Radiated EMI Characteristics

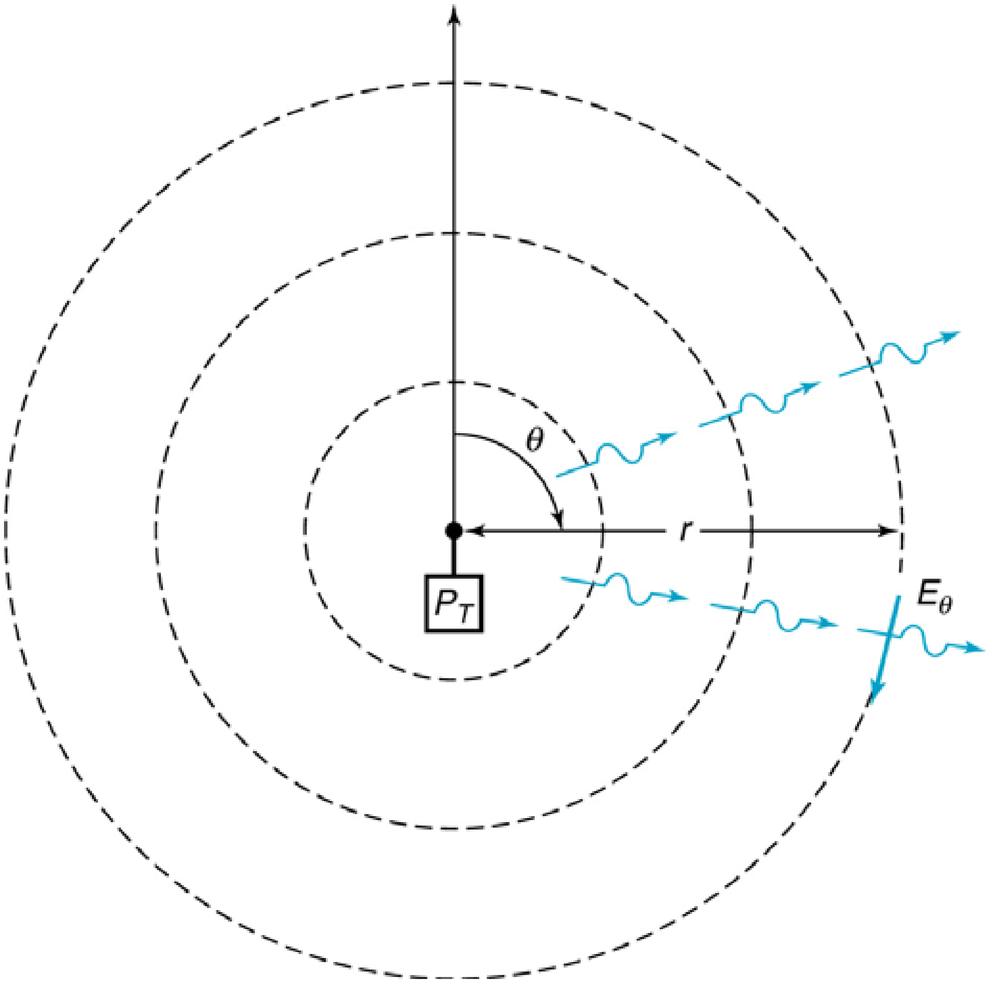
How fields, but not pigs, fly!

Topics

- EM Propagation
  - Summary of free space effects
- Close Proximity Effects
  - Coupling on pcbs
  - Screening/shielding
  - Look at these by considering antennas

Antennas and Plane Waves

Waves radiated from an antenna are spherical waves but appear to a local observer as uniform plane waves



Why Antennas?

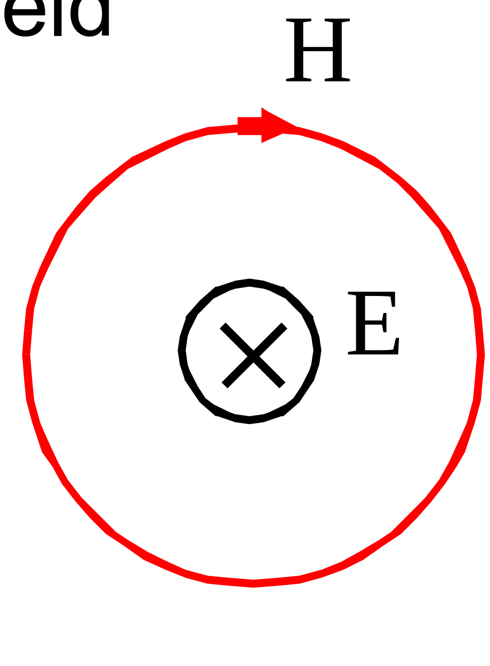
- Necessary for Measurements
- Basic radiation theory applies to radiative coupling
- Used for shielding considerations
  - Can simplify the problem if we understand what is going on

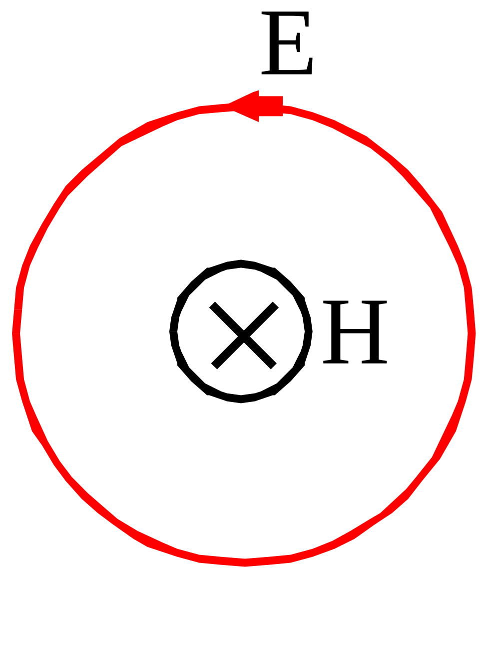
Free Space Propagation

- We are a long way from the source
  - Far Field Approximation
  - Plane wave
    - **E** and **H** fields are normal to each other and the direction of propagation
- Time varying **E** and **H** fields are inter-related and always present together

Time Varying Fields

- **E** and **H** are orthogonal
- Combination forms the Electromagnetic Field

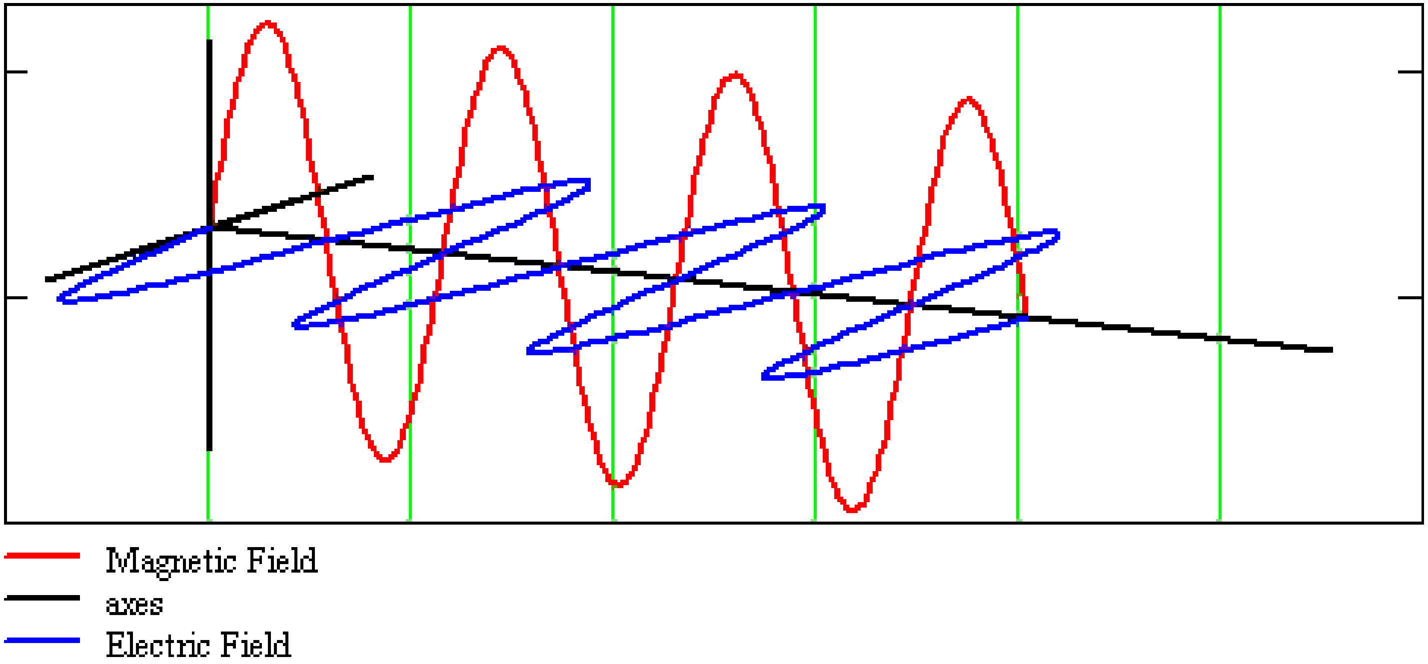




Plane Wave in 3-D Space

- If phase and amplitudes are correct we get a plane wave.
- **<u>E</u>** and **<u>H</u>** are in Phase
- Their magnitudes have a fixed ratio
  - The Wave Impedance, η

Plane Wave in 3-D Space



Plane Wave Properties

- Wave travels one wavelength in one time period $\omega T = 2\pi$

- Propagation Velocity - $v = \frac{\lambda}{T} = f\lambda$

- Phase change per m - $k = \frac{2\pi}{\lambda} \quad rad/m$

Plane Wave Properties

- Propagation Velocity $$u = \frac{1}{\sqrt{\mu\varepsilon}} \quad m/s$$
- Permeability $$\mu = \mu_0 \mu_r \quad H/m$$
- Permittivity $$\varepsilon = \varepsilon_0 \varepsilon_r \quad F/m$$
- Free Space $$k = k_0 \qquad c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3x10^8 \quad m/s$$

Plane Wave Properties

- Ratio of Fields is constant
  - In Free Space

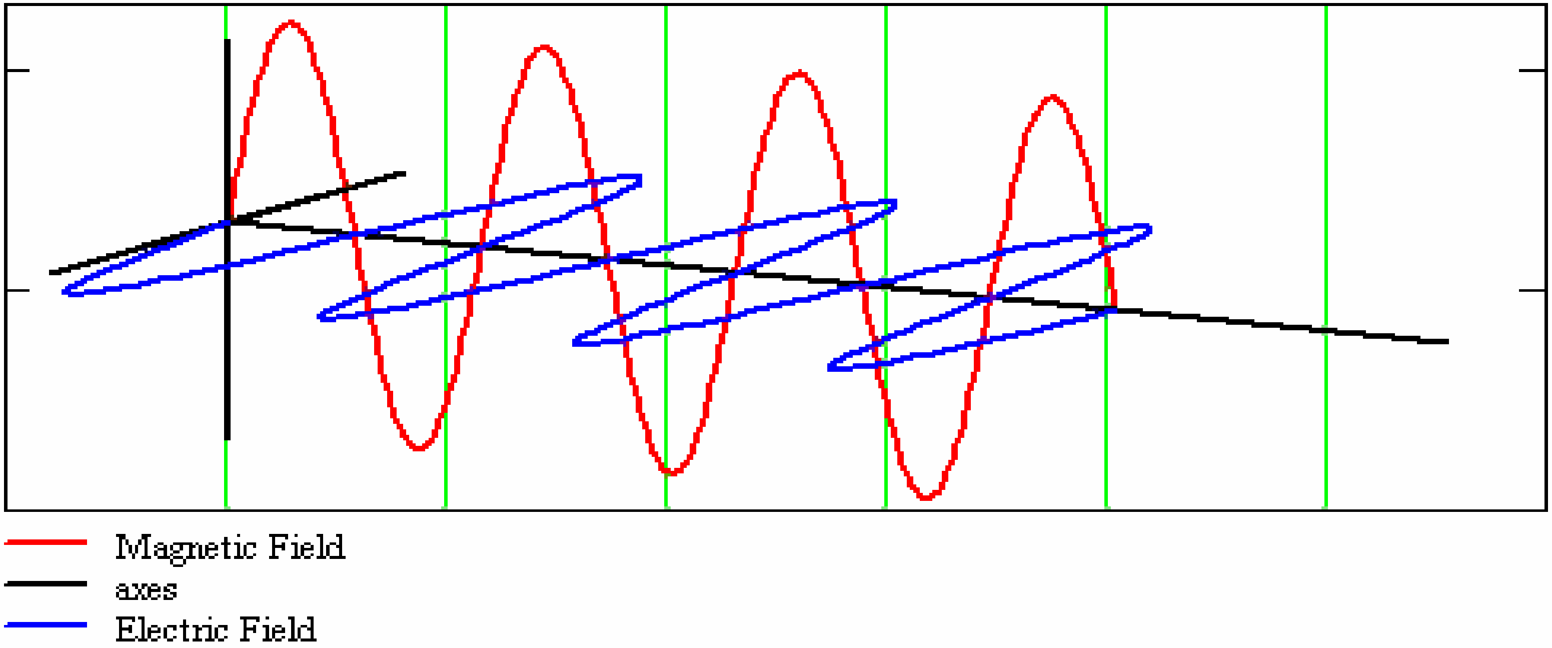
$$\frac{\underline{E}}{\underline{H}} = 120\pi = 377 \quad \Omega$$

- This is the wave impedance, η_0

Field Components

- We consider cosinusoidal signals
  - Simplest building block. c.f. Fourier Analysis
- Phase shift can be seen
  - at a fixed point as time changes
  - at a fixed time as distance changes
- Equations must show this

Sinusoidal Signal in Free Space



Field Components

- Fields obtained by solving Maxwell's equations

$$\underline{E}_x = E_0 \cos\left(2\pi f\left(t - \frac{z}{v}\right)\right) \qquad V/m$$

$$\underline{H}_y = H_0 \cos\left(2\pi f\left(t - \frac{z}{v}\right)\right) \qquad A/m$$

- Distance and time affect phase of waveform

Field Components

- Putting $v = f\lambda$ we get

$$\underline{E}_x = E_0 \cos(\omega t - k_0 z) \quad V/m$$

$$\underline{H}_y = H_0 \cos(\omega t - k_0 z) \quad A/m$$

- This is a simplification of $\underline{E}_x = E_0 e^{\pm j k_0 z}$
  - Comes from the wave equation which is of the form $$\nabla^2 E_x + k_0^2 E_x = 0$$

Field Components

- At any point in space and time the argument of the cosine function is constant

$$\cos(\omega t - k_0 z) = const.$$

$$\omega t - k_0 z = const = a$$

$$z = \frac{-a + \omega t}{k_0}$$

Field Components

- Differentiating this gives

$$\frac{dz}{dt} = \frac{\omega}{k_0} = c$$

- For arbitrary lossy media

$$v = \frac{\omega}{\gamma} = \frac{1}{\sqrt{\mu\varepsilon}}$$

- Where γ is the complex propagation constant

Characteristic Impedance of a Medium

- Obtained from Maxwell's Equations

$$\nabla \times \underline{E} = -j\omega\mu_0 \underline{H}$$

- Simpler version would be

$$\frac{\partial E_x}{\partial z} = \frac{\omega\mu_0}{j} H_y$$

- giving

$$H_y = \frac{1}{\sqrt{\frac{\varepsilon_0}{\mu_0}}} E_x \qquad H_y = \frac{1}{\eta_0} E_x \qquad H_y = \frac{k_0}{\omega\mu_0} E_x$$

Characteristic Impedance of a Medium

- Generally $$\eta = \sqrt{\frac{\mu}{\varepsilon}} = \frac{|\underline{E}|}{|\underline{H}|}$$

- Wave Impedance in Ω.

$$\eta_0 = 120\pi = 377\Omega$$

Power in an Plane Wave

- Power is Vector Cross Product of Electric and Magnetic Fields.
  - This defines power propagation direction.
- Average power is more useful

$$\underline{P}_{av} = \frac{1}{2}\mathrm{Re}\left(\underline{E} \times \underline{H}^*\right) \quad W$$

- or

$$\underline{P}_{av} = \frac{\left|\underline{E}\right|^2}{2\eta_0} \quad W$$

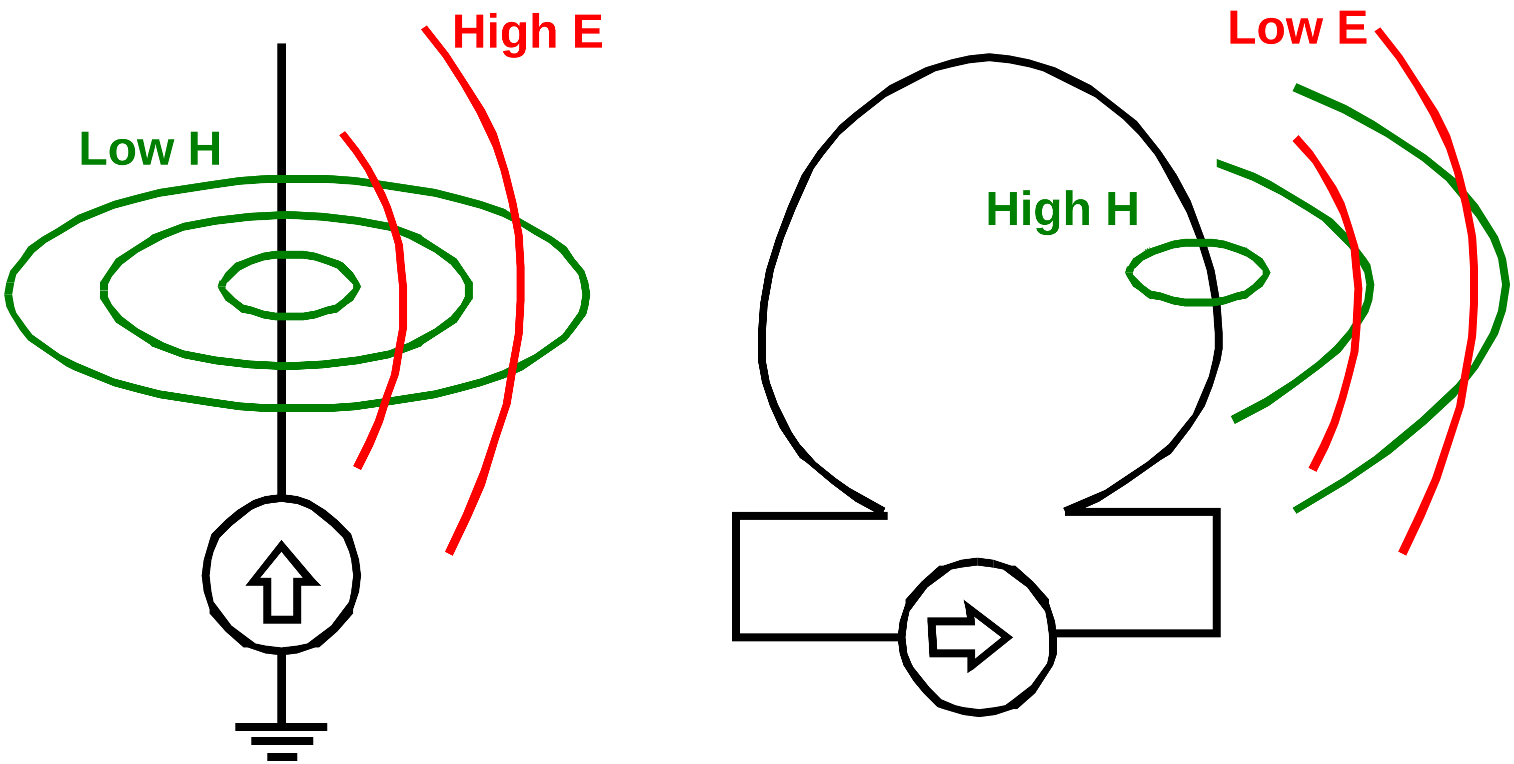
Summary

- Basic EM wave propagation is as a plane wave
- Holds for all waves any reasonable distance from the radiating source.
- Electric and Magnetic fields are normal to each other and to the propagation direction.
- Wave impedance is the ratio of the fields

Antennas

- Impedance Transformer
- Transition Device
- Radiates and receives EM power, as fields, efficiently
- Fields describes as components in 3-D

Generic Radiating Devices



Electric Field Source
Low Current

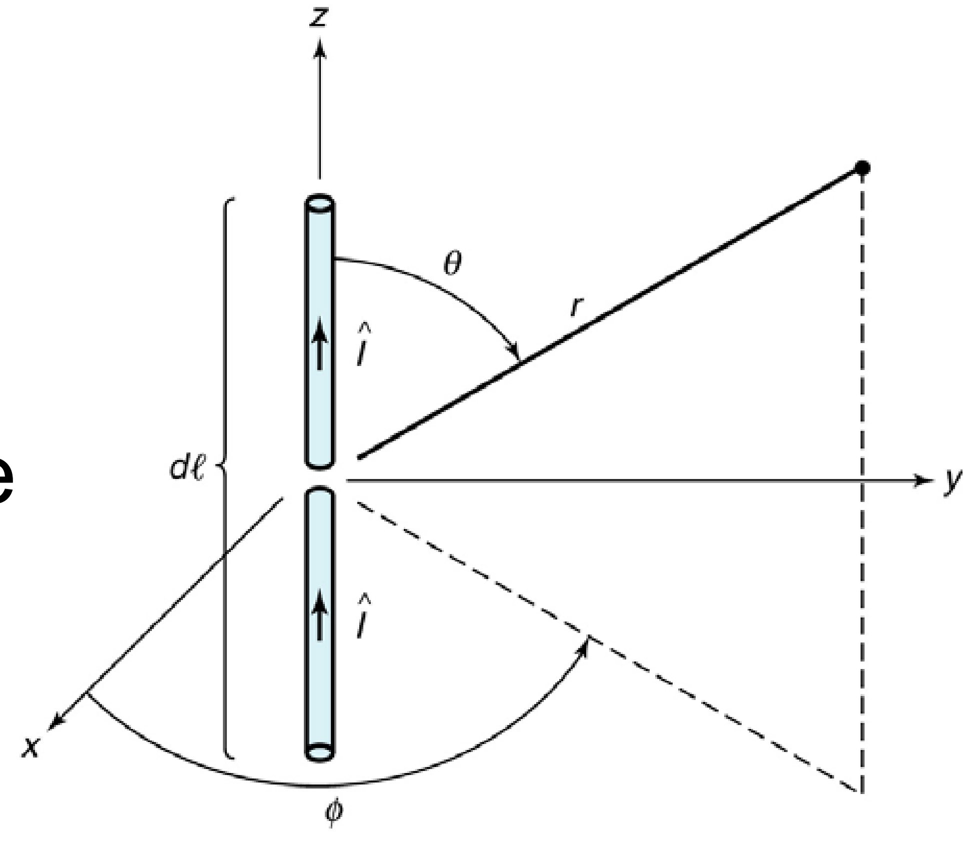
Magnetic Field Source
High Current

Fields Radiating from Antennas

- Defined on a spherical co-ordinate system
  - Radiating fields form a spherical wavefront
- May be “near” or “far” from the antenna.
  - Have different properties.
  - Far Field is a plane wave
- Consider two fundamental radiators

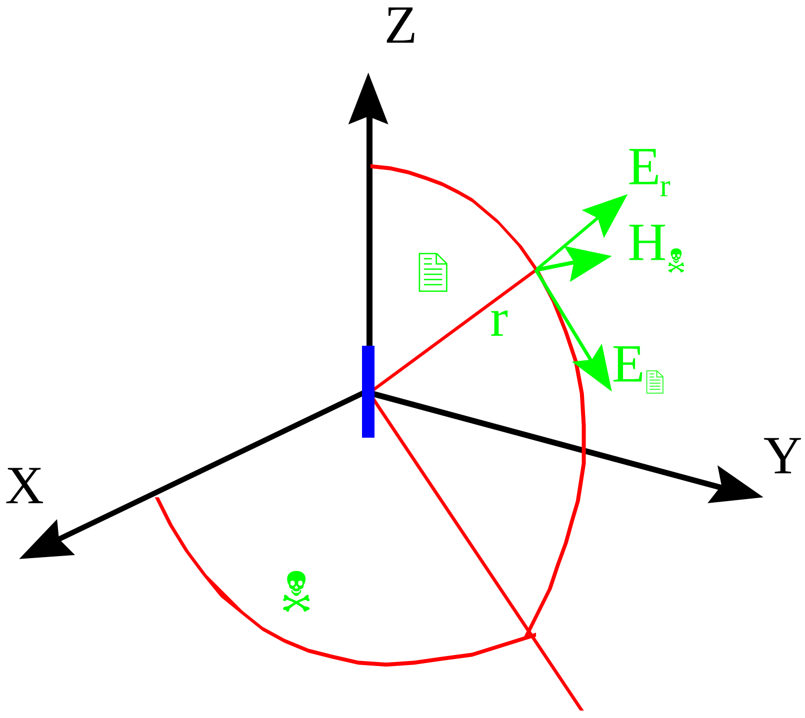
Radiating Elements - Wire

- Correctly known as Hertzian Dipole
- Note Co-ordinate System

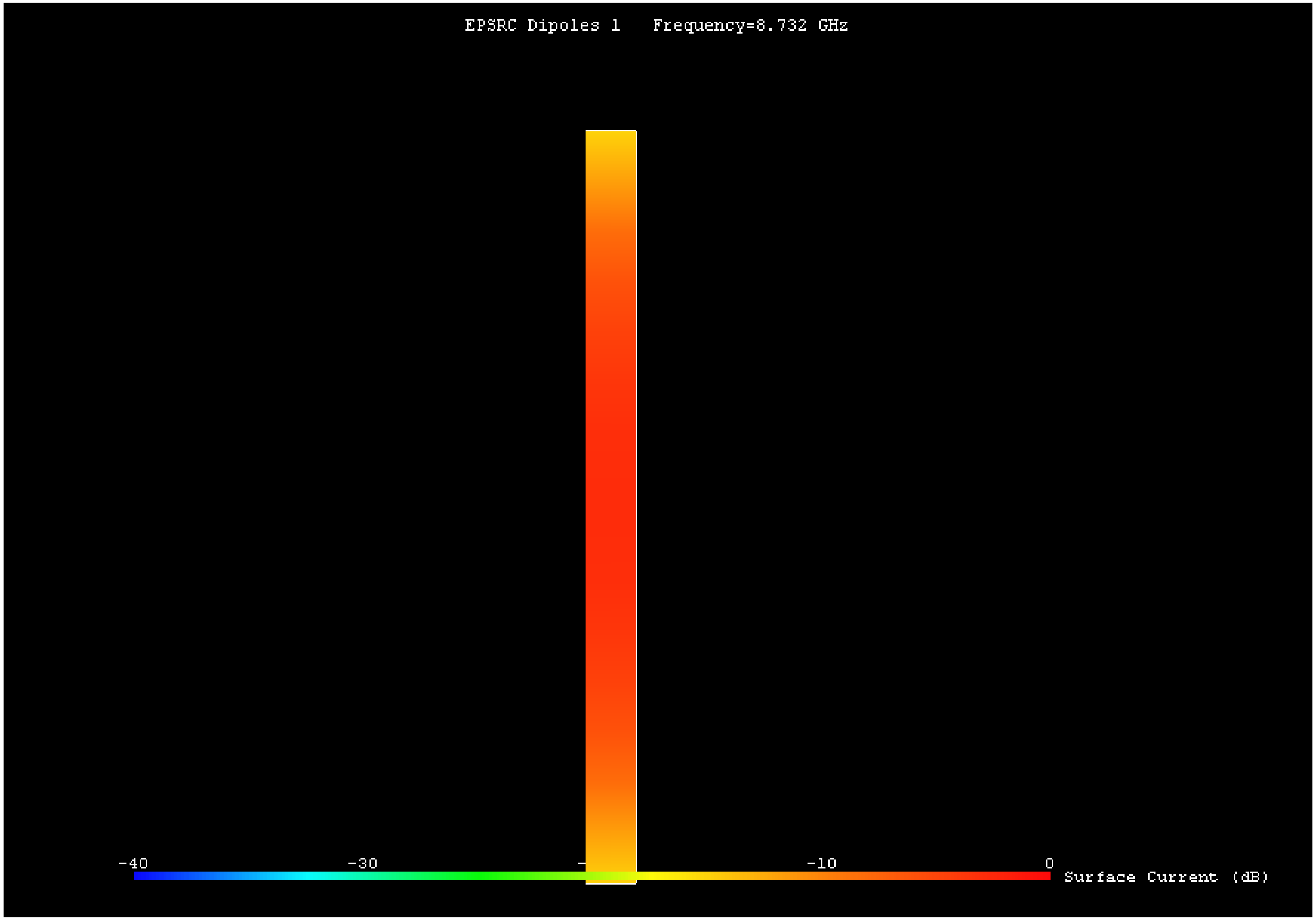


Radiating Elements - Wire

- Co-ordinate system and Field components are shown



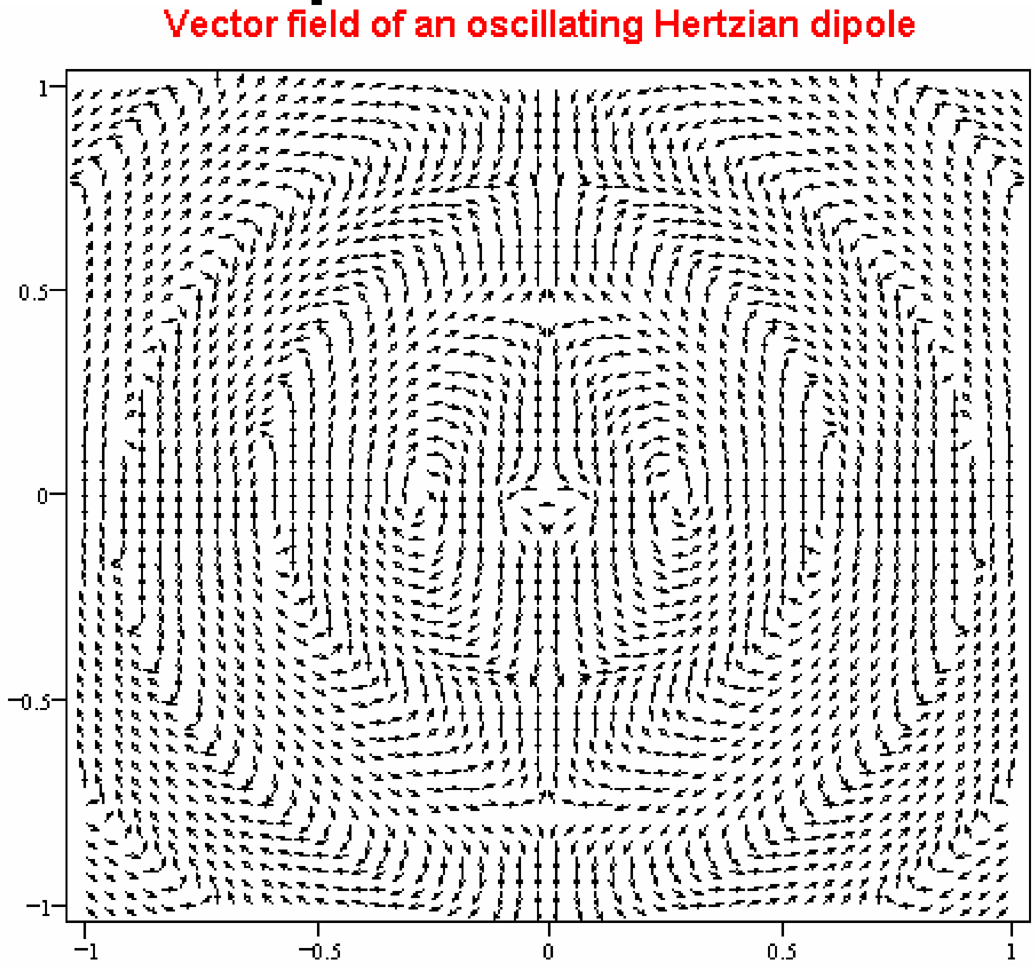
Simulated Dipole Currents



Field Components

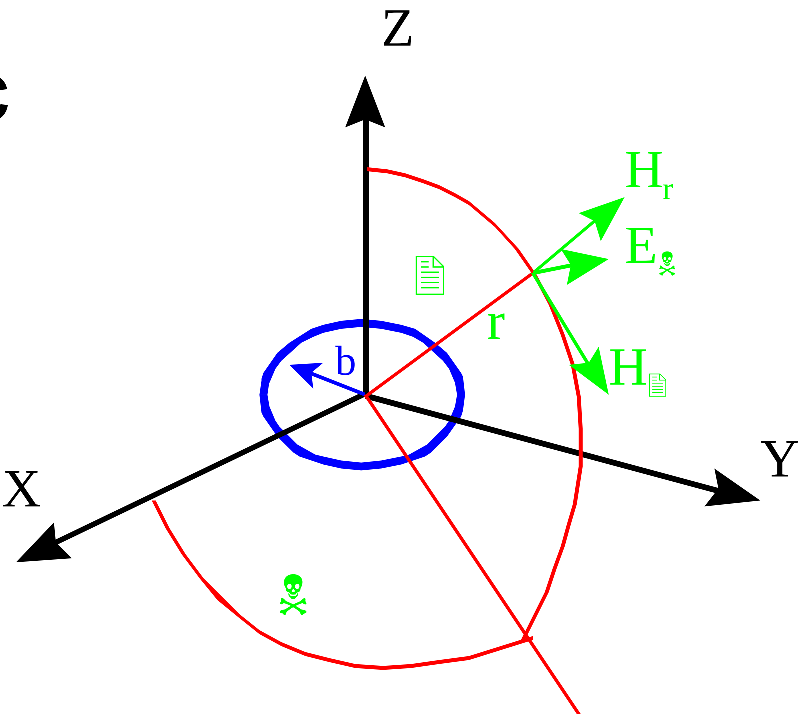
- Radial $\vec{E}_r$
- Azimuthal $\vec{H}_\phi$
- Elevation $\vec{E}_\theta$
- Specific to a wire

Simulated Dipole Fields



Radiating Elements - Loop

- Known as Magnetic Dipole
- Co-ordinate system and Field components are shown



Field Components

- Radial $\vec{H}_r$
- Azimuthal $\vec{E}_\phi$
- Elevation $\vec{H}_\theta$
- Specific to a loop

Field Components - Wire

$$E_r = \frac{-e^{-j\cdot k\cdot r}}{4\cdot\pi}\cdot I\cdot l\cdot\eta_0\cdot k^2\cdot 2\cdot\cos(\theta)\cdot\left[\frac{1}{(j\cdot k\cdot r)^2}+\frac{1}{(j\cdot k\cdot r)^3}\right]$$

$$E_\theta = \frac{-e^{-j\cdot k\cdot r}}{4\cdot\pi}\cdot I\cdot l\cdot\eta_0\cdot k^2\cdot\sin(\theta)\cdot\left[\frac{1}{j\cdot k\cdot r}+\frac{1}{(j\cdot k\cdot r)^2}+\frac{1}{(j\cdot k\cdot r)^3}\right]$$

$$H_\phi = \frac{-e^{-j\cdot k\cdot r}}{4\cdot\pi}\cdot I\cdot l\cdot k^2\cdot\sin(\theta)\cdot\left[\frac{1}{j\cdot k\cdot r}+\frac{1}{(j\cdot k\cdot r)^2}\right]$$

Field Components - Loop

- Magnetic Moment $m = I \cdot \pi \cdot b^2$

$$H_r = \frac{-e^{-j \cdot k \cdot r}}{4 \cdot \pi} \cdot j \cdot \frac{\omega \cdot \mu \cdot m}{\eta_0} \cdot k^2 \cdot 2 \cdot \cos(\theta) \cdot \left[\frac{1}{(j \cdot k \cdot r)^2} + \frac{1}{(j \cdot k \cdot r)^3} \right]$$

$$H_\theta = \frac{-e^{-j \cdot k \cdot r}}{4 \cdot \pi} \cdot j \cdot \frac{\omega \cdot \mu \cdot m}{\eta_0} \cdot k^2 \cdot \sin(\theta) \cdot \left[\frac{1}{j \cdot k \cdot r} + \frac{1}{(j \cdot k \cdot r)^2} + \frac{1}{(j \cdot k \cdot r)^3} \right]$$

$$E_\phi = \frac{-e^{-j \cdot k \cdot r}}{4 \cdot \pi} \cdot j \cdot \omega \cdot \mu \cdot m \cdot k^2 \cdot \sin(\theta) \cdot \left[\frac{1}{j \cdot k \cdot r} + \frac{1}{(j \cdot k \cdot r)^2} \right]$$

Far Field

$$r >> \lambda$$

- Distance from radiator
  - Many different definitions
- Only 1/r terms significant
- Plane Wave

$$E_\theta = j\omega\mu \frac{e^{-jkr}}{4\pi r} Il \sin(\theta)$$

$$H_\phi = jk \frac{e^{-jkr}}{4\pi r} Il \sin(\theta)$$

$$\left|\frac{E_\theta}{H\phi}\right| = \frac{j\omega\mu}{jk} = \eta_0$$

Near Field

- $r \ll \lambda$ so higher power terms relevant
- Wave impedance for wire and loop are different
- Consider radiated field equations
- Find that either **E** or **H** is the larger quantity

Near Field - Wire

- **E** field is dominant

$$Z_{nf} = \left|\frac{E_\theta}{H_\phi}\right| = \frac{1}{\omega\varepsilon}\left[\frac{1/r^2}{1/r}\right] = \frac{1}{\omega\varepsilon r} \quad \Omega$$

- Impedance is very high close to radiator and reduces as r increases.

Near Field - Loop

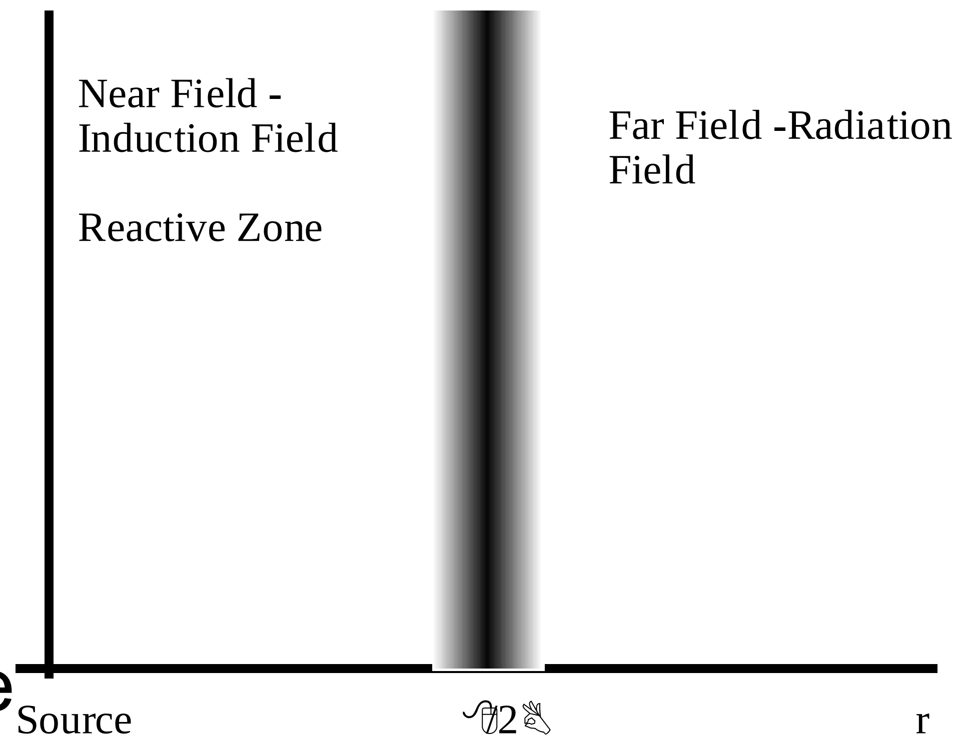
- **H** field dominates

$$Z_{nf} = \left| \frac{E_\phi}{H_\theta} \right| = \omega\mu \left[\frac{1/r}{1/r^2} \right] = \omega\mu r \qquad \Omega$$

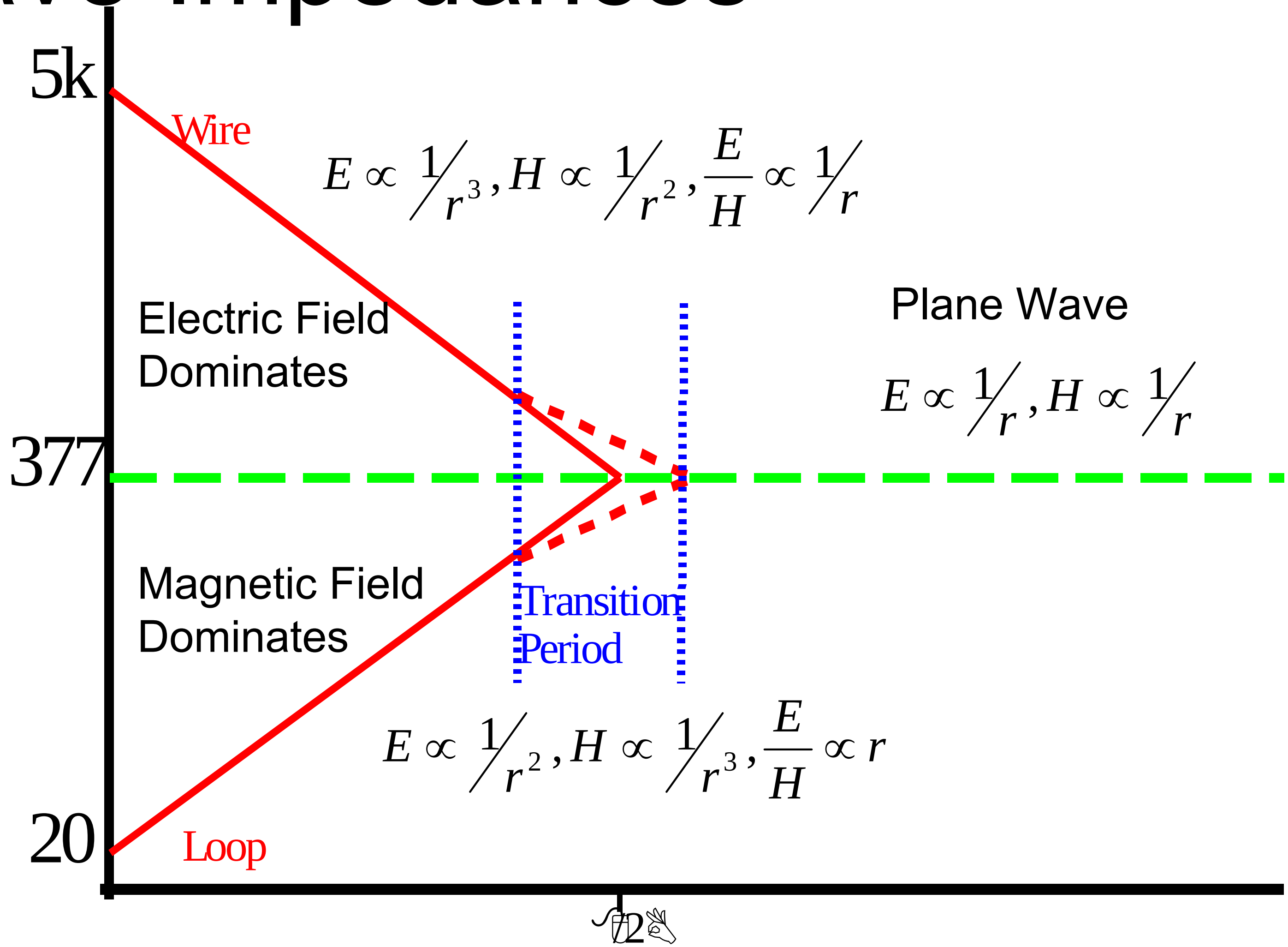
- Impedance close to radiator is very low and increases with r

Near to Far Transition

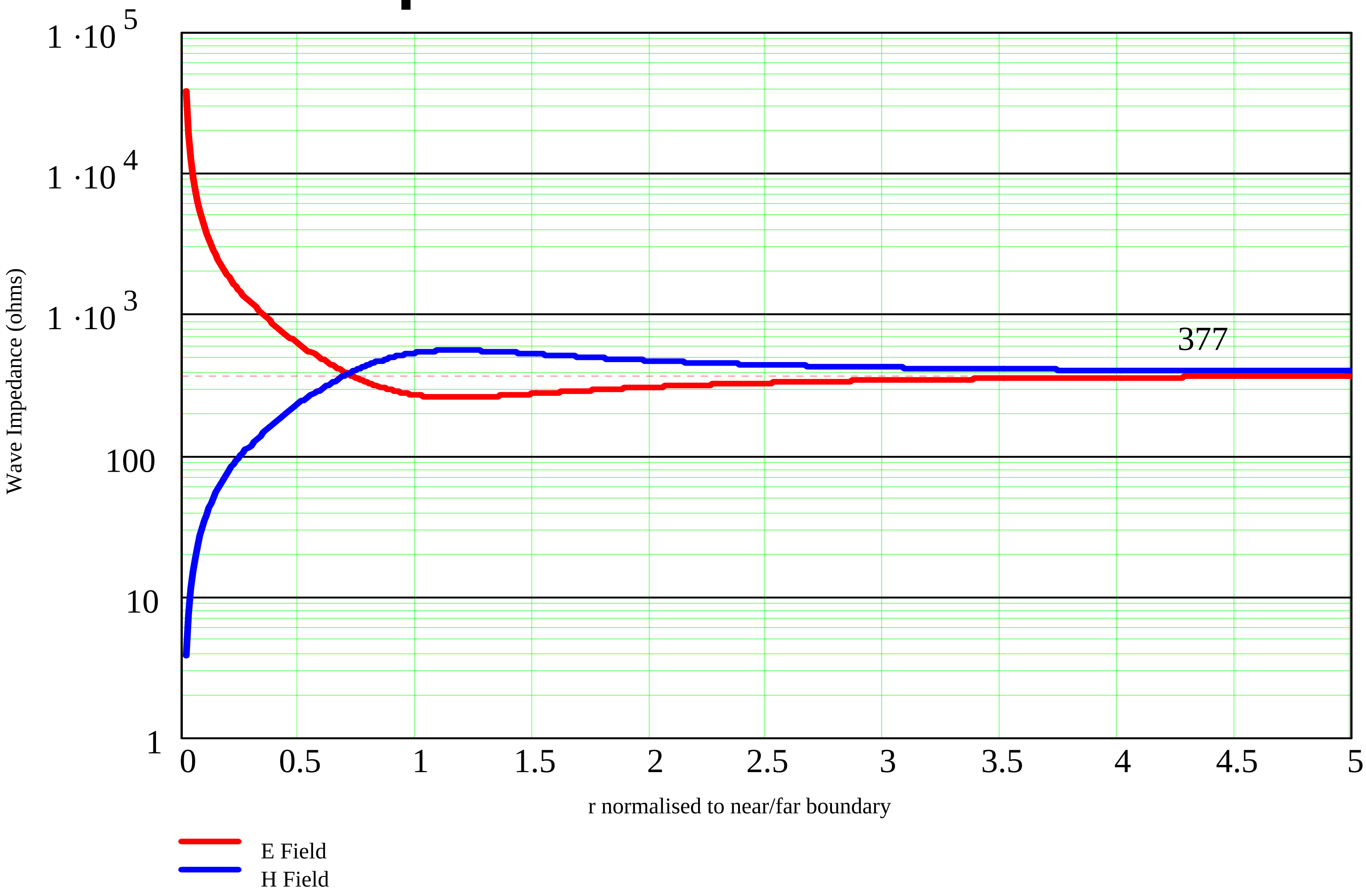
- Higher powers of r become less effective
- 1/r starts to dominate
  - None are dominant in the transition zone



Wave Impedances



Wave Impedances



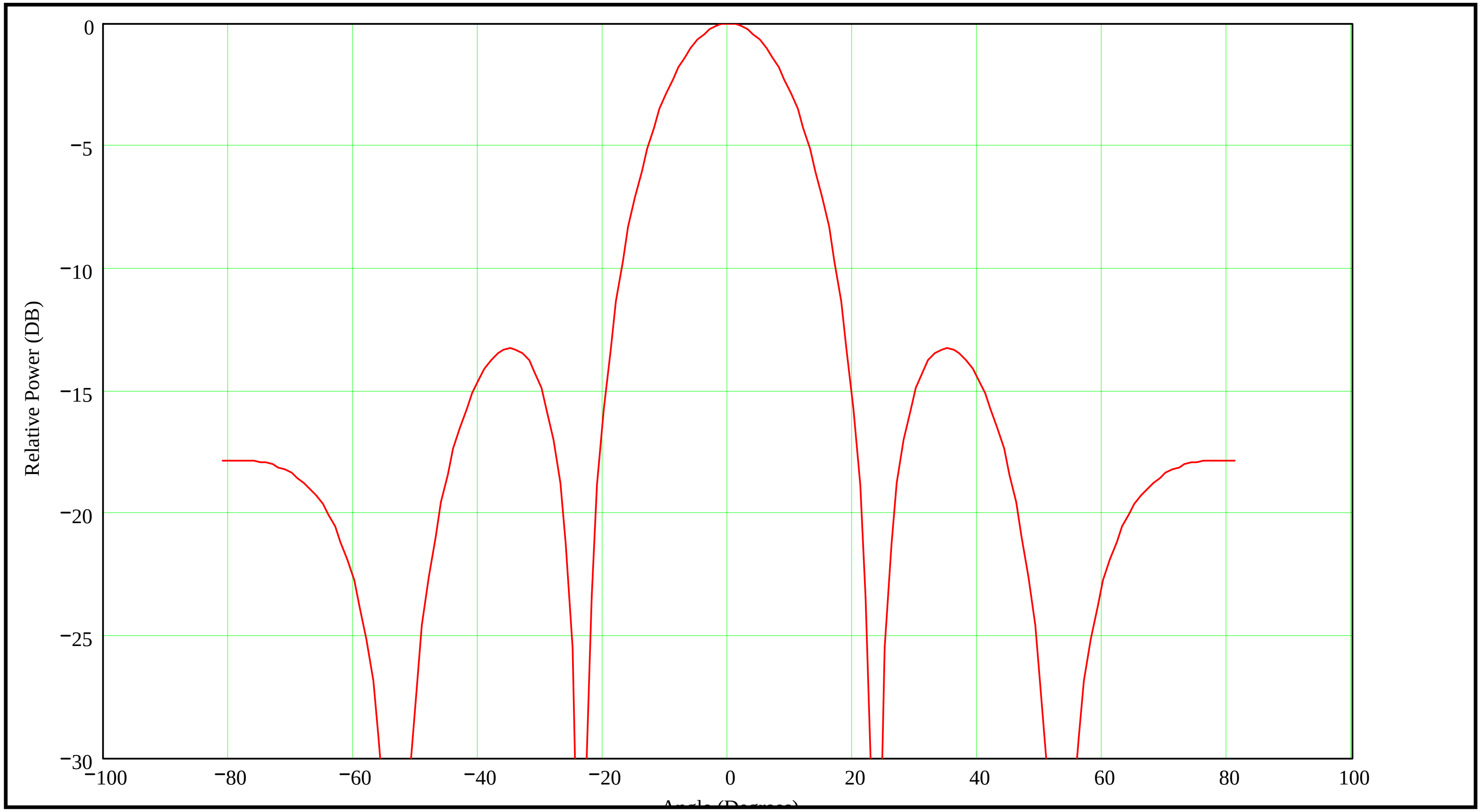
Some Antenna Principles

- Efficient radiators and susceptors are normally at least about one wavelength in size.
- Quarter and half wavelength dimensions are resonant radiators.
  - Omnidirectional
- Larger radiators tend to focus and direct power in a preferred direction

Antenna Characteristics

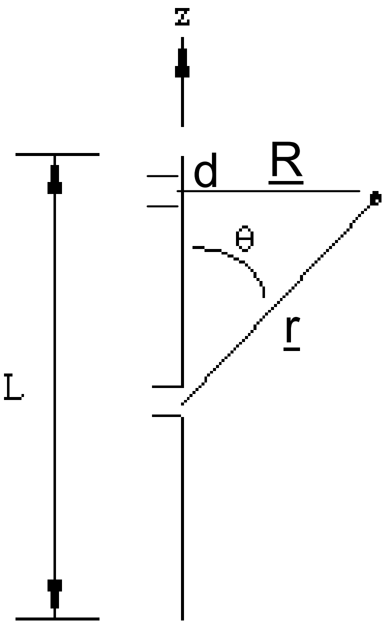
- Define antennas by how they radiate power
  - Radiation Pattern
  - Gain
  - Directivity
- Also look at impedance match

Radiation Pattern

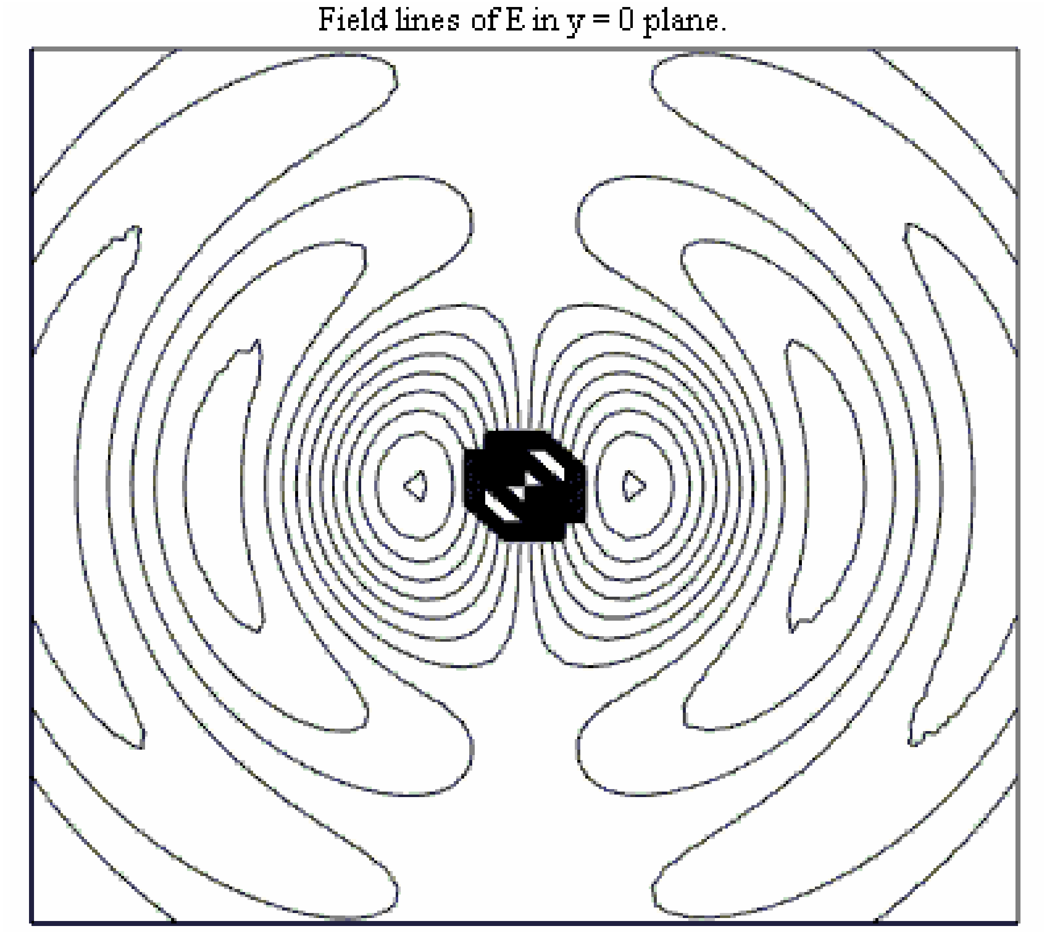


Radiation Pattern

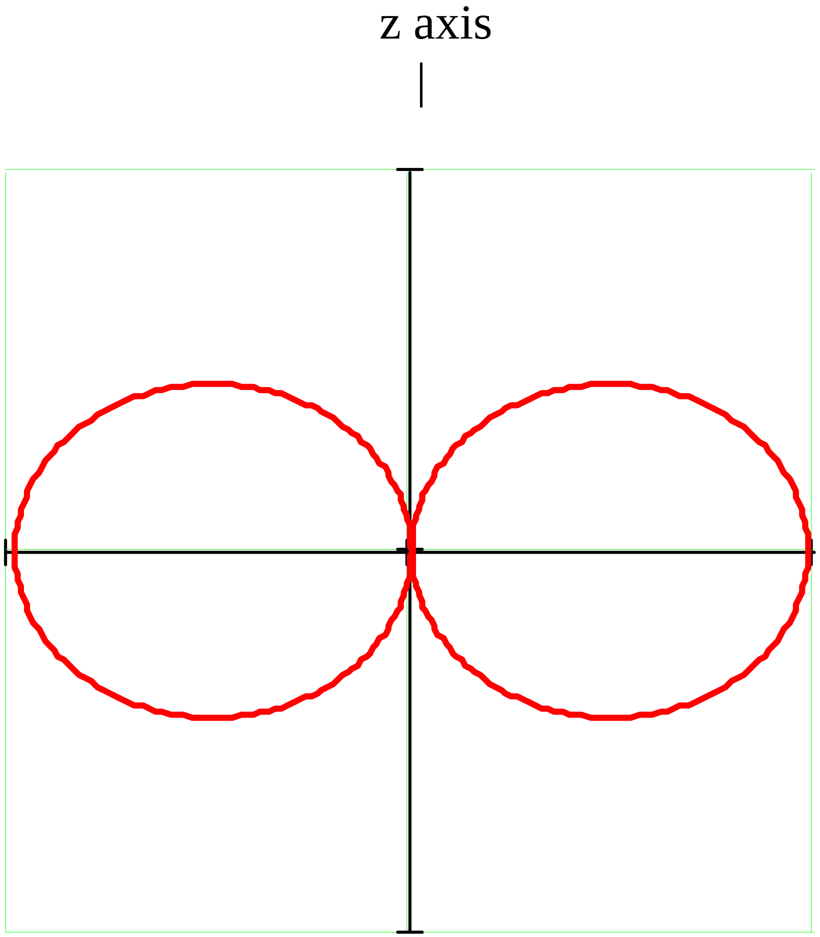
- Three dimensional plot of radiated power density
- Often presented as cuts in azimuth or elevation
- Consider a dipole
  - Uniform current (Iz)
  - Length, a.



Dipole Radiating Fields



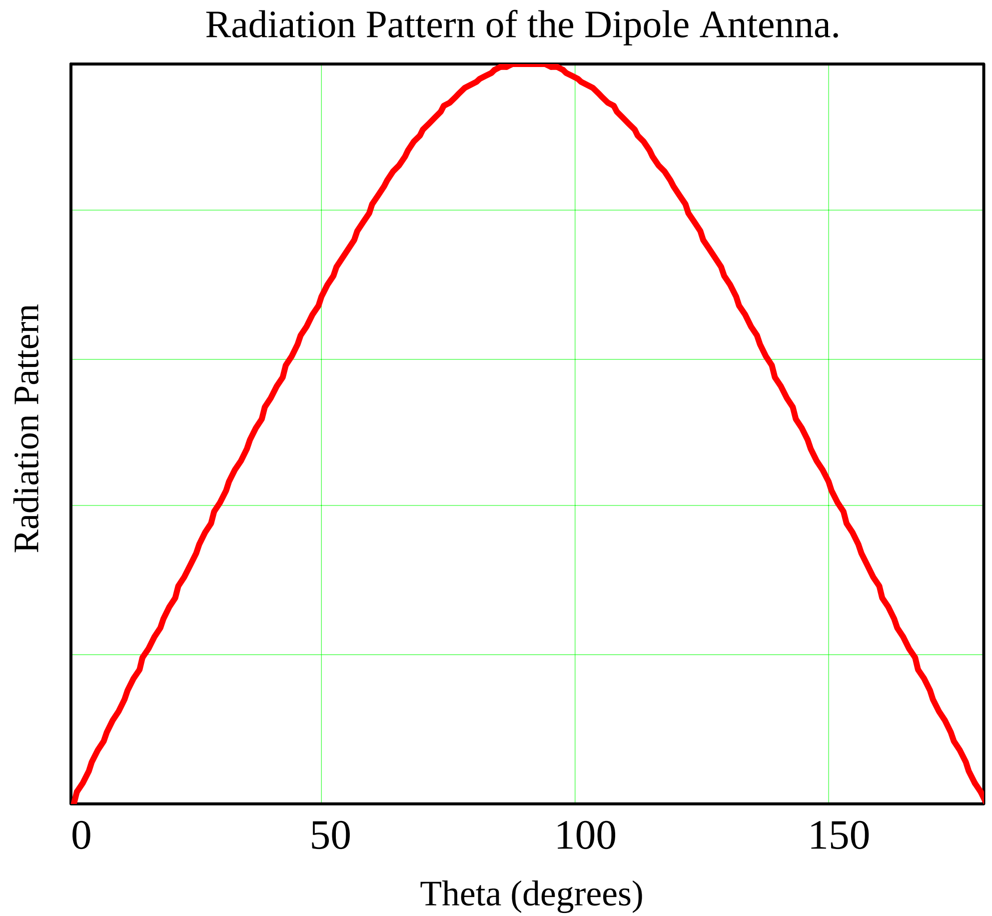
Elevation Pattern



Far-Field Pattern of the Dipole Antenna.

For a dipole of length $L = 0.5 \ (\lambda_0)$.

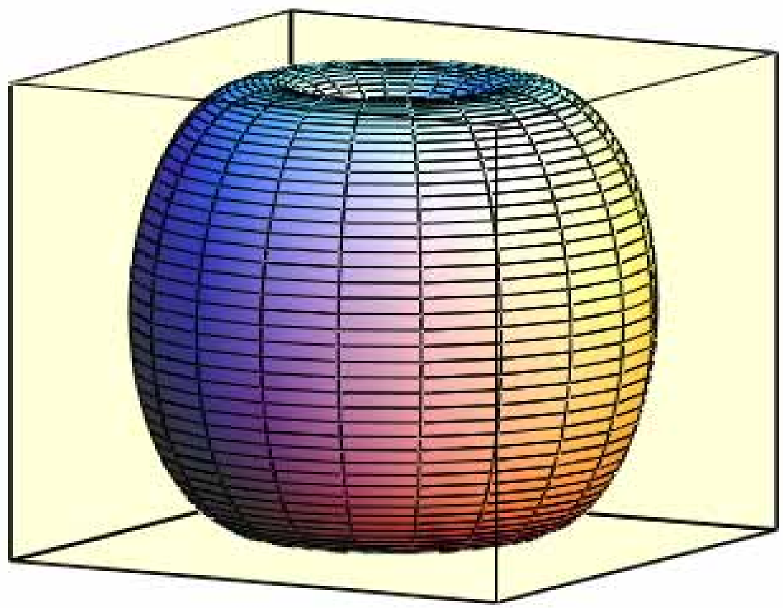
Dipole Radiation Pattern - Azimuthal



For a dipole of length $L = 0.5\ (\lambda_0)$.

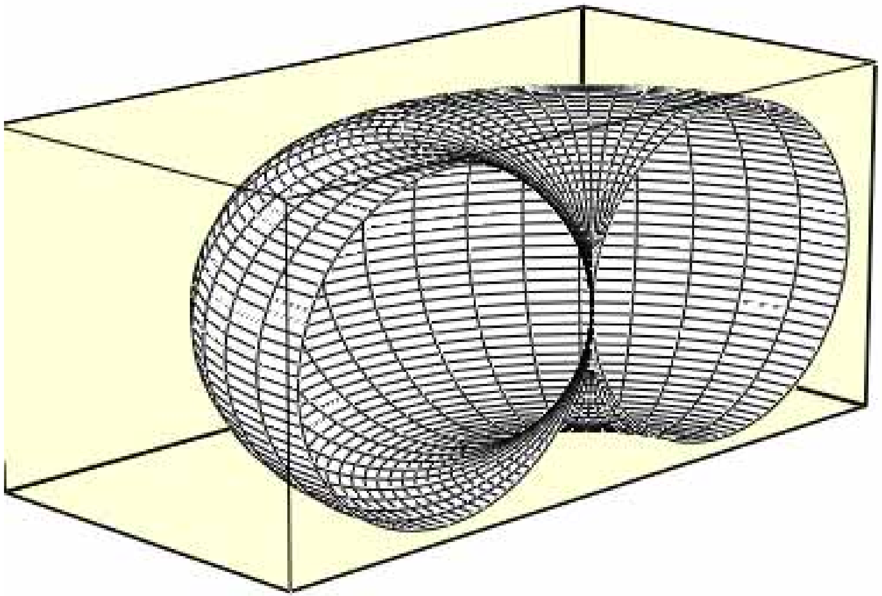
Dipole Radiation Pattern

Radiation Pattern of the Dipole Antenna.



Cutaway radiation pattern

Radiation Pattern of the Dipole Antenna.



(X, Y, Z)

The Maths of it!

- Dipole of length, a, with current, I, in z direction

- Far Field $r > \frac{2a^2}{\lambda}$ $r >> a$ $r >> \lambda$

- Electric and Magnetic Fields

$$\underline{E} \approx -j\omega\mu\underline{A} \qquad \underline{H} \approx \frac{1}{\eta}\hat{r} \times \underline{E}$$

The Maths of it!

- Vector Magnetic Potential, A, is

$$A_z = \int_{-a/2}^{a/2} I(z) \frac{e^{-jkr}}{4\pi r} e^{jkz\cos(\theta)} dz$$

- This gives

Current, Distance

$$E_\theta = \frac{\eta}{2} I \frac{a}{\lambda} \frac{1}{r} j e^{-jkr} \frac{\sin(u)}{u} \sin(\theta) \qquad u = \frac{ka}{2}\cos(\theta)$$

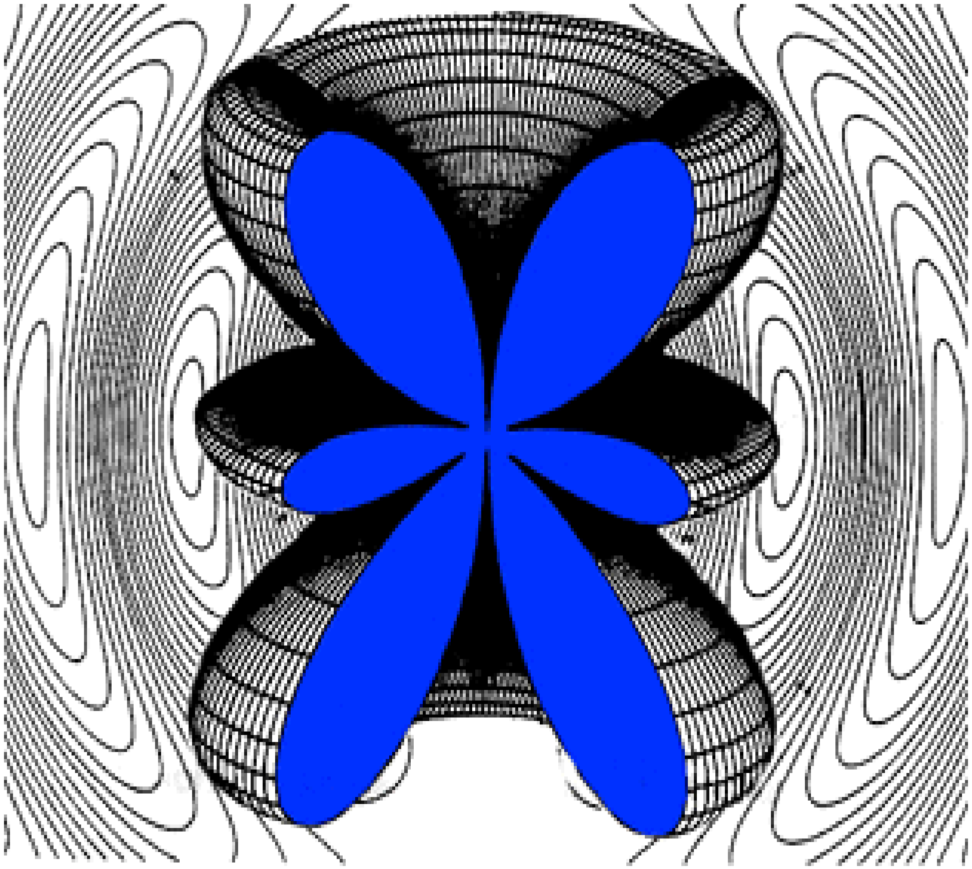
Magnitude, Length, Phase, Pattern

Power Pattern

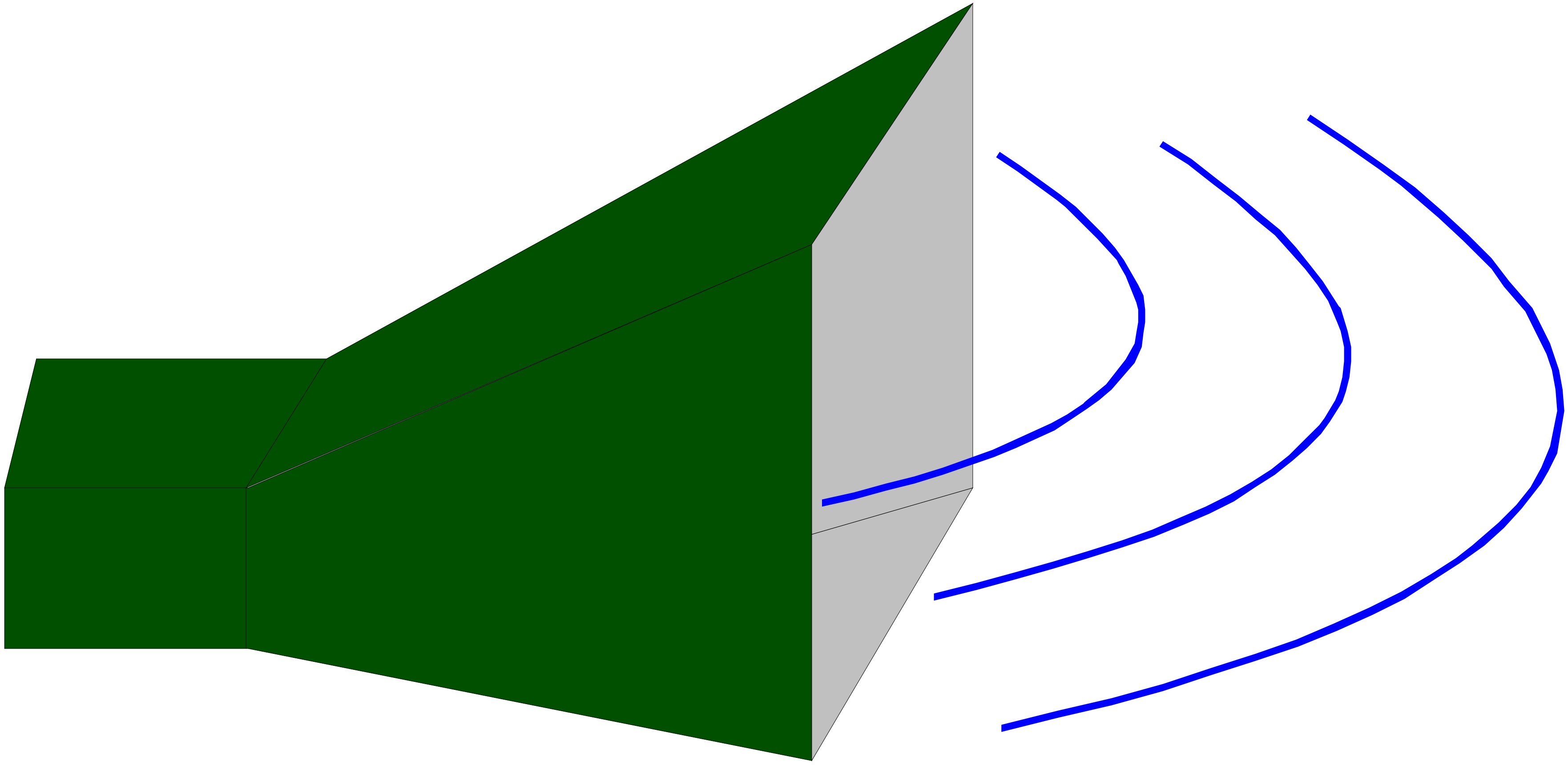
- Normal to plot the power pattern based on the Poynting Vector.
- Total Power is obtained by integrating radiation intensity over full sphere

Antenna Pattern and Fields

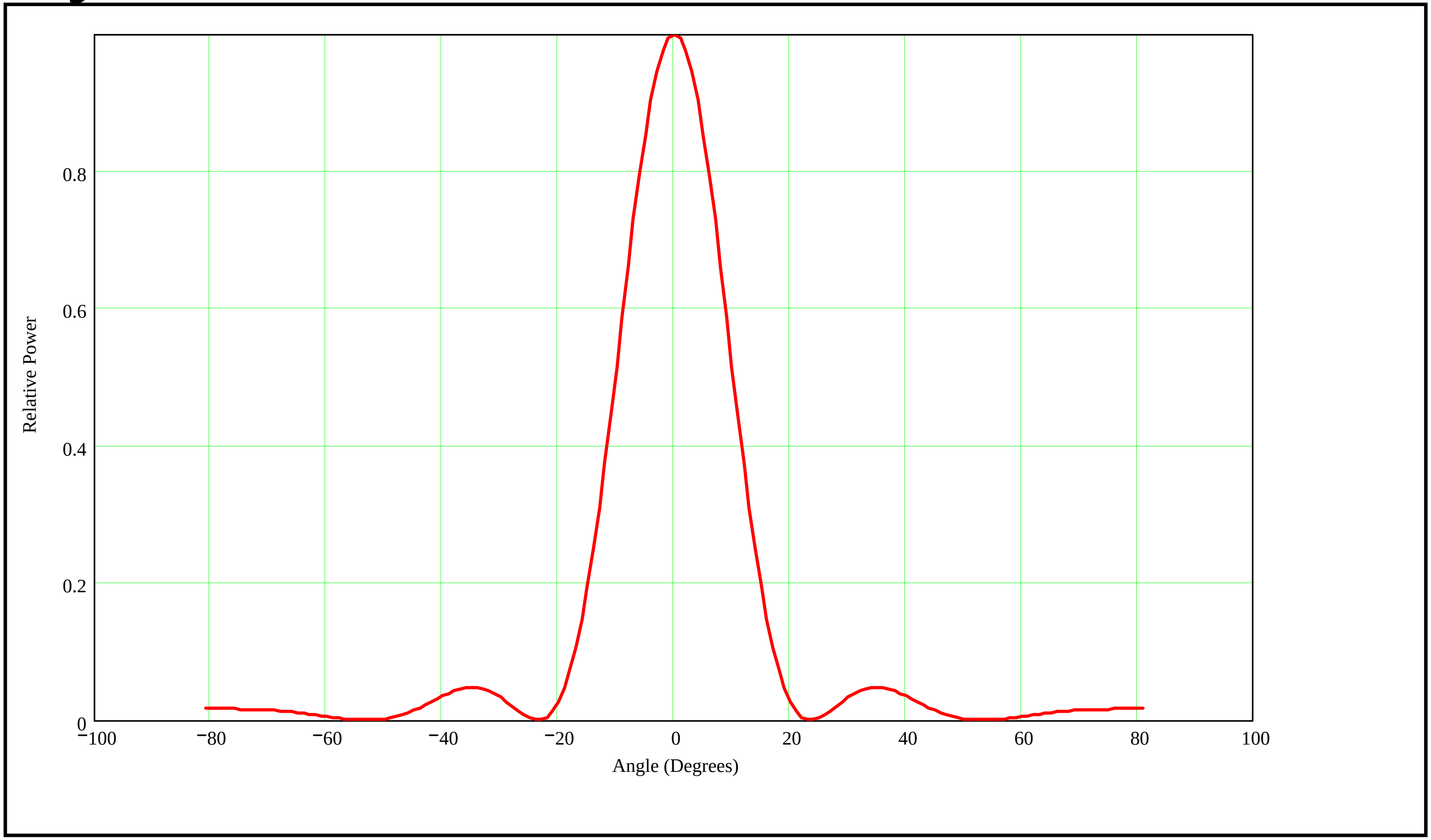
- This is for a 1.5λ dipole



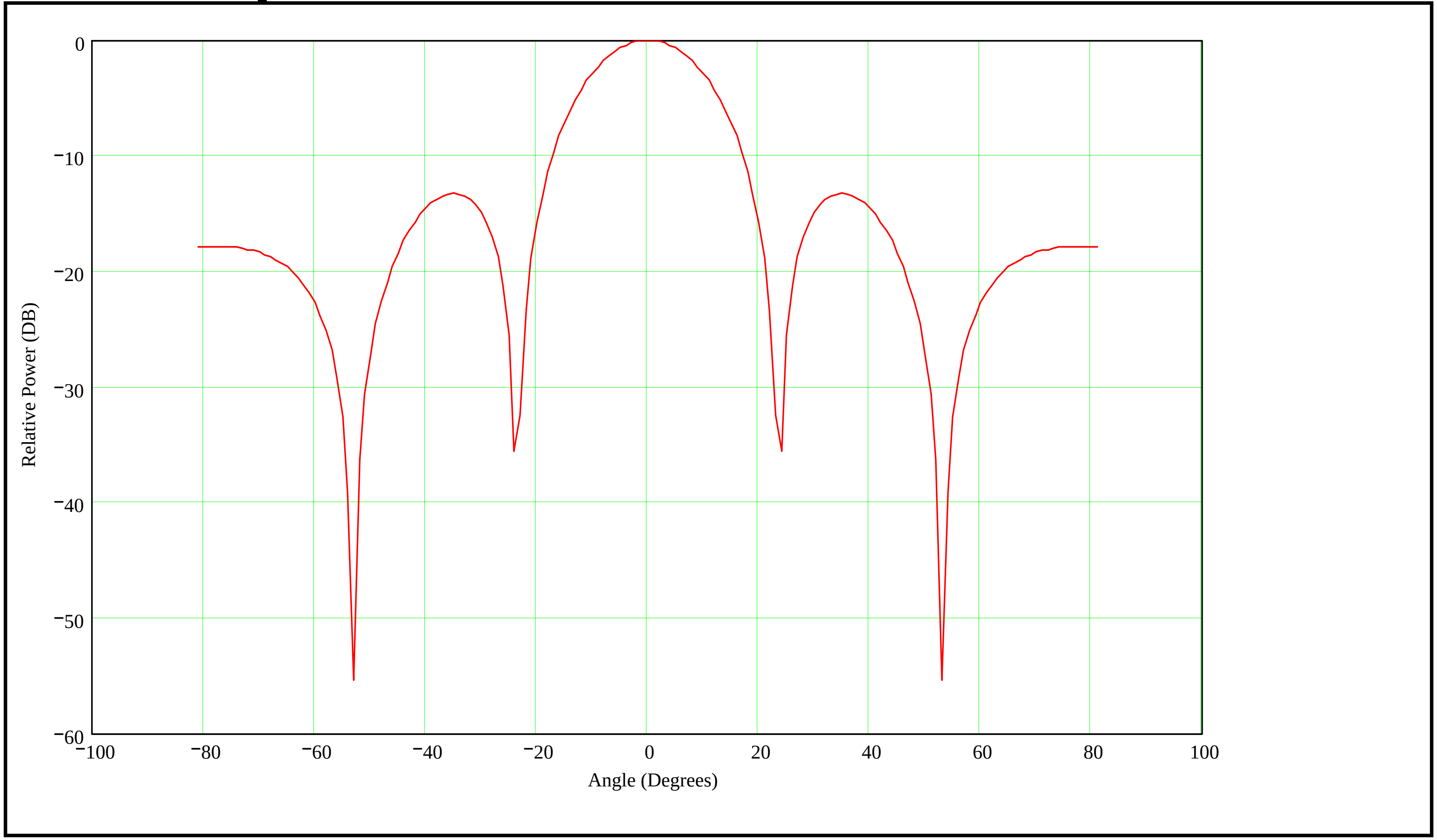
Pyramidal Horn Power Pattern



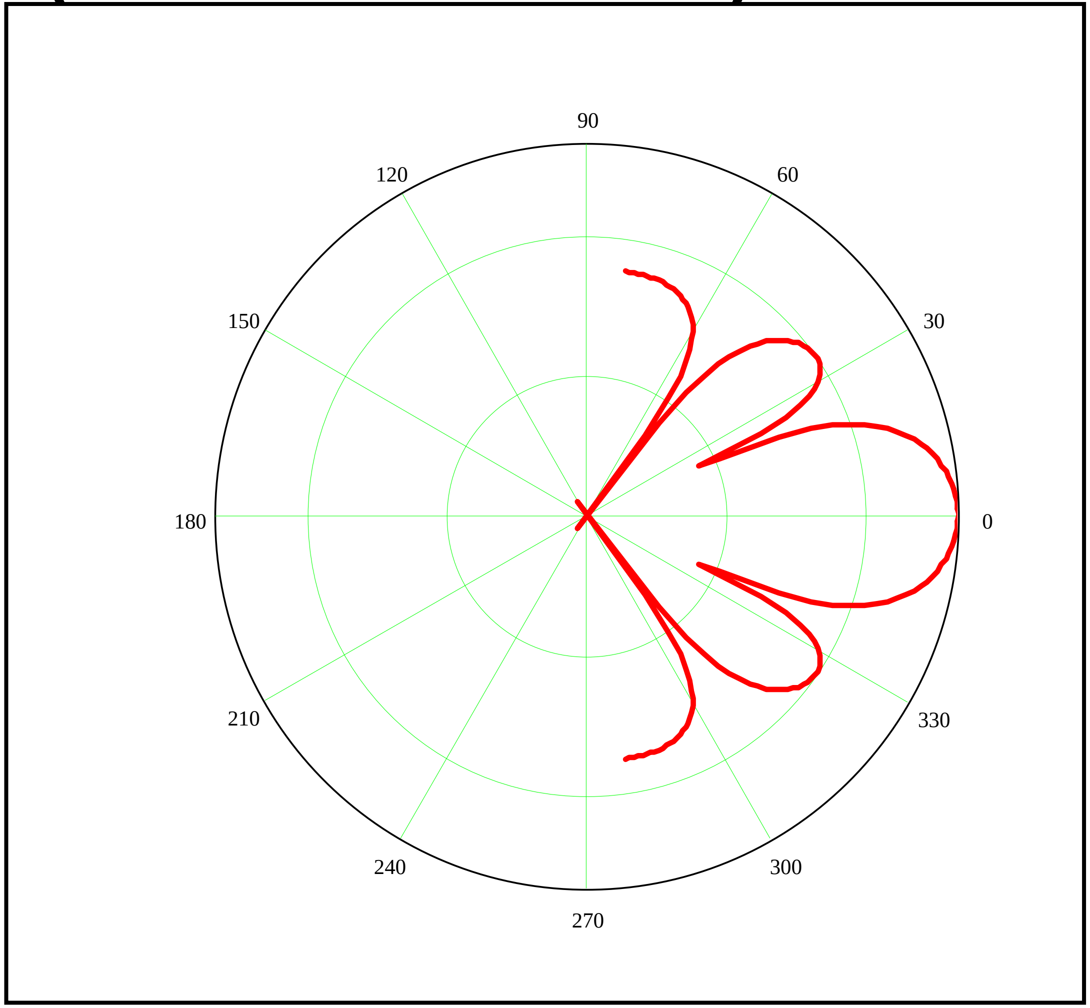
Pyramidal Horn Power Pattern



dB Equivalent



Polar Plot (dB or Linear)



Directivity

- Measure of how well an antenna concentrates, or directs, transmitted power.
- Also measure of antenna’s receiving sensitivity.
- Correct definition is 3-D function over full sphere.
- Normally quote maximum radiation direction.

Directivity

- Radiated power density in a certain direction compared to power density of an isotropic radiator radiating same power.

$$D(\theta,\phi) = \frac{U(\theta,\phi)}{U_{average}}$$

- Relates directly to beamwidth
  - Higher Directivity gives a narrower beam

Directivity

- Can be related to the Normalised Electric Field Pattern (Max value = 1)

$$U(\theta,\phi) = U_{\max} \left| F(\theta,\phi) \right|^2$$

- Average Radiated Power Density

$$U_{average} = \frac{P_r}{4\pi} \qquad W / steradian$$

Radiated Power

- Two ways of looking at it

$$P_r = \int_0^{2\pi}\int_0^{\pi} U(\theta,\phi)\,d\Omega$$

- and, for an isotropic radiator

$$P_r = \int_0^{2\pi}\int_0^{\pi} U_{average}\,d\Omega \quad = \quad 4\pi U_{average}$$

Directivity

- Picking from these equations

$$D(\theta,\phi)=\frac{U_{\max}\left|F(\theta,\phi)\right|^2 4\pi}{\int_0^{2\pi}\int_0^{\pi}U(\theta,\phi)d\Omega}$$

- giving

$$D(\theta,\phi)=\frac{\left|F(\theta,\phi)\right|^2 4\pi}{\int_0^{2\pi}\int_0^{\pi}\left|F(\theta,\phi)\right|^2 d\Omega} = \frac{4\pi}{\Omega_A}$$

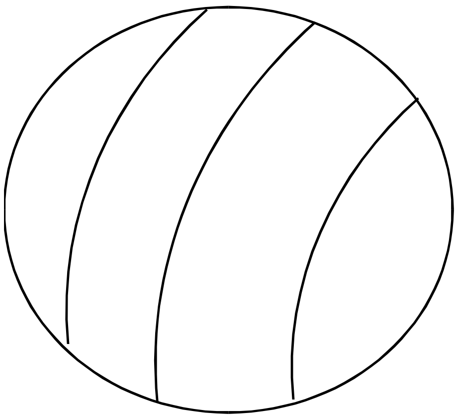
Directivity

- Antenna Directivity is maximum value of directive gain

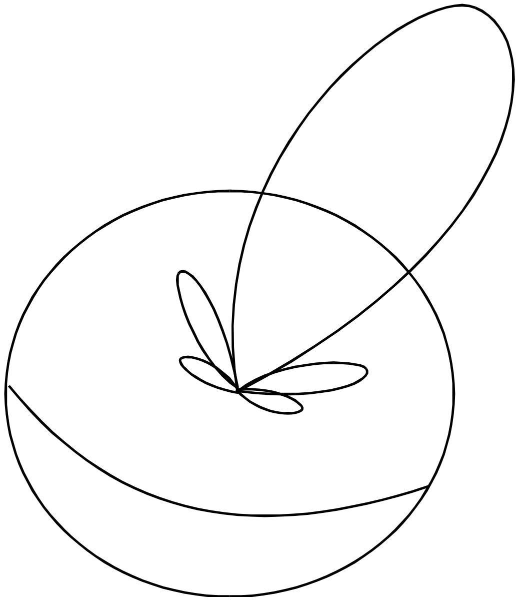
$$D = \max D(\theta, \phi) = \frac{4\pi}{\Omega_A}$$

- Derivation in notes or obtain by looking at previous equation
- Depends directly on beamwidth

Directivity



Isotropically Distributed
D = 1

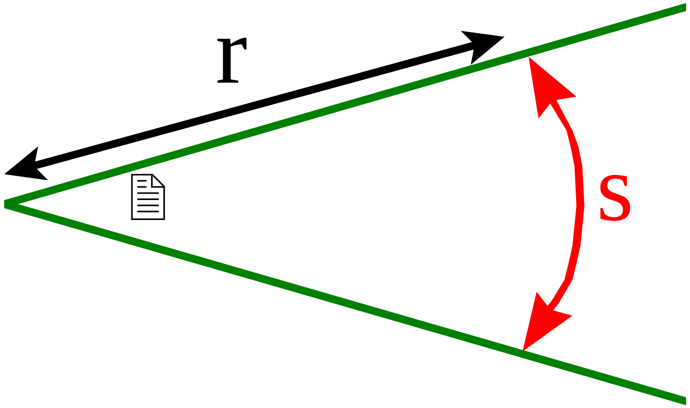


Radiation intensity from an Actual Antenna

$$D = \frac{4\pi}{\Omega_A}$$

Solid Angle - 1

- In 2-D the angle in radians is given by the length of the arc cut off by the bounding lines of the angle
- $\theta = s/r$ radians



Solid Angle - 2

- In 3-D the solid angle is defined by a cone.
- Solid angle is given as the ratio of the surface area of the sphere cut-out by the cone
- $\omega = S/r^2$.

Gain

- Why?
  - Directivity is also known as directive gain
  - Why use a second measure of the same thing?
- Convenience
  - Relates input power to transmitted power
  - Shows how efficient the antenna is at transforming guided energy to transmitted energy

Gain

- Definition
  - 4π x ratio of radiation intensity in a given direction to the net power accepted by the antenna

$$G(\theta,\phi) = 4\pi \frac{U(\theta,\phi)}{P_{in}}$$

Losses

- There will be losses
- We define antenna efficiency as

$$e = \frac{P_r}{P_{in}}$$

- Substitute into Gain equation

$$G(\theta,\phi) = 4\pi \frac{U(\theta,\phi)}{P_r} e \quad = \frac{U(\theta,\phi)}{U_{average}} e \quad = eD(\theta,\phi)$$

Gain

- Maximum Power Gain G=eD
- G and D are dimensionless.
- Often quoted in dB
- Also quoted in dB relative to a Dipole (dBd) or Isotropic Radiator (dBi)
- Dipole Directivity
  - D=1.5
  - D=1.76dBi
  - D=0dBd

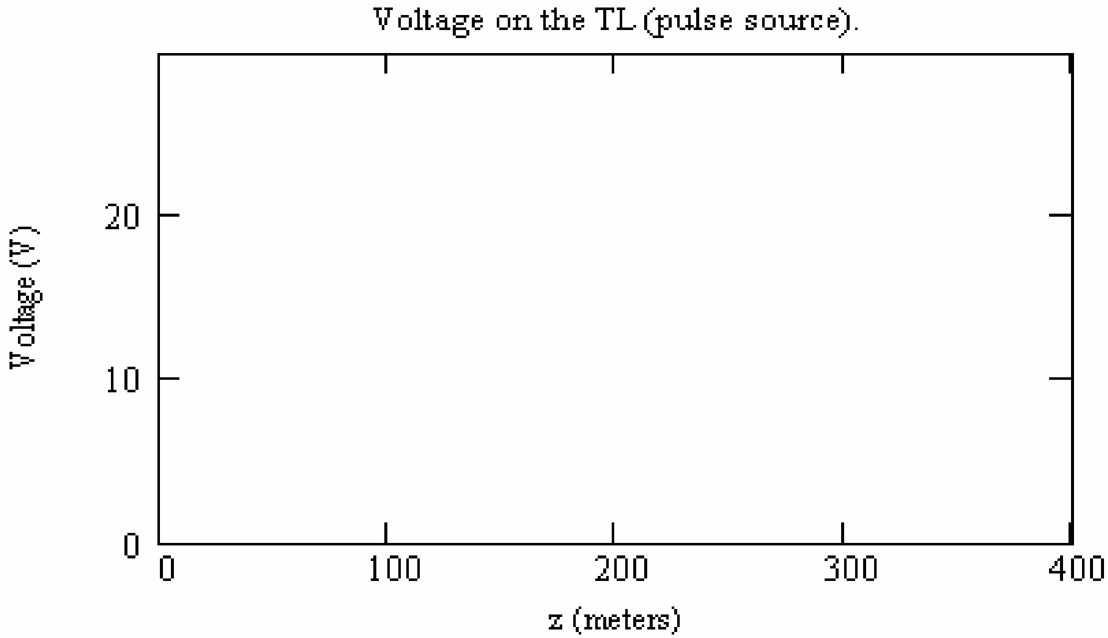
Antenna Losses

- Efficiency reduced by two loss sources
- Reflection at antenna input
- Ohmic losses in antenna
- Simulation on next slide
- 50Ω line with 60Ω load and 150Ω source resistance

Pulse on a Transmission Line

$k := 1 .. nz + 1 \qquad z_k := (k-1)\cdot\frac{L}{nz} \qquad time := \frac{FRAME\cdot(n_{skip}+1)\cdot\Delta t}{10^{-6}}$

Now generate an animation clip of the voltage on this TL. For best results, in the "Animate" dialog box choose To = 120 .



At time (μs)

time = 0.000

For a TL with

L = 400 (m)

$u = 2\times10^{8}$ (m/s)

Reflection Loss

- Caused by reflection coefficient, Γ
  - Γ defined by line and load impedances

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

  - Γ gives ratio of reflected signal to incident signal – E, H, V or I.
  - It is not a power ratio
    - Square it to get the power ratio

Antenna Measurements

- Equations to date would allow measurement of
  - Antenna gain by two methods
    - Comparison
    - Summation of measured radiated powers
  - Efficiency
    - Compare measured output power to input power

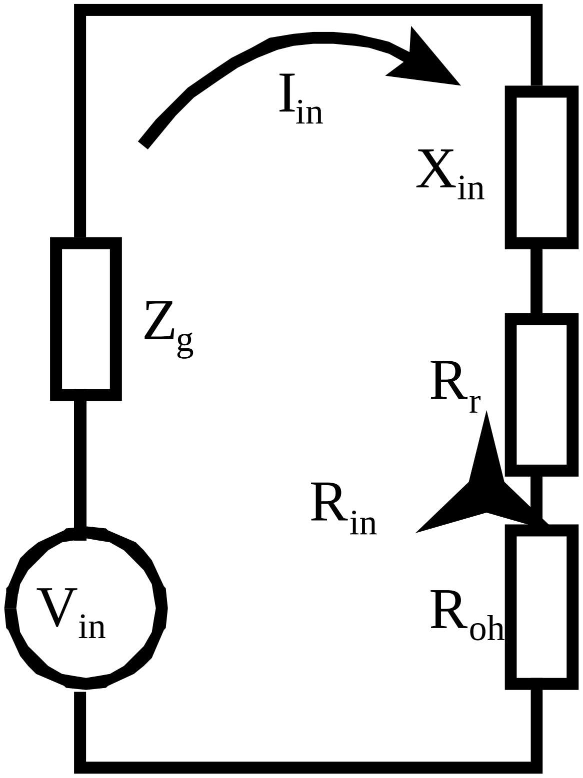
Radiation Resistance

- Transmitting Antenna equivalent circuit
- Power dissipated

$$P_{in} = \frac{1}{2}\left|I_{in}\right|^2 R_{in} \quad = \quad P_r + P_{oh}$$

- Radiation Resistance

$$R_r = \frac{2P_r}{\left|I_{in}\right|^2} \quad \Omega$$



Effective Collecting Aperture

- Multiply Effective Aperture (A_e) by incident power density to get received power
- A_e is actual aperture multiplied by efficiency
- Used for aperture antennas
  - Horns
  - Patches

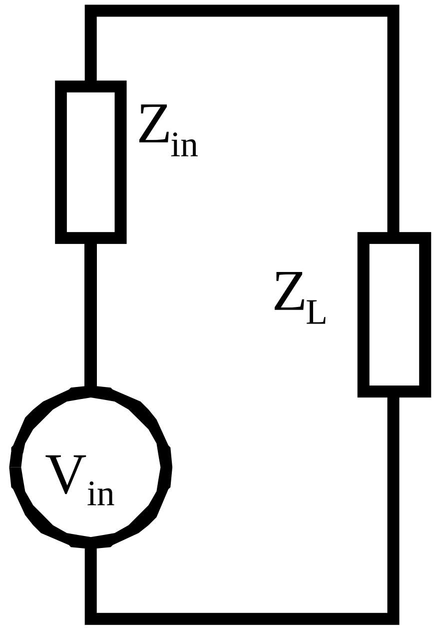
Effective Collecting Aperture

- Receiving Antenna Equivalent Circuit

$$P_r = \frac{1}{2}\left|I_{in}\right|^2 R_L$$

- Substitute for I

$$P_r = \frac{1}{2} R_L \frac{\left|V_{in}\right|^2}{\left(R_{in} + R_L\right)^2 \left(X_{in} + X_L\right)^2}$$



Maximum Power Transfer

$$R_{in} = R_L \qquad X_{in} = -X_L$$

- Conjugate match
- Substitute this plus equation for Input Resistance

$$P_r = \frac{|V|^2}{8R_r}$$

- Assume zero losses

Effective Area

- Substitute into original equation

$$A_e = \frac{|V|^2}{8R_r P_v}$$

- As power density $P_v = \dfrac{|E|^2}{2\eta}$

$$A_e = \frac{\eta |V|^2}{4R_r |E|^2}$$

Effective Length

- Used for wire antennas with no real area
  - Received voltage for incident Field

$$l_e = \frac{V}{E}$$

- This gives

$$l_e = \sqrt{\frac{R_r A_e}{30\pi}} \qquad m$$

Some Final Useful Equations

- Apertures of antennas

$$A_e(\theta,\phi) = D(\theta,\phi)\frac{\lambda^2}{4\pi}$$

- So

$$eA_e(\theta,\phi) = G(\theta,\phi)\frac{\lambda^2}{4\pi}$$

- for an aperture Antenna