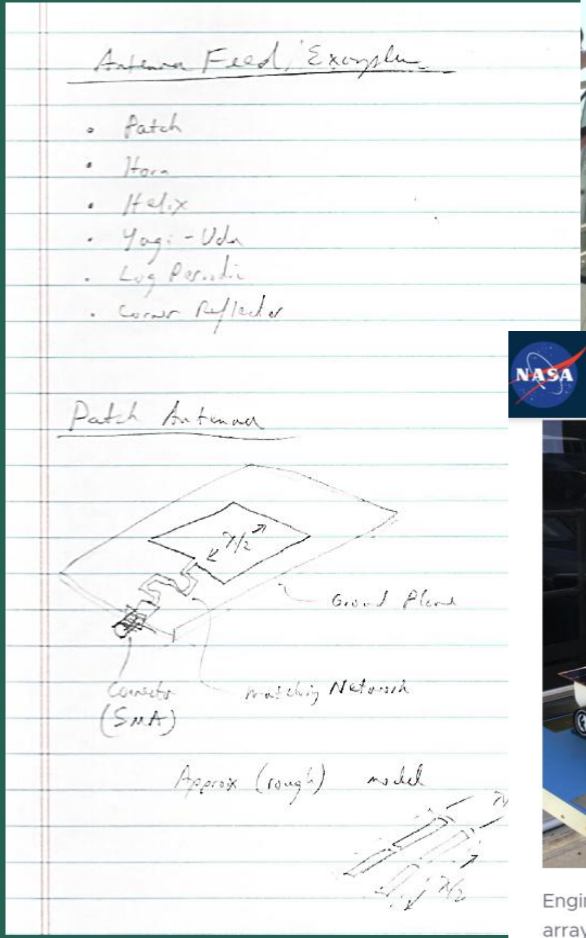
⇒ Similar to field from (2D) discrete array

⇒ Similar far field pattern

1-D Dipole array $BW = 50° \frac{\lambda}{L}$

2-D Dish $BW = 70° \frac{\lambda}{D}$ in both dimensions!

Non-uniform Excitation in aperture plane


Antenna Feed Examples
- Patch
- Horn
- Helix
- Yagi-Uda
- Log Periodic
- Corner Reflector

Patch Antenna

Ground Plane

Connector (SMA)

matching Network

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/missions/mars-cube-one/in-depth/

***Thanks For Watching !***

[MegawattKS - YouTube]  [https://ecefiles.org]