

Fundamentals of Electromagnetics

Everything You Always Wanted to Know About Dipoles*

*But Were Afraid To Ask

Part 2

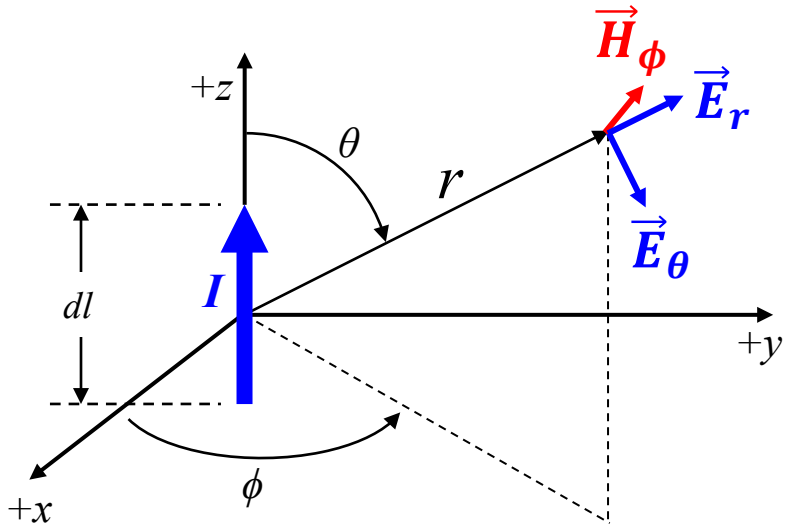
John McCloskey
Chief EMC Engineer
NASA/Goddard Space Flight Center
Greenbelt, MD
John.C.McCloskey@nasa.gov

Topics

- **Linear Dipole**
- **Half-Wave Dipole – Impedance, Directivity (Gain), Half Power (-3 dB) Beamwidth**
- **Quarter-Wave Monopole**
- **Virtual Demonstration: Example Monopole Impedance Measurement**
- **Reciprocity and Receiving Antennas - Effective Aperture & Effective Height**
- **Friis Transmission Equation**

- ***Shameless plug: "Fundamentals of Electromagnetics" video series***
  - *Publicly available on YouTube; search for above title*
  - *Direct playlist link:*
    - https://youtube.com/playlist?list=PLtrpQ-gPvnJn2r9Mw49jij7Ky0mb6RJYF&si=UxEKqVRgsR9w6nZ7

Recall from Part 1: Elemental Electric (Hertzian) Dipole



$$\beta = \frac{2\pi}{\lambda}$$

Magnetic field intensity:

$$H_r = 0$$

$$H_\theta = 0$$

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

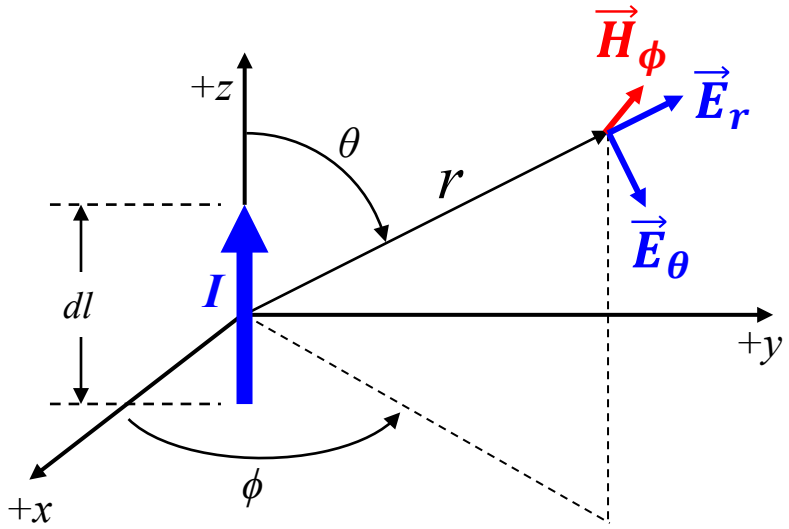
Electric field intensity:

$$E_r = -2\frac{Idl}{4\pi}\eta\beta^2 \cos\theta \left[\frac{1}{(j\beta r)^2} + \frac{1}{(j\beta r)^3}\right] e^{-j\beta r}$$

$$E_\theta = -\frac{Idl}{4\pi}\eta\beta^2 \sin\theta \left[\frac{1}{j\beta r} + \frac{1}{(j\beta r)^2} + \frac{1}{(j\beta r)^3}\right] e^{-j\beta r}$$

$$E_\phi = 0$$

Elemental Electric Dipole: Far Field



$$\beta = \frac{2\pi}{\lambda}$$

Magnetic field intensity, "far field" ($\beta r >> 1 \rightarrow r >> \lambda/2\pi$):

$$H_\phi = j\frac{Idl}{4\pi r}\beta \sin\theta e^{-j\beta r}$$

Electric field intensity, "far field" ($\beta r >> 1 \rightarrow r >> \lambda/2\pi$):

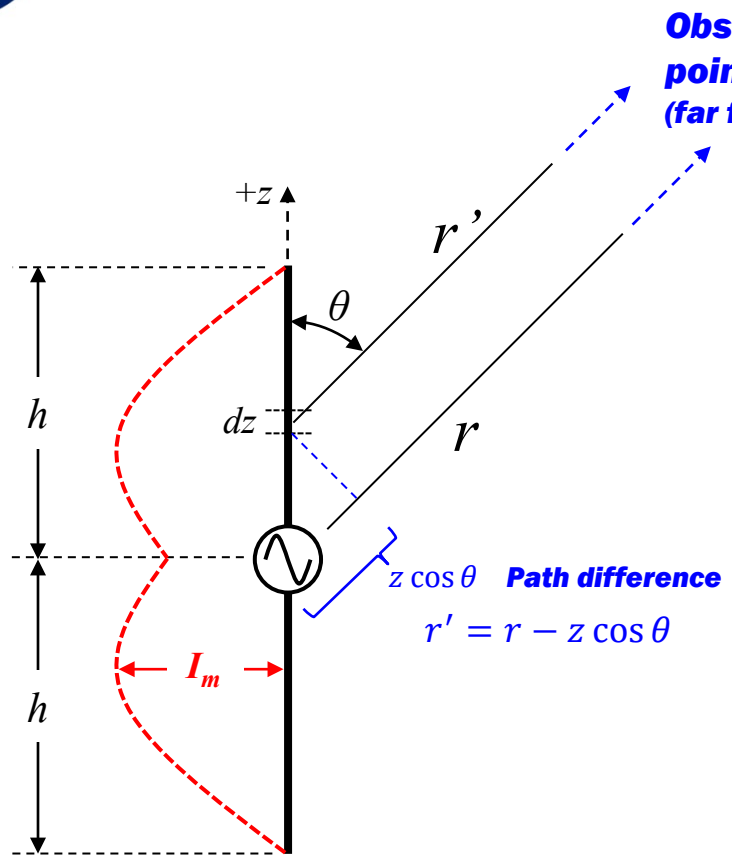
$$E_\theta = j\frac{Idl}{4\pi r}\eta\beta \sin\theta e^{-j\beta r}$$

In far field:

$$\frac{E_\theta}{H_\phi} = \eta$$

Characteristic impedance of medium (377 Ω in air/vacuum)

Linear Dipole (Center-Driven)



$$I(z) = I_m \sin[\beta(h - |z|)]$$

Current goes to 0 at end points

Electric field contribution from element dz:

$$dE_\theta = j\frac{I(z)dz}{4\pi}\eta\beta\sin\theta\frac{e^{-j\beta r'}}{r'}$$

$$dE_\theta = j\frac{I_m\eta\beta\sin\theta}{4\pi}\sin[\beta(h-|z|)]\frac{e^{-j\beta(r-z\cos\theta)}}{r-z\cos\theta}dz$$

Need to maintain full expression for phase term

For r >> h, distance term in denominator may be simplified to r

$$dE_\theta = j\frac{I_m\eta\beta\sin\theta}{4\pi r}e^{-j\beta r}\sin[\beta(h-|z|)]\,e^{-j\beta z\cos\theta}dz$$

r comes out front

Total electric field integrated from –h to +h:

$$E_\theta = j\frac{I_m\eta\beta\sin\theta}{4\pi r}e^{-j\beta r}\int_{-h}^{h}\sin[\beta(h-|z|)]\,e^{-j\beta z\cos\theta}dz$$

$$E_\theta = j\frac{I_m\eta\beta\sin\theta}{4\pi r}e^{-j\beta r}\int_{-h}^{h}\{\sin[\beta(h-|z|)]\cos(\beta z\cos\theta) - j\sin[\beta(h-|z|)]\ \sin(\beta z\cos\theta)\}dz$$

Sine terms integrate to 0 over symmetric limits

$$E_\theta = j\frac{I_m\eta\beta\sin\theta}{2\pi r}e^{-j\beta r}\int_{0}^{h}\{\sin[\beta(h-z)]\cos(\beta z\cos\theta)\}dz$$

Change limits to 0 to h
Multiply by 2

Taking z ≥ 0
Absolute value no longer needed

Continued

Linear Dipole (cont.)

$$E_\theta = j\frac{I_m\eta\beta\sin\theta}{2\pi r}e^{-j\beta r}\int_0^h \{\sin[\beta(h-z)]\cos(\beta z\cos\theta)\}dz \qquad \sin A\cos B = \frac{1}{2}[\sin(A+B)+\sin(A-B)]$$

$$= j\frac{I_m\eta\beta\sin\theta}{4\pi r}e^{-j\beta r}\int_0^h \{\sin[\beta(h-z)+\beta z\cos\theta]+\sin[\beta(h-z)-\beta z\cos\theta]\}dz$$

$$= j\frac{I_m\eta\beta\sin\theta}{4\pi r}e^{-j\beta r}\left\{\frac{-1}{(-\beta+\beta\cos\theta)}\cos[\beta(h-z)+\beta z\cos\theta]-\frac{1}{(-\beta-\beta\cos\theta)}\cos[\beta(h-z)-\beta z\cos\theta]\right\}\Bigg|_0^h$$

Plug 'n' chug

$$= j\frac{I_m\eta\beta\sin\theta}{4\pi r}e^{-j\beta r}\left\{\frac{1}{\beta(1-\cos\theta)}[\cos(\beta h\cos\theta)-\cos\beta h]+\frac{1}{\beta(1+\cos\theta)}[\cos(\beta h\cos\theta)-\cos\beta h]\right\}$$

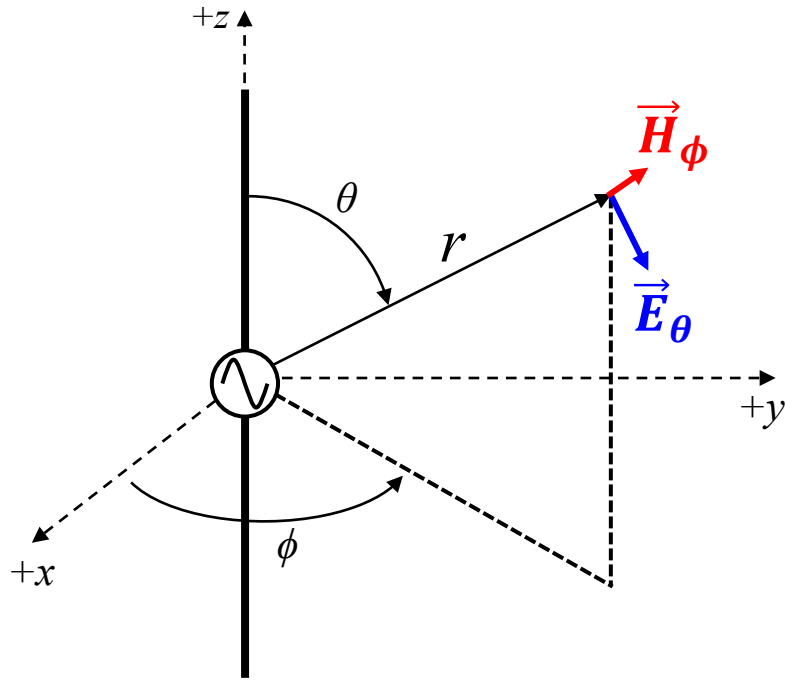
$$= j\frac{I_m\eta\beta\sin\theta}{4\pi r}e^{-j\beta r}\left\{\frac{1+\cos\theta+1-\cos\theta}{\beta(1-\cos^2\theta)}[\cos(\beta h\cos\theta)-\cos\beta h]\right\}$$

$$= j\frac{I_m\eta\beta\sin\theta}{4\pi r}e^{-j\beta r}\left\{\frac{2}{\beta\sin^2\theta}[\cos(\beta h\cos\theta)-\cos\beta h]\right\}$$

$$E_\theta = j\frac{I_m\eta}{2\pi r}e^{-j\beta r}\underbrace{\left[\frac{\cos(\beta h\cos\theta)-\cos\beta h}{\sin\theta}\right]}_{\textbf{Pattern function}}$$

$$\boldsymbol{F(\theta)}$$

Linear Dipole – E and H Fields



$$E_\theta = j\frac{I_m \eta}{2\pi r} e^{-j\beta r} F(\theta) \qquad F(\theta) = \left[\frac{\cos(\beta h \cos\theta) - \cos\beta h}{\sin\theta}\right]$$

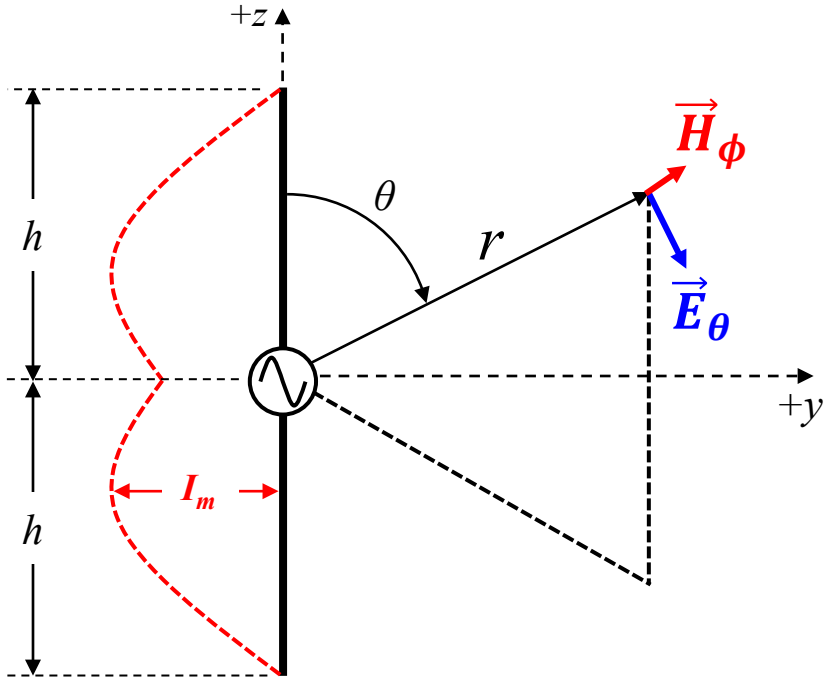
In free space/air:

$$\eta = 120\pi$$

$$E_\theta = j\frac{60 I_m}{r} e^{-j\beta r} F(\theta)$$

$$H_\phi = \frac{E_\theta}{\eta} = j\frac{I_m}{2\pi r} e^{-j\beta r} F(\theta)$$

Linear Dipole – E and H Fields (cont.)



$$I(z) = I_m \sin[\beta(h - |z|)]$$

$$E_\theta = j\frac{I_m \eta}{2\pi r} e^{-j\beta r} F(\theta) \qquad F(\theta) = \left[\frac{\cos(\beta h \cos\theta) - \cos\beta h}{\sin\theta}\right]$$

In free space/air:

$$\eta = 120\pi$$

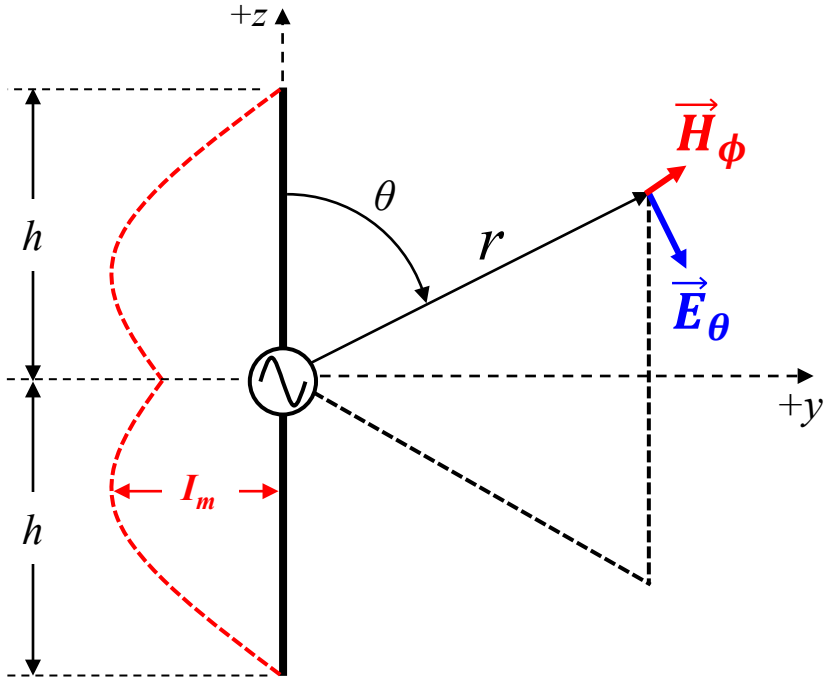
$$E_\theta = j\frac{60 I_m}{r} e^{-j\beta r} F(\theta)$$

$$H_\phi = \frac{E_\theta}{\eta} = j\frac{I_m}{2\pi r} e^{-j\beta r} F(\theta)$$

Radiated fields directly related to CURRENT

Control the current, control the fields…

Linear Dipole – E and H Fields (cont.)



$$I(z) = I_m \sin[\beta(h - |z|)]$$

$$E_\theta = j\frac{I_m \eta}{2\pi r} e^{-j\beta r} F(\theta) \qquad F(\theta) = \left[\frac{\cos(\beta h \cos\theta) - \cos\beta h}{\sin\theta}\right]$$

In free space/air:

$$\eta = 120\pi$$

$$E_\theta = j\frac{60 I_m}{r} e^{-j\beta r} F(\theta)$$

$$H_\phi = \frac{E_\theta}{\eta} = j\frac{I_m}{2\pi r} e^{-j\beta r} F(\theta)$$

$$(E_\theta)_{MAX} = \frac{60 I_m}{r}$$

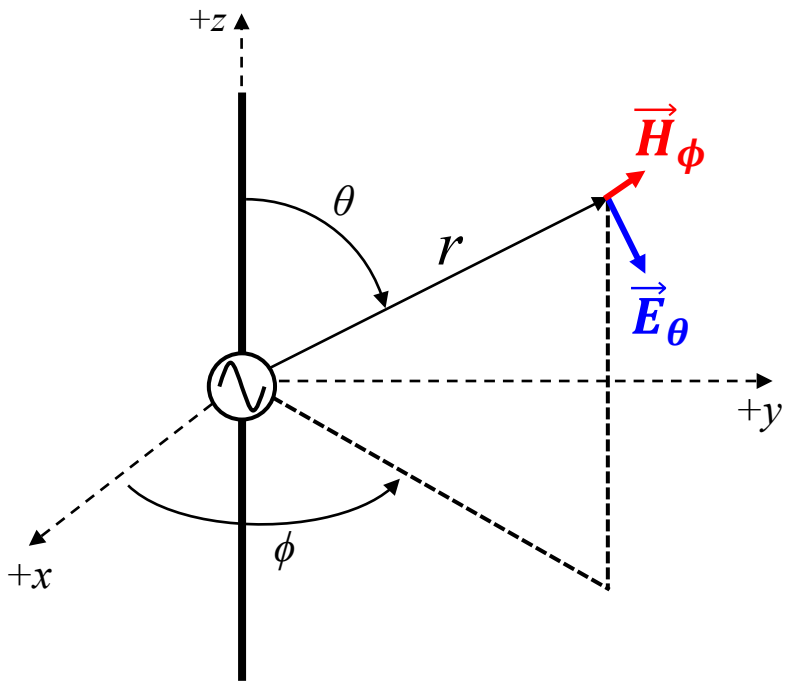
E_θ = 1 V/m at r = 1 m:
→ I_m = 16 mA

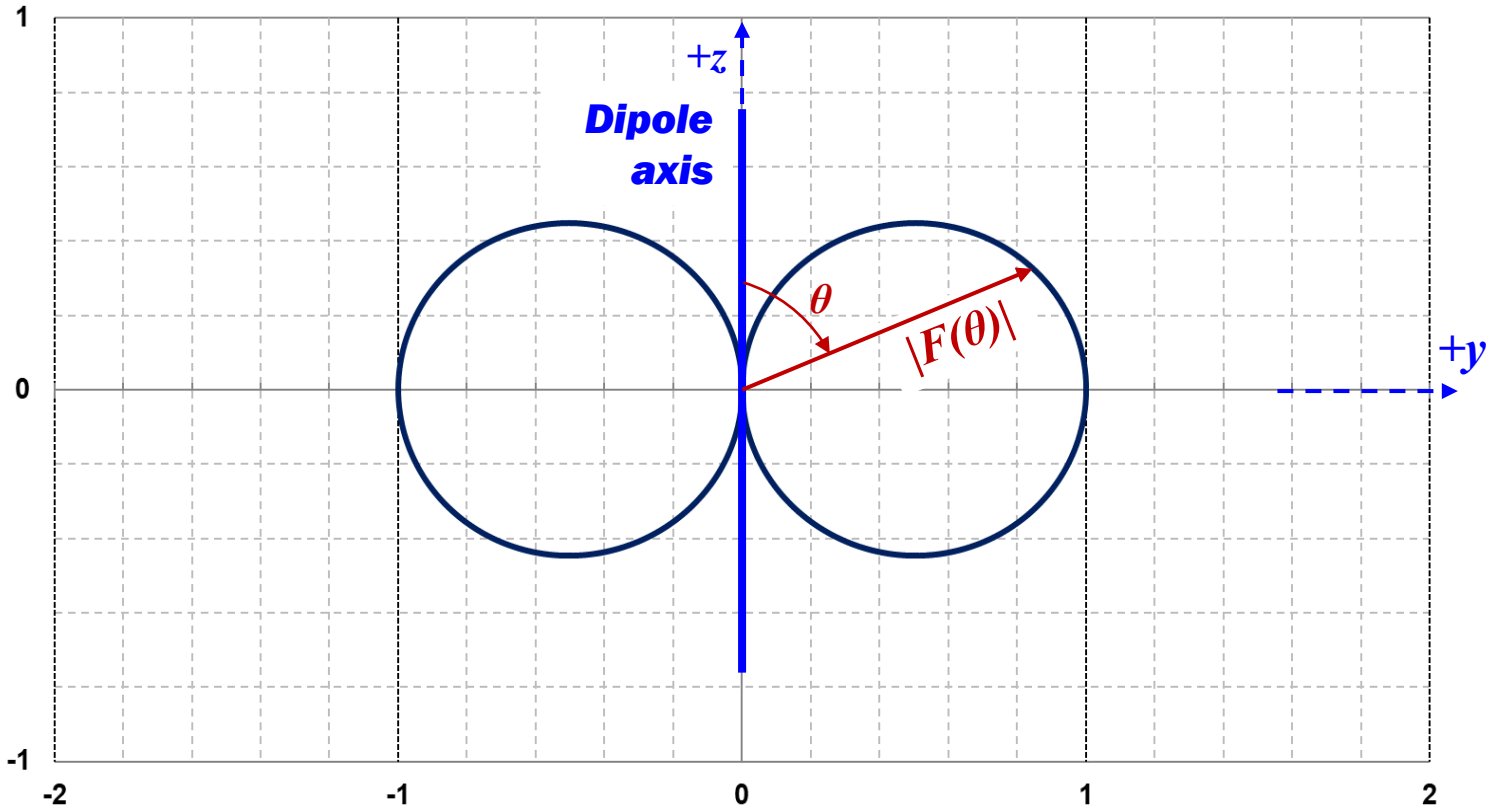
High common mode current to achieve "by accident" (and into tuned half-wave dipole)

Radiated susceptibility levels > 1 V/m only achievable from intentionally radiating structures (NOT from incidental emissions)

Linear Dipole – Pattern Function F(θ)

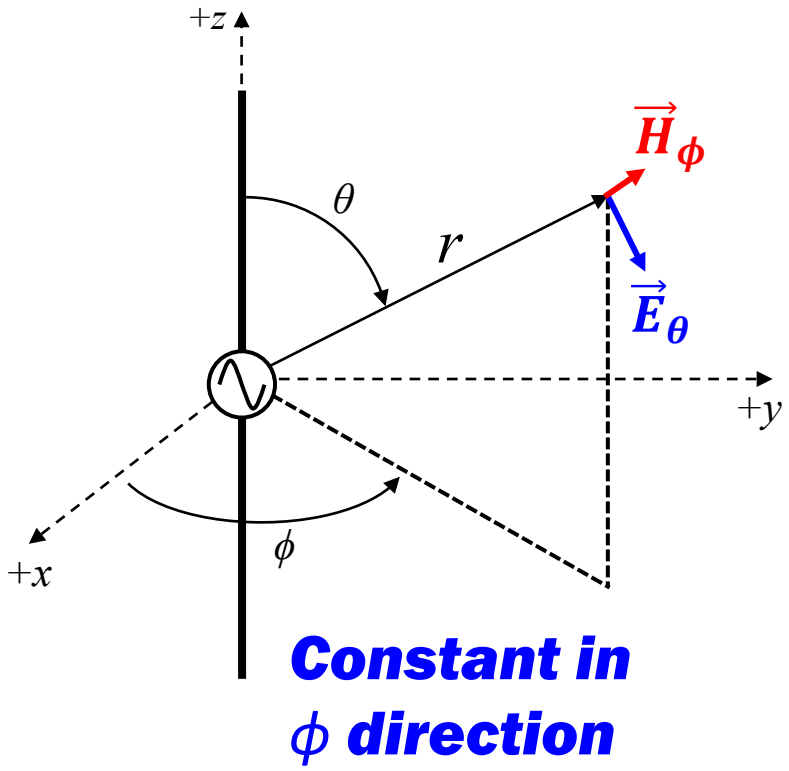
$$F(\theta) = \left[\frac{\cos(\beta h \cos\theta) - \cos\beta h}{\sin\theta}\right]$$



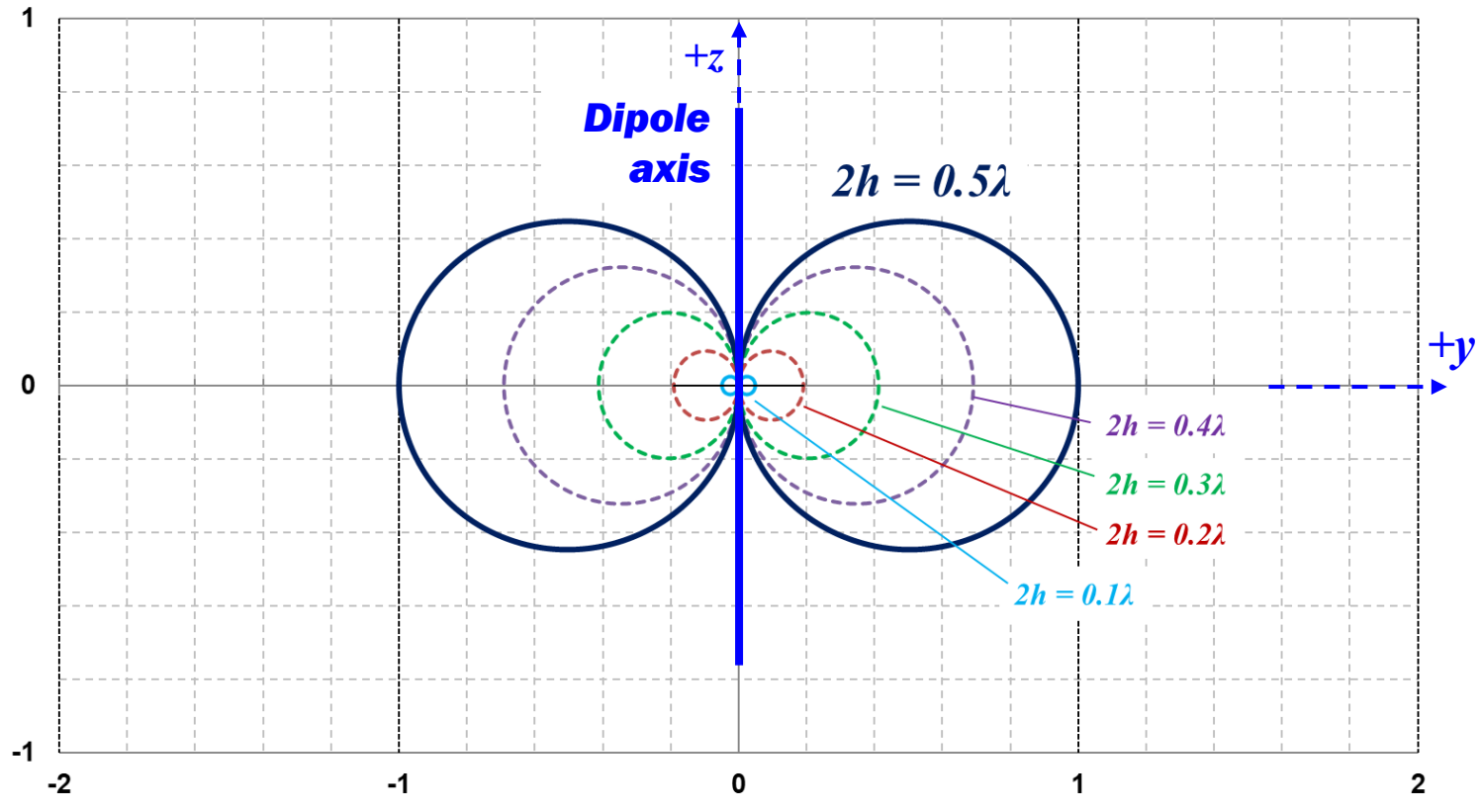


Linear Dipole – Pattern Function F(θ)

$$F(\theta) = \left[\frac{\cos(\beta h \cos\theta) - \cos\beta h}{\sin\theta}\right]$$

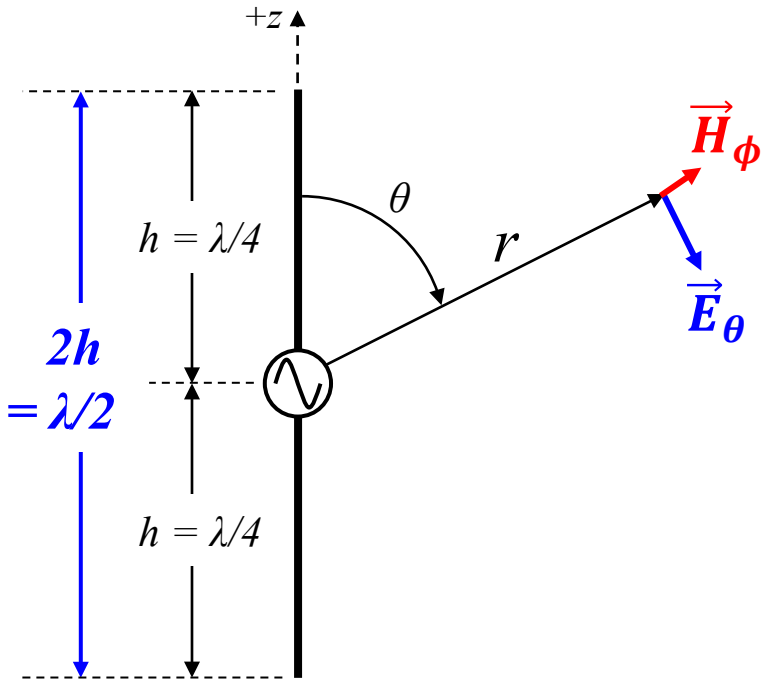


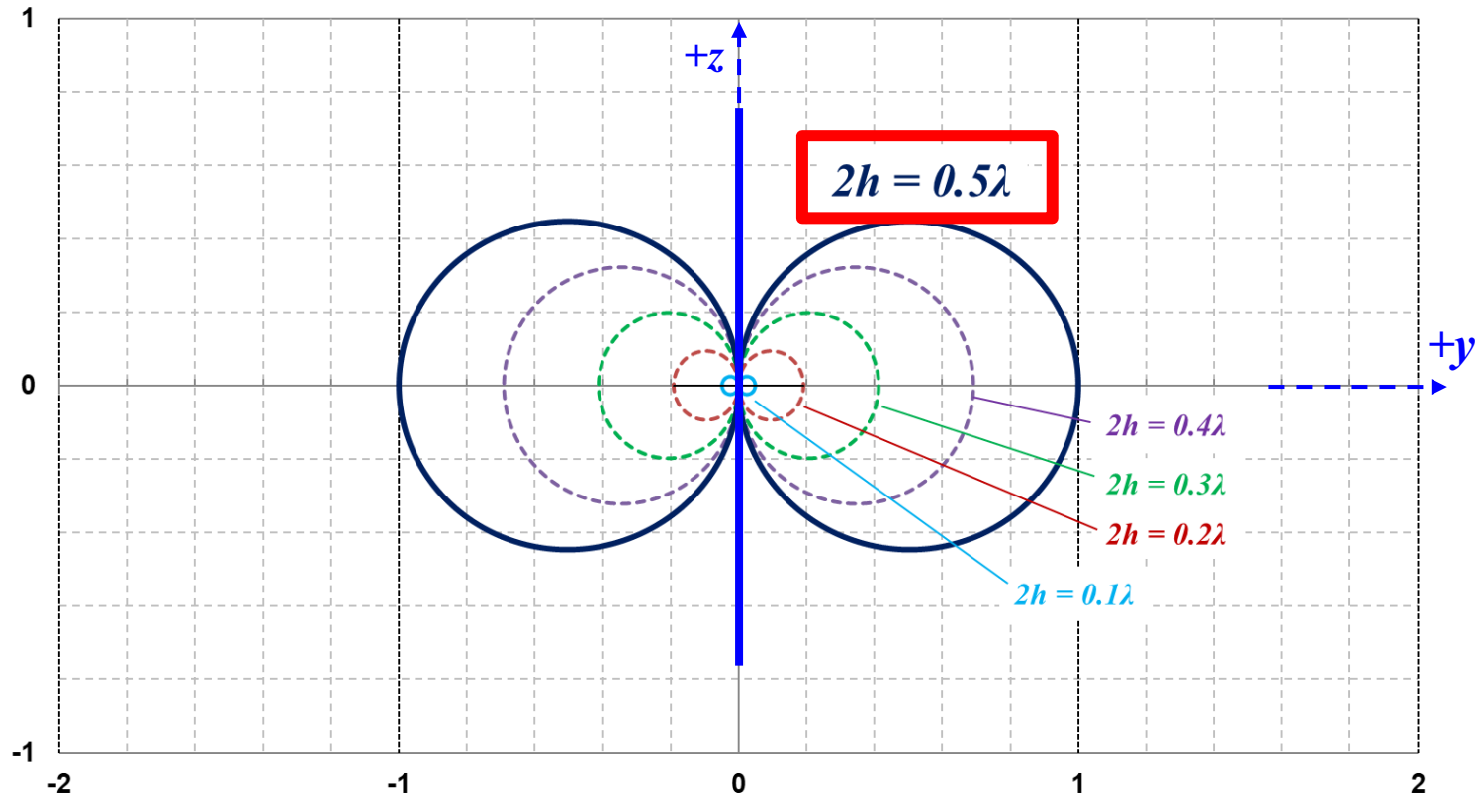
Constant in ϕ direction



Linear Dipole – Pattern Function F(θ) (cont.)

$$F(\theta) = \left[\frac{\cos(\beta h \cos\theta) - \cos\beta h}{\sin\theta}\right]$$



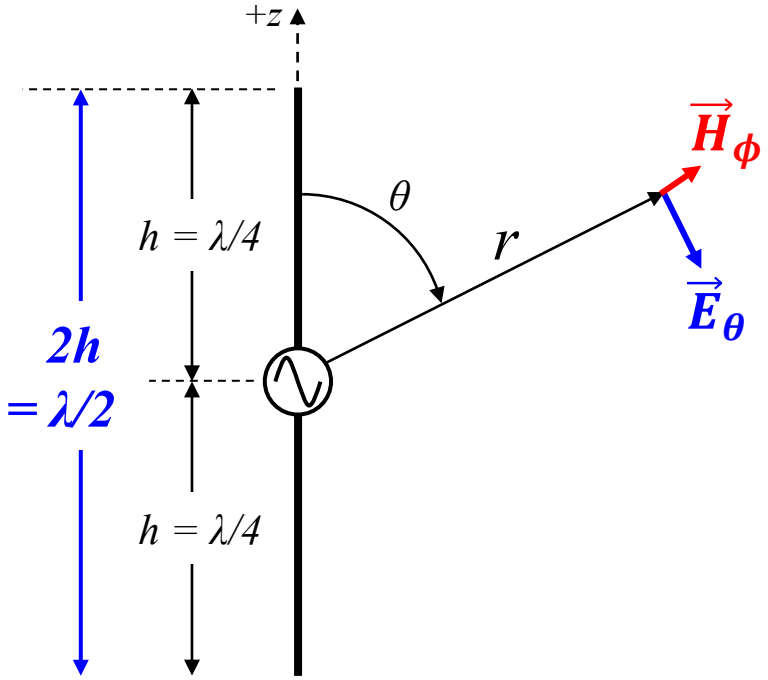


Maximum radiation when

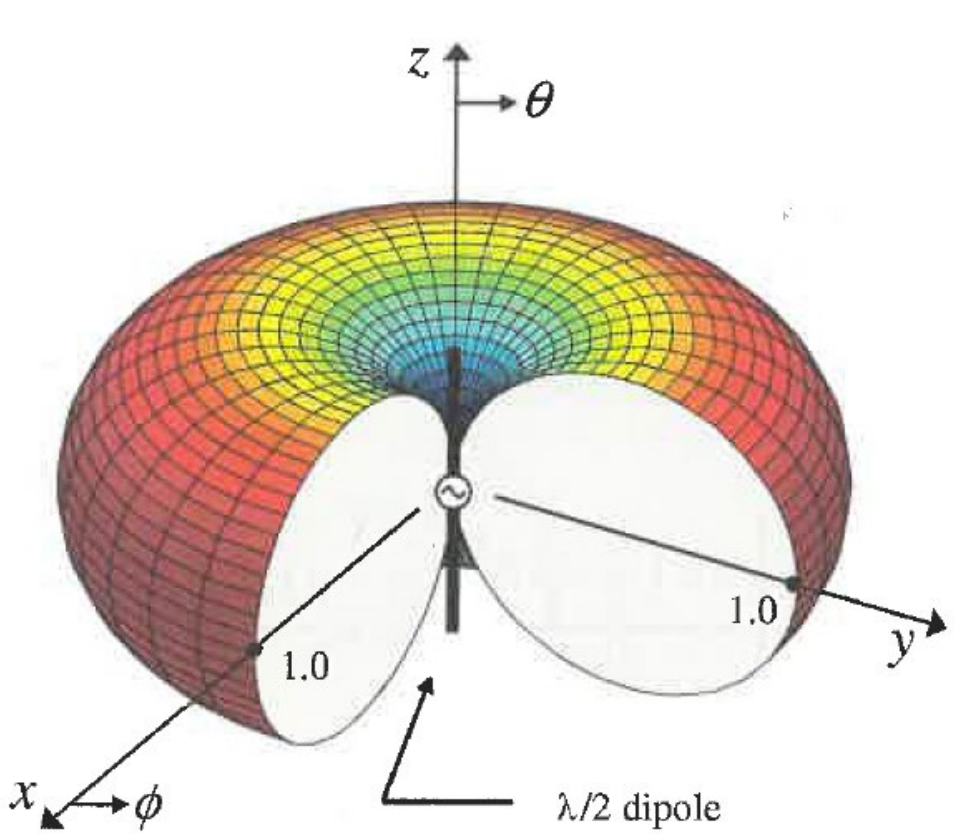
$$2h = \lambda/2$$

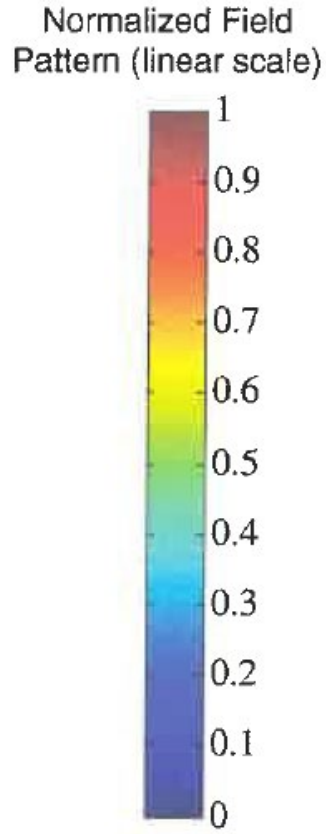
(half-wave dipole)

Linear Dipole – Pattern Function F(θ) (cont.)



Balanis (5th edition), Figure 4-12a, p. 178:





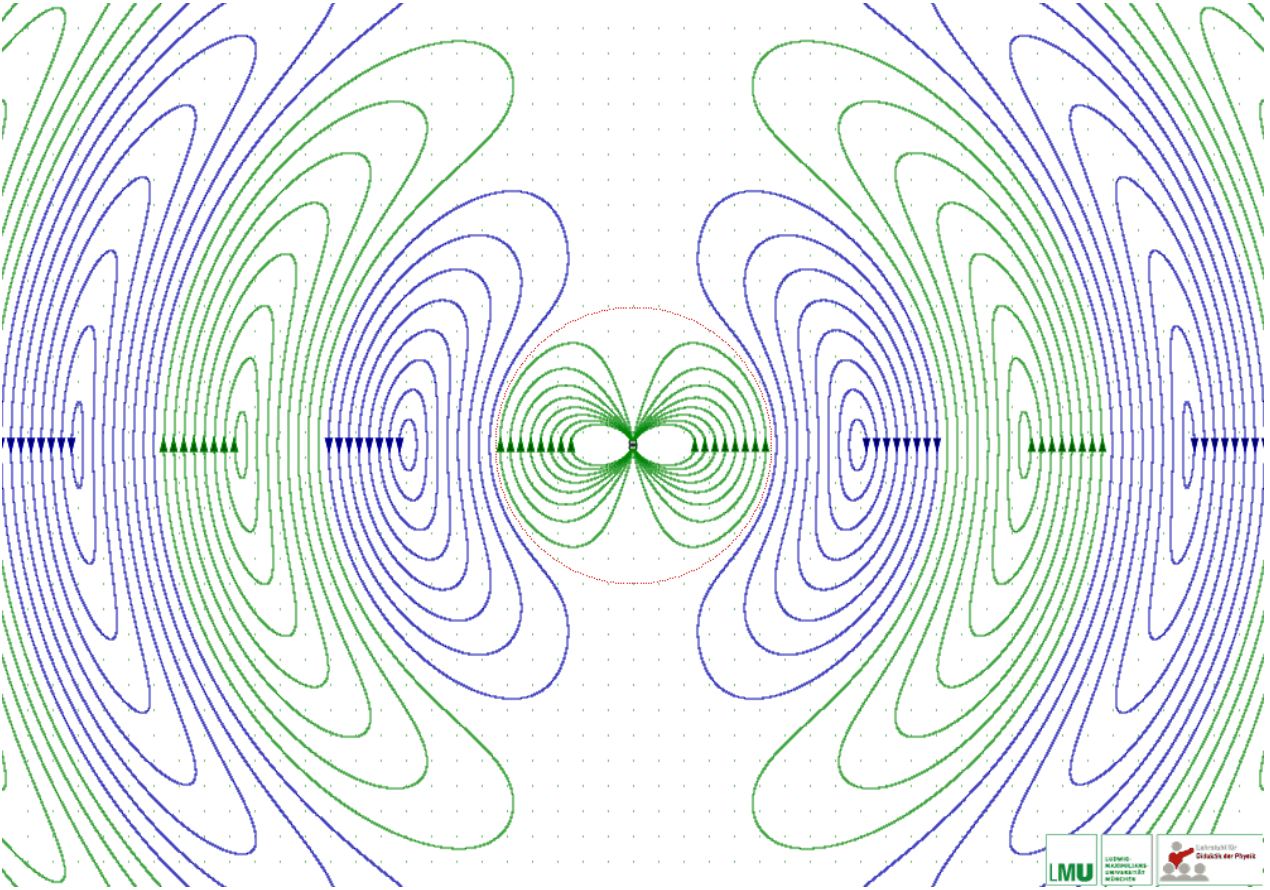
Essentially omnidirectional in ϕ direction

Radiation Patterns: Hertzian Dipole and Half-Wave Dipole

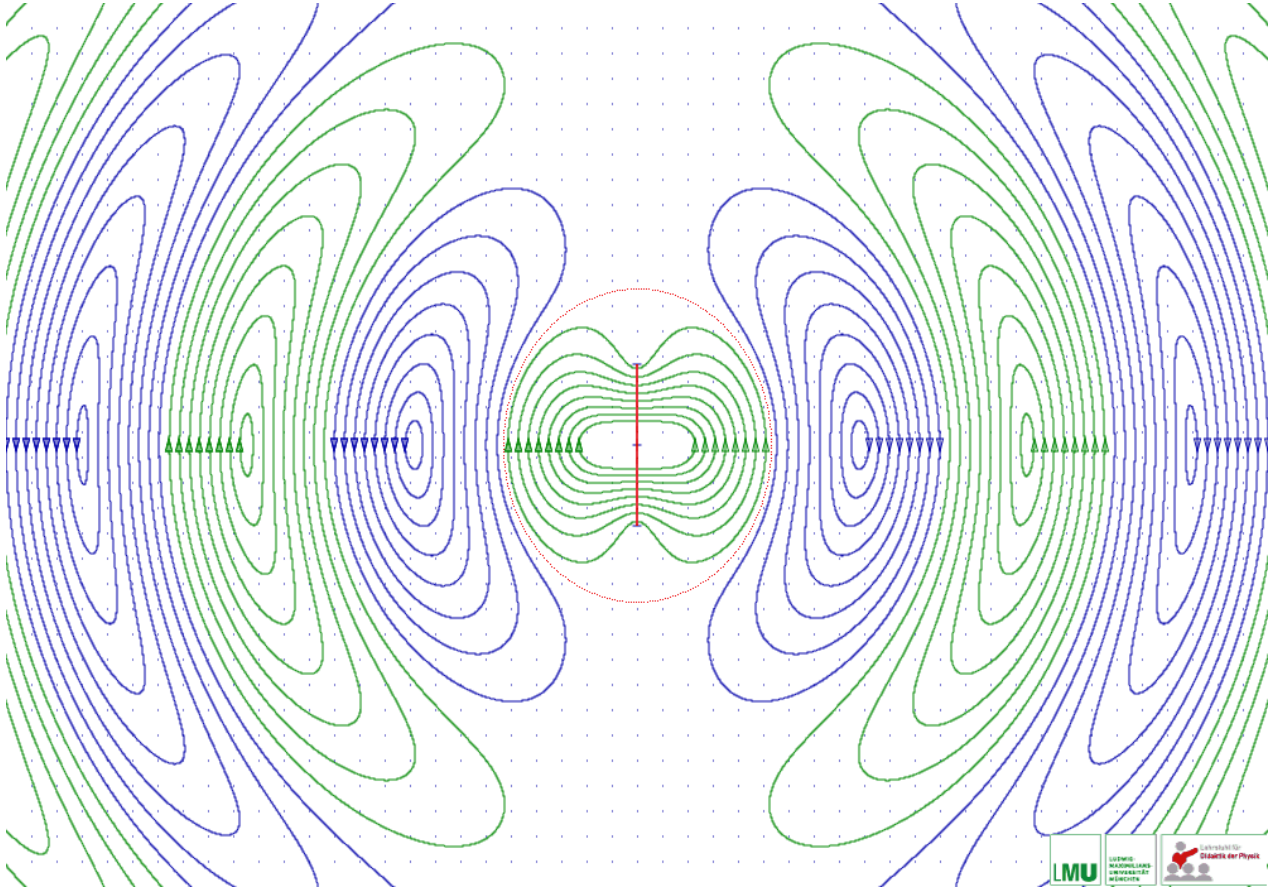
https://www.didaktik.physik.uni-muenchen.de/_assets/bilder/Multimedia/bilder_dipol/web_bilder_orig/dip_1h___o.gif

Courtesy Ludwig Maximilians-Universität München

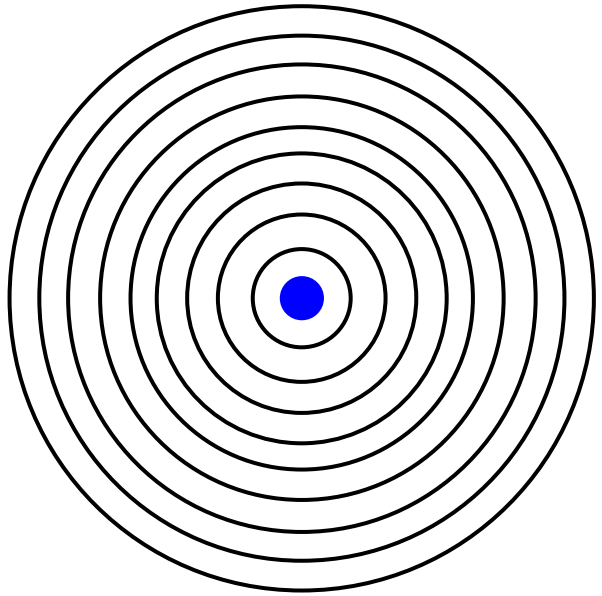
Hertzian Dipole



Half-Wave Dipole



What is this thing called “Far Field”?



Recall point source approximation…

In general terms, you are in the “far field” when you are at sufficient distance from source that it can be approximated as a point source

Energy propagates outward as expanding spherical wave

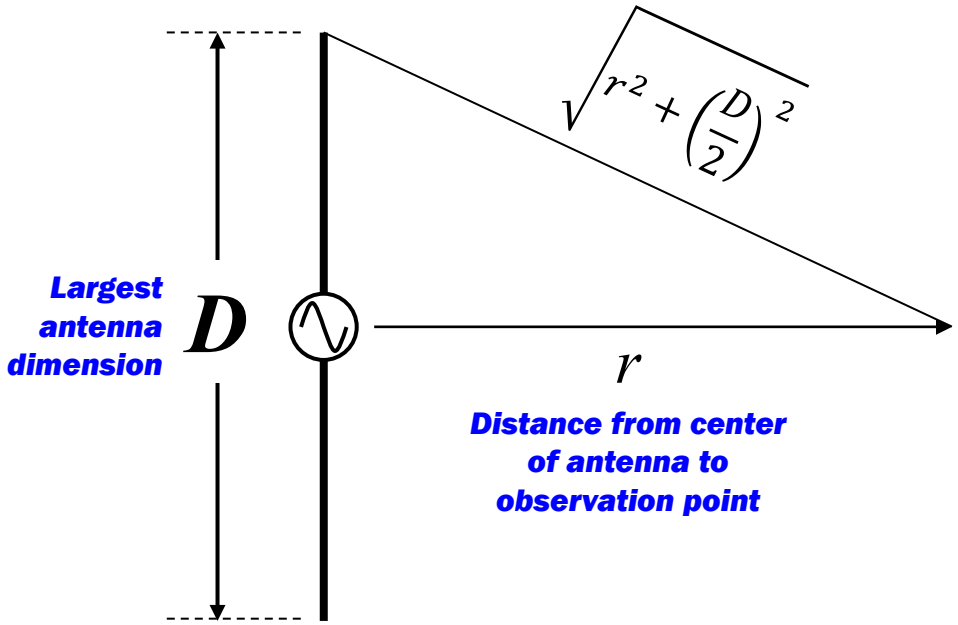
Plane Wave Approximation

Farther still from source, small portion of spherical wave front can be approximated as uniform plane wave



Uniform power density and field intensities (and phases) across surface area of interest

How uniform is uniform enough?



Rule of thumb:
Worst-case path difference between points on antenna surface to observation point should be less than $\lambda/16$ (minimize phase cancellations)

$$\sqrt{r^2+\left(\frac{D}{2}\right)^2}-r \le \frac{\lambda}{16} \rightarrow \sqrt{r^2+\left(\frac{D}{2}\right)^2} \le r+\frac{\lambda}{16}$$

Worst-case path difference

$$r^2+\left(\frac{D}{2}\right)^2 \le r^2+\frac{\lambda}{8}r+\left(\frac{\lambda}{16}\right)^2$$

$$\frac{\lambda}{8}r \ge \frac{D^2}{4}-\left(\frac{\lambda}{16}\right)^2$$

For D >> λ $\rightarrow \frac{D^2}{4} \gg \left(\frac{\lambda}{16}\right)^2$

$$\frac{\lambda}{8}r \ge \frac{D^2}{4}$$

$$r \ge \frac{2D^2}{\lambda}$$

General far field rule of thumb

For D >> λ

How uniform is uniform enough? (cont.)

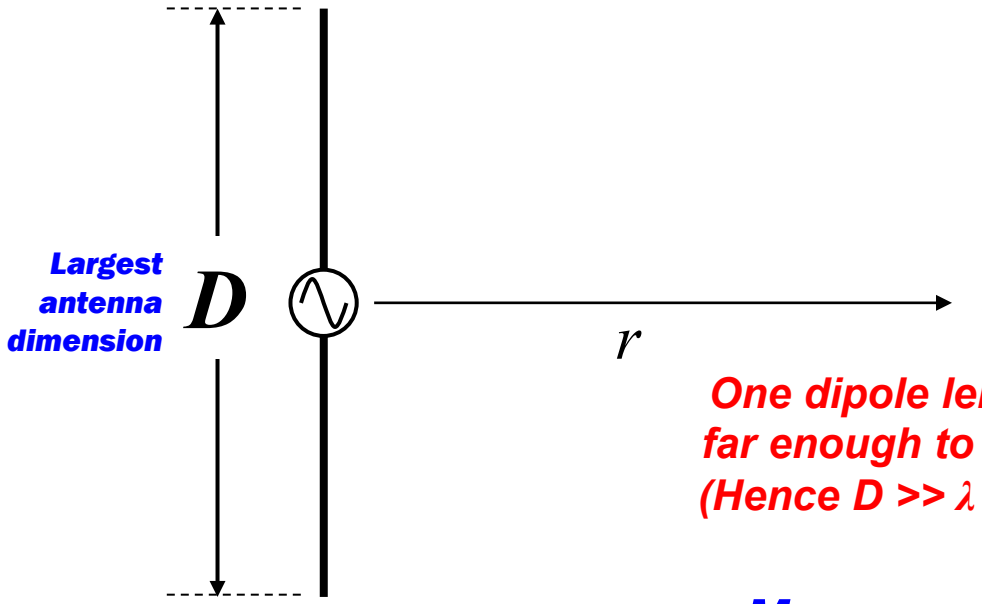
$$r \geq \frac{2D^2}{\lambda}$$ *For D >> λ*

For half-wave dipole:

$$D = \frac{\lambda}{2} \rightarrow \lambda = 2D$$ *(Not D >> λ)*

$$r \geq \frac{2D^2}{2D}$$

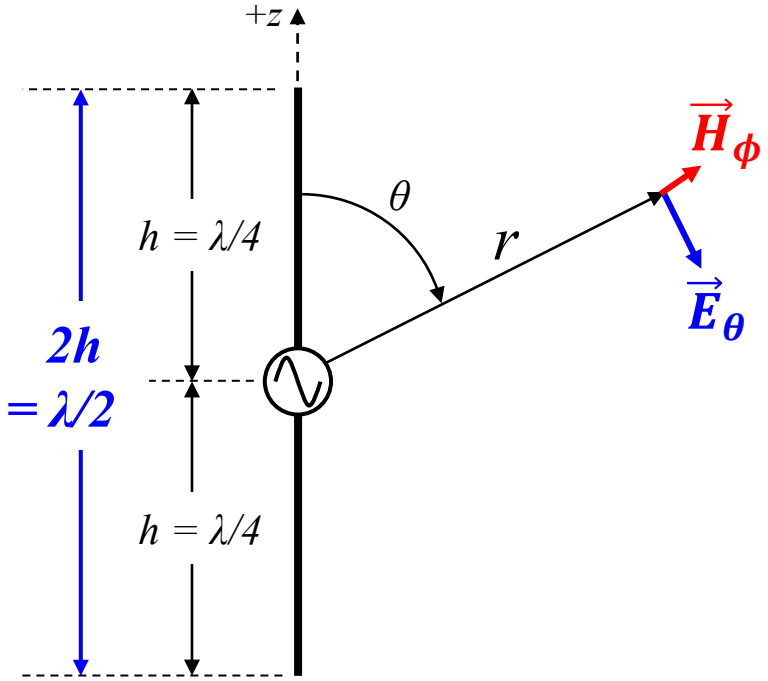
$$r \geq D$$



One dipole length is not far enough to be far field (Hence D >> λ constraint)

More meaningful guidance (per Paul p. 423):
Far-field "boundary" is the larger of 3λ or $2D^2/\lambda$
(6D for half-wave dipole)

Half-Wave Dipole – Impedance



$$E_\theta = j\frac{60I_m}{r}e^{-j\beta r}F(\theta) \qquad H_\phi = \frac{E_\theta}{\eta} = j\frac{I_m}{2\pi r}e^{-j\beta r}F(\theta)$$

Average power density

$$P_{av} = \frac{1}{2}E_\theta H_\phi^* = \frac{15I_m^2}{\pi r^2}F^2(\theta)$$

Total transmitted power (integrated over 4π steradians)

$$P_T = \int_0^{2\pi}\int_0^{\pi} P_{av} r^2 \sin\theta \, d\theta d\phi$$

$$= \frac{15I_m^2}{\pi}\int_0^{2\pi}\int_0^{\pi} F^2(\theta)\sin\theta \, d\theta d\phi$$

$$= \frac{15I_m^2}{\pi}(2\pi)\int_0^{\pi}\left[\frac{\cos(\beta h\cos\theta) - \cos\beta h}{\sin\theta}\right]^2 \sin\theta \, d\theta$$

$$P_T = 30I_m^2\int_0^{\pi}\underbrace{\frac{[\cos(\beta h\cos\theta) - \cos\beta h]^2}{\sin\theta}}_{\text{Evaluated numerically}} d\theta$$

For half-wave dipole, $2h = \lambda/2$, $\beta h = \pi/2$:

$$P_T = 30I_m^2(1.218)$$

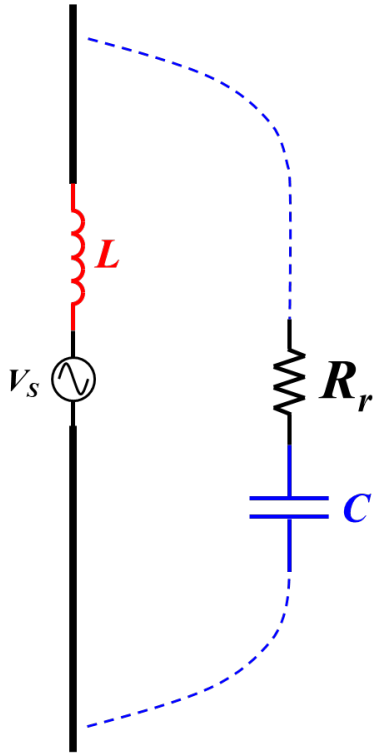
$$P_T = 36.54I_m^2$$

$$P_T = \frac{1}{2}I_m^2 R_r \rightarrow \underline{R_r = 73\ \Omega}$$

Radiation resistance (and input impedance) of half-wave dipole

Dipole Impedance – Resistive and Reactive

Dipole impedance includes reactive component



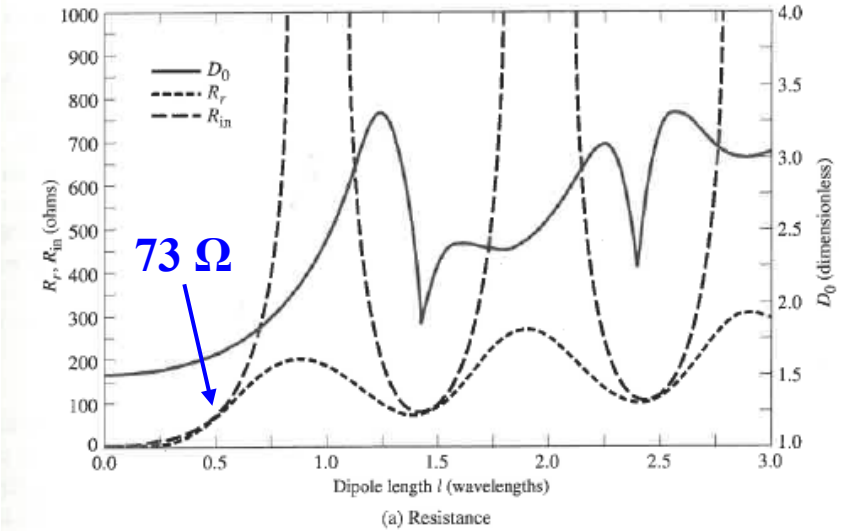
Half-wave dipole impedance:

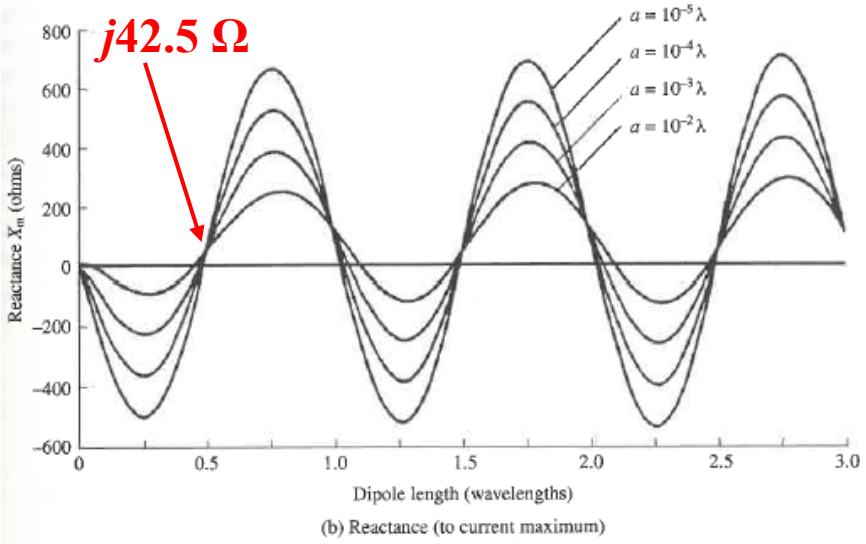
$$Z_{hwd} = 73\ \Omega + j42.5\ \Omega$$

For intentional antenna, it is desirable to maximize radiated power by reducing reactive component to 0

Reduce dipole length to:
~0.48λ for thin wires
< 0.48λ for thicker wires

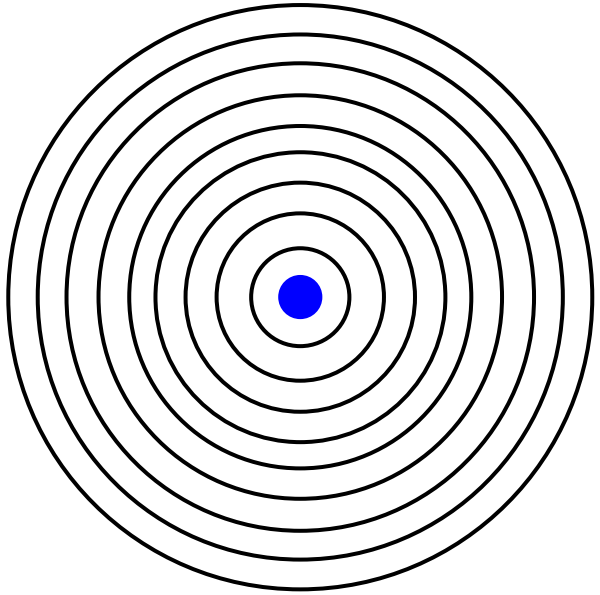
Balanis (5th edition), Figure 4-9, p. 171:





Directivity & Gain

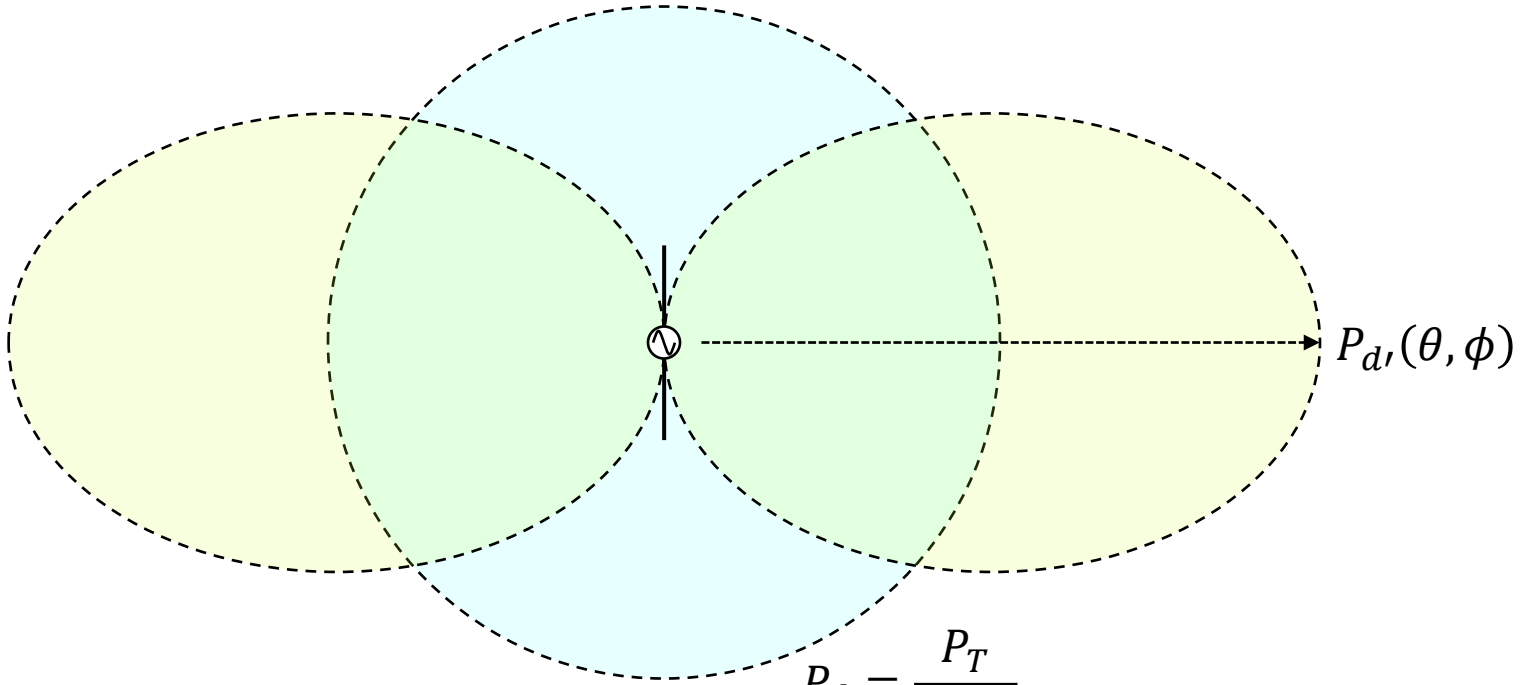
Directivity is referenced to power density of ideal isotropic point source



At distance r from point source, power density (P_d) equals total transmitted power (P_T) over surface area of sphere of radius r

$$P_d = \frac{P_T}{4\pi r^2}$$

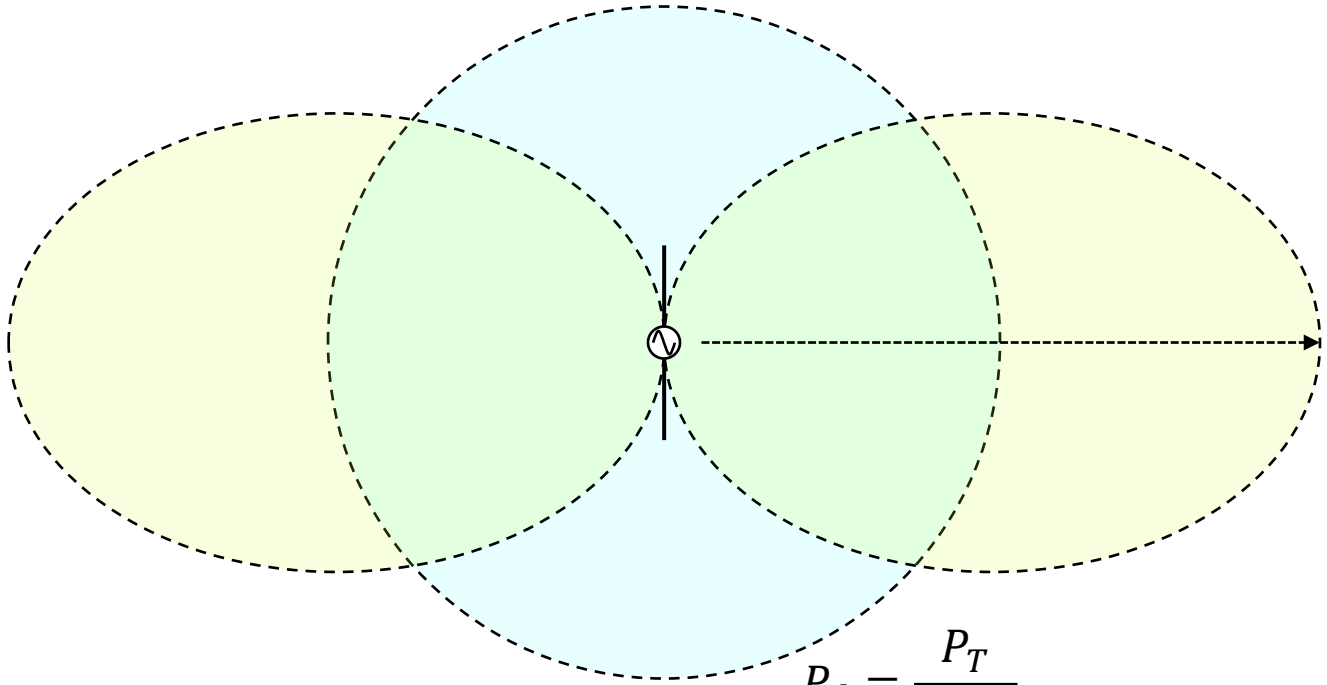
Directivity & Gain (cont.)



Antenna directivity D as function of (θ, ϕ) is defined as ratio of:

$$\frac{\textbf{Actual power density in given direction } (\theta, \phi)}{\textbf{Power density of ideal isotropic source transmitting same power } P_T}$$

Directivity & Gain (cont.)

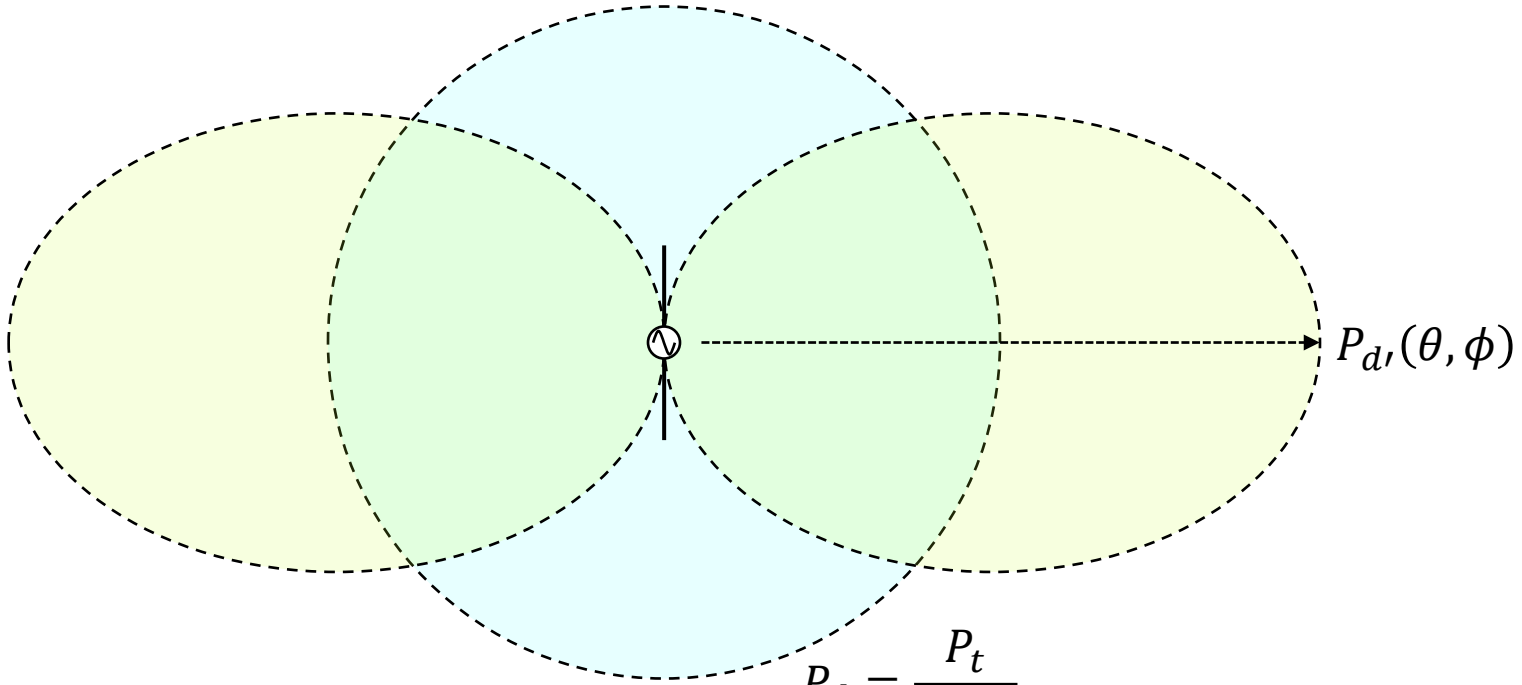


Generally given as single number at maximum value ("boresight")

Numeric: $D = \dfrac{P_{d'}(\theta, \phi)}{P_d}$

dB above isotropic: $D_{dBi} = 10 \log_{10} \left[\dfrac{P_{d'}(\theta, \phi)}{P_d} \right]$

Directivity & Gain (cont.)



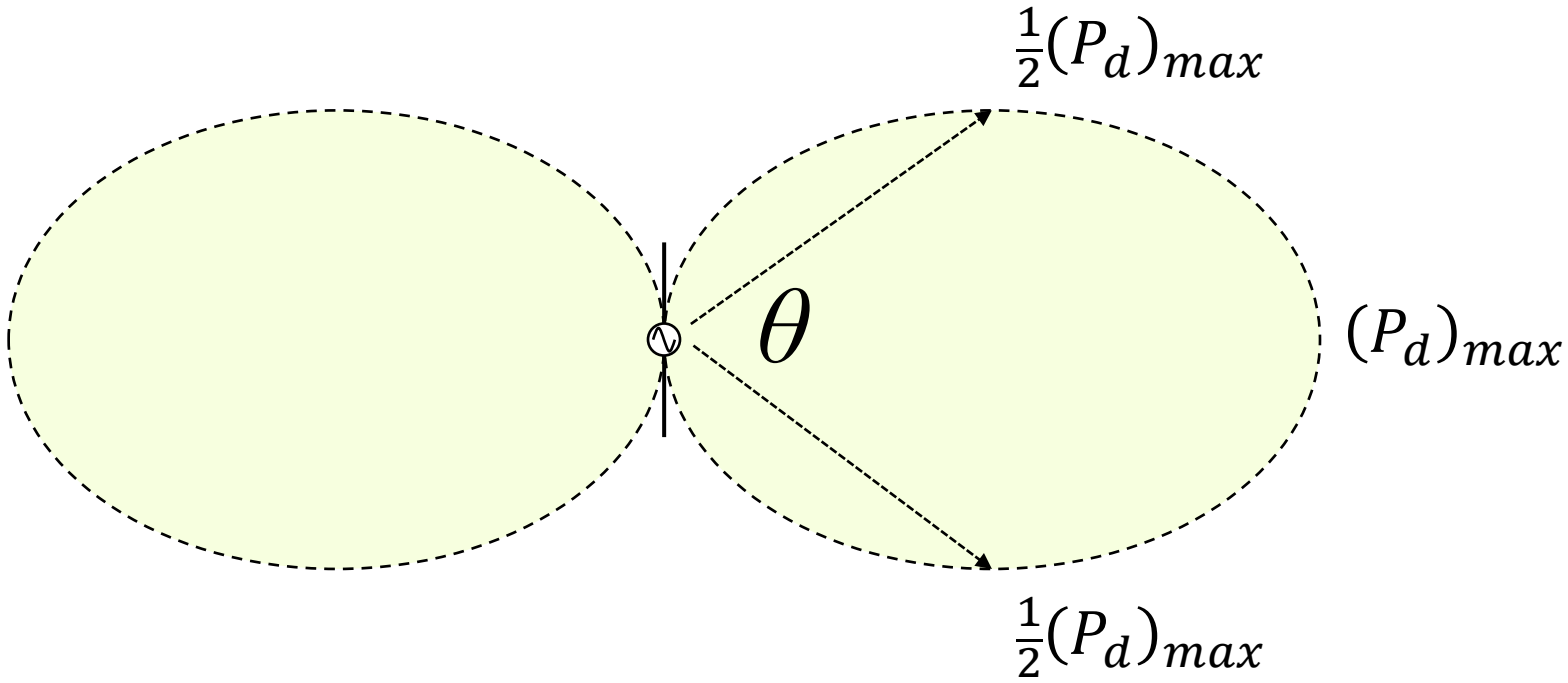
NOTES/CAUTIONS:

- ***Directivity D is sometimes (and lazily) used interchangeably with "gain" G***
- ***D and G are related but distinct*** $\longrightarrow$ $G = D \cdot (efficiency\ terms)$

Losses, impedance mismatch, etc.

Different symbols used in different texts, e.g., e, η, etc.

Half-Power (-3 dB) Beamwidth

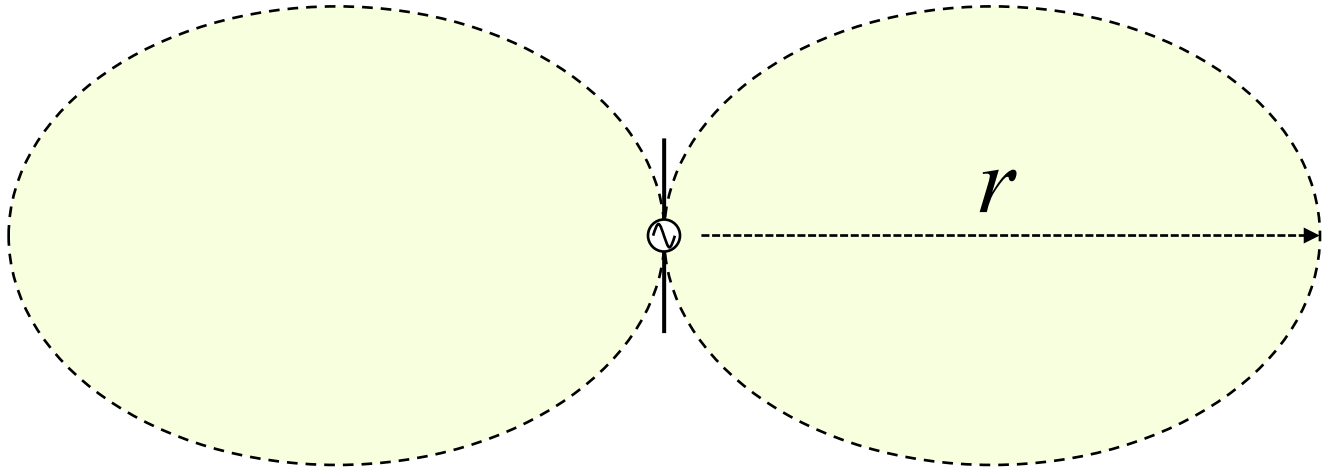


Half-power (-3 dB) beamwidth:

The angle between the two directions in which the power density is one-half (-3 dB) that of the maximum power density of the beam

Clearly inversely related to directivity

Radiation Intensity (U)



Radiation Intensity (U)

Radiated power per unit solid angle

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

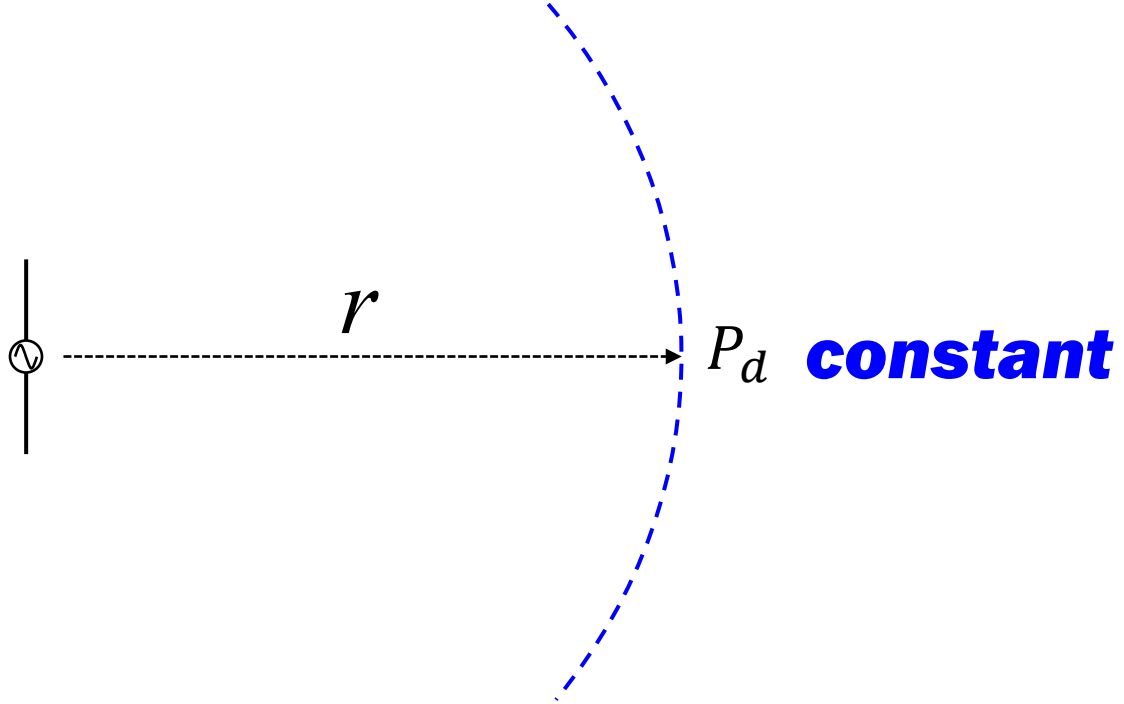
(eliminates r dependence)

$$= r^2 P_d(\theta,\phi)$$

Effective Isotropic Radiated Power (EIRP)

Effective Isotropic Radiated Power (EIRP)

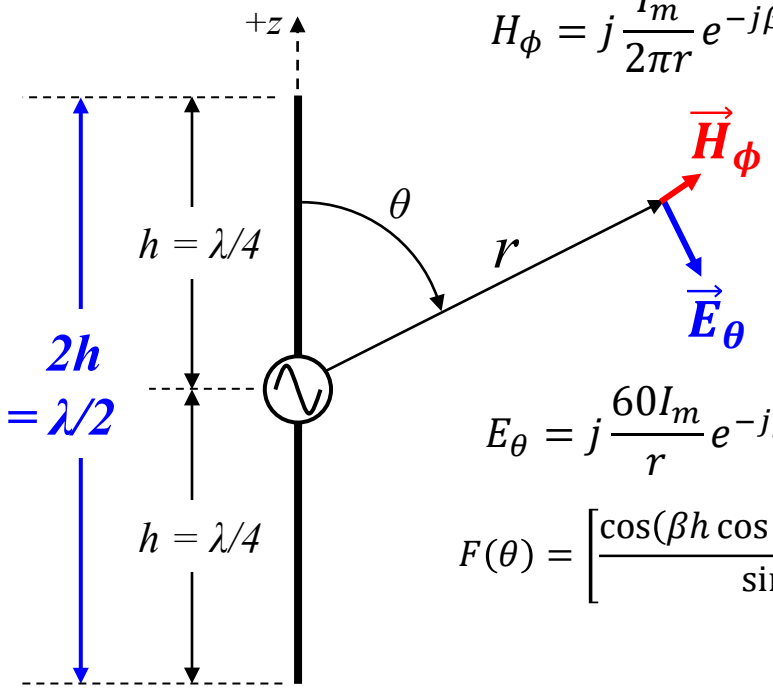
Power that would be transmitted from ideal isotropic source to produce constant power density over sphere of given radius



Artificial construct used by RF/comm engineers

Not as useful for EMC engineers, but you should at least know the term

Half-Wave Dipole - Directivity



$$H_\phi = j\frac{I_m}{2\pi r}e^{-j\beta r}F(\theta)$$

$$E_\theta = j\frac{60I_m}{r}e^{-j\beta r}F(\theta)$$

$$F(\theta) = \left[\frac{\cos(\beta h\cos\theta) - \cos\beta h}{\sin\theta}\right]$$

Dipole transmitted power:

$$P_T = 36.54I_m^2$$

Treated as ideal isotropic radiator:

$$P_d = \frac{P_T}{4\pi r^2} = \frac{36.54I_m^2}{4\pi r^2}$$

Average power density

$$P_{av} = \frac{1}{2}E_\theta H_\phi^* = \frac{15I_m^2}{\pi r^2}F^2(\theta)$$

$$= \frac{15I_m^2}{\pi r^2}\left[\frac{\cos(\beta h\cos\theta) - \cos\beta h}{\sin\theta}\right]^2$$

For half-wave dipole *$2h = \lambda/2$, $\beta h = \pi/2$:*

$$= \frac{15I_m^2}{\pi r^2}\left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right) - \cos\frac{\pi}{2}}{\sin\theta}\right]^2$$

Maximum at $\theta = \frac{\pi}{2}$:

$$= \frac{15I_m^2}{\pi r^2}\left[\frac{\cos\left(\frac{\pi}{2}\cos\frac{\pi}{2}\right) - \cos\frac{\pi}{2}}{\sin\frac{\pi}{2}}\right]^2 \quad \cos\frac{\pi}{2} = 0, \quad \sin\frac{\pi}{2} = 1$$

$$= \frac{15I_m^2}{\pi r^2}\left[\frac{\cos\left(\frac{\pi}{2}\cdot 0\right) - 0}{1}\right]^2 \quad \cos 0 = 1$$

$$P_{av} = \frac{15I_m^2}{\pi r^2}$$

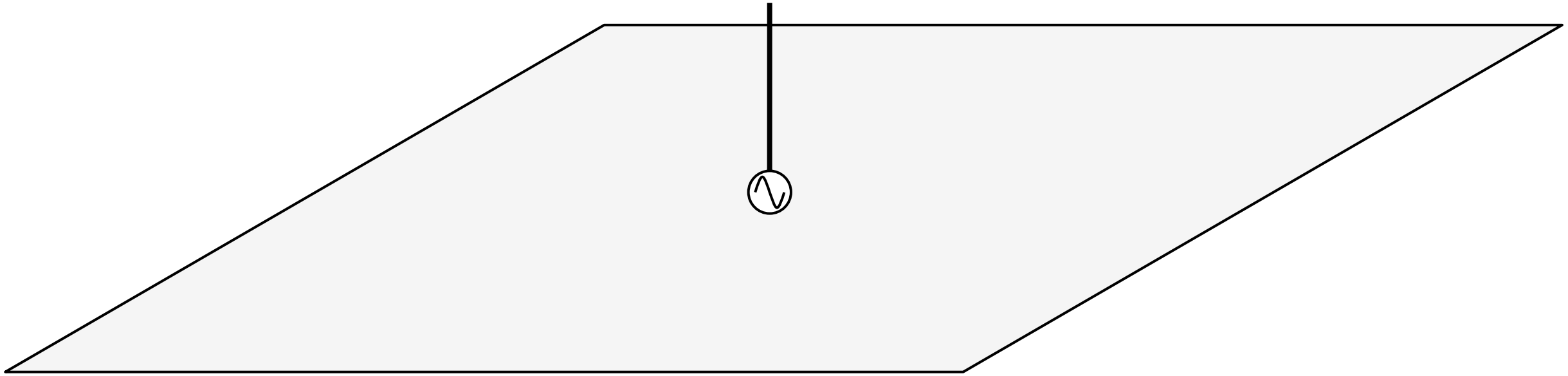
$$D_{hwd} = \frac{P_{av}}{P_d} = \frac{\left(\frac{15I_m^2}{\pi r^2}\right)}{\left(\frac{36.54I_m^2}{4\pi r^2}\right)} = \frac{60}{36.54} = 1.64$$

$$10\log_{10}(1.64) = 2.15\ dBi$$

Directivity of half-wave dipole ($\theta = \pi/2$)

Not terribly directional...

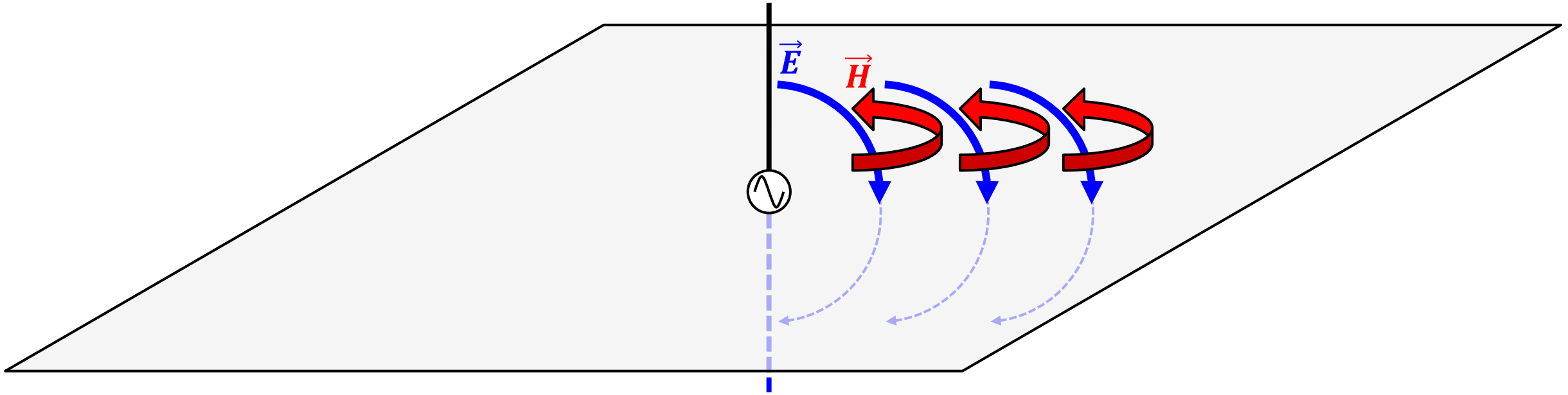
Quarter Wave Monopole



Return (-) arm of dipole replaced with (theoretically infinite) ground plane

Quarter Wave Monopole (cont.)

Field lines above ground plane look same as dipole due to image "arm"



Transmitted power is half that of half-wave dipole

$$R_r = 36.5\ \Omega$$

Why Do We Care About Dipole/Monopole Impedance?

MINIMUM IMPEDANCE

$$Z_{min} = R_r$$

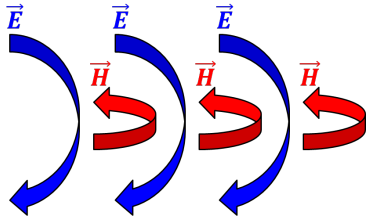
MAXIMUM CURRENT FOR GIVEN DRIVE POTENTIAL

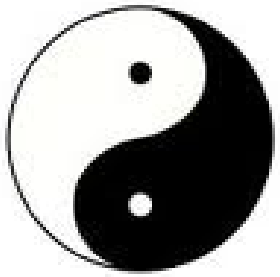
$$I = \frac{V}{R_r}$$

MAXIMUM TRANSMITTED POWER

$$P_{av} = \frac{1}{2} I^2 R_r$$

HIGHER RADIATED EMISSIONS



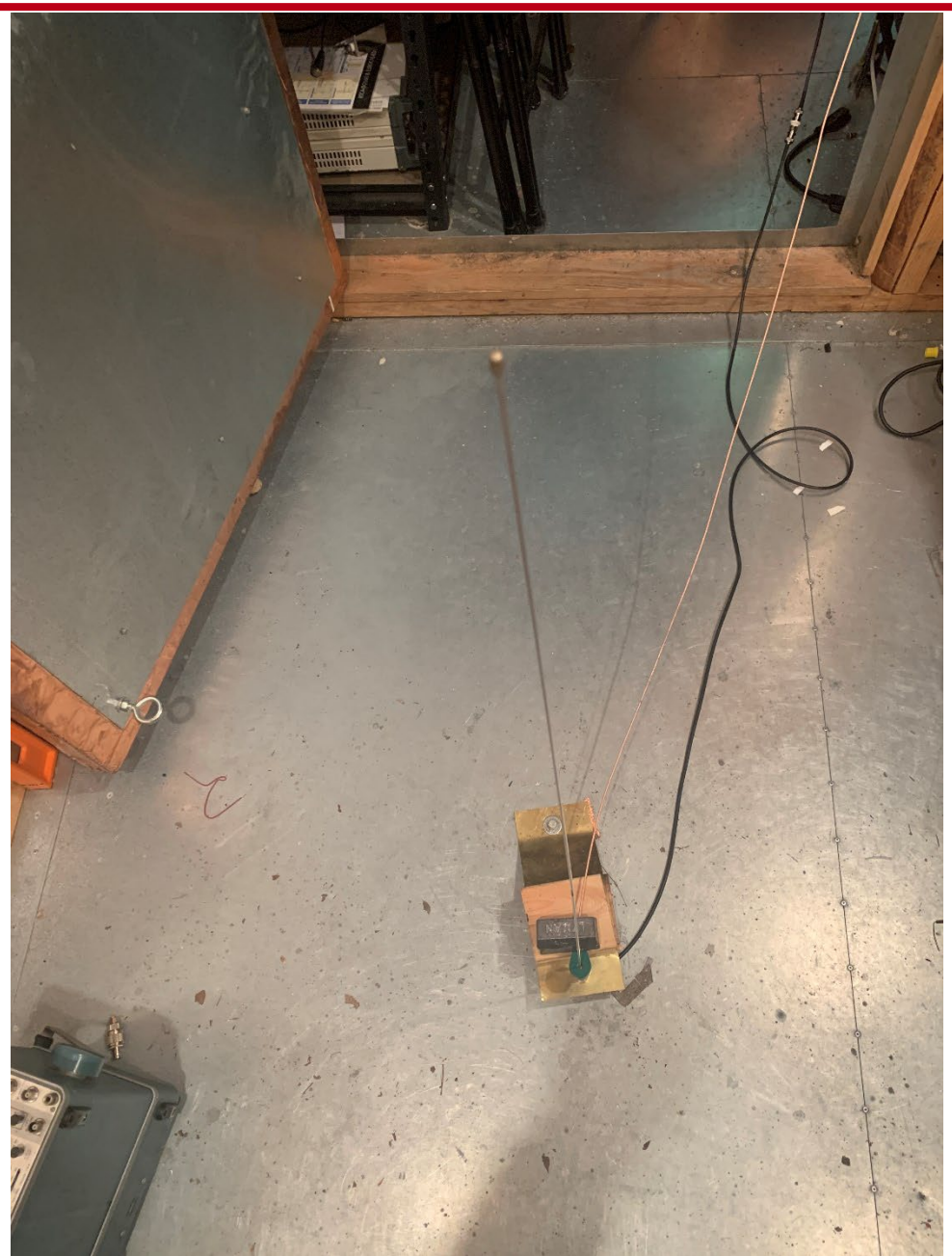


Example Monopole Measurement (Courtesy of Ken Javor)

41” rod (1.04 m), removed from active base, driven by 50 Ω source through 50 Ω coax
(black coax from HP 4195A source output set to 15 dBm)

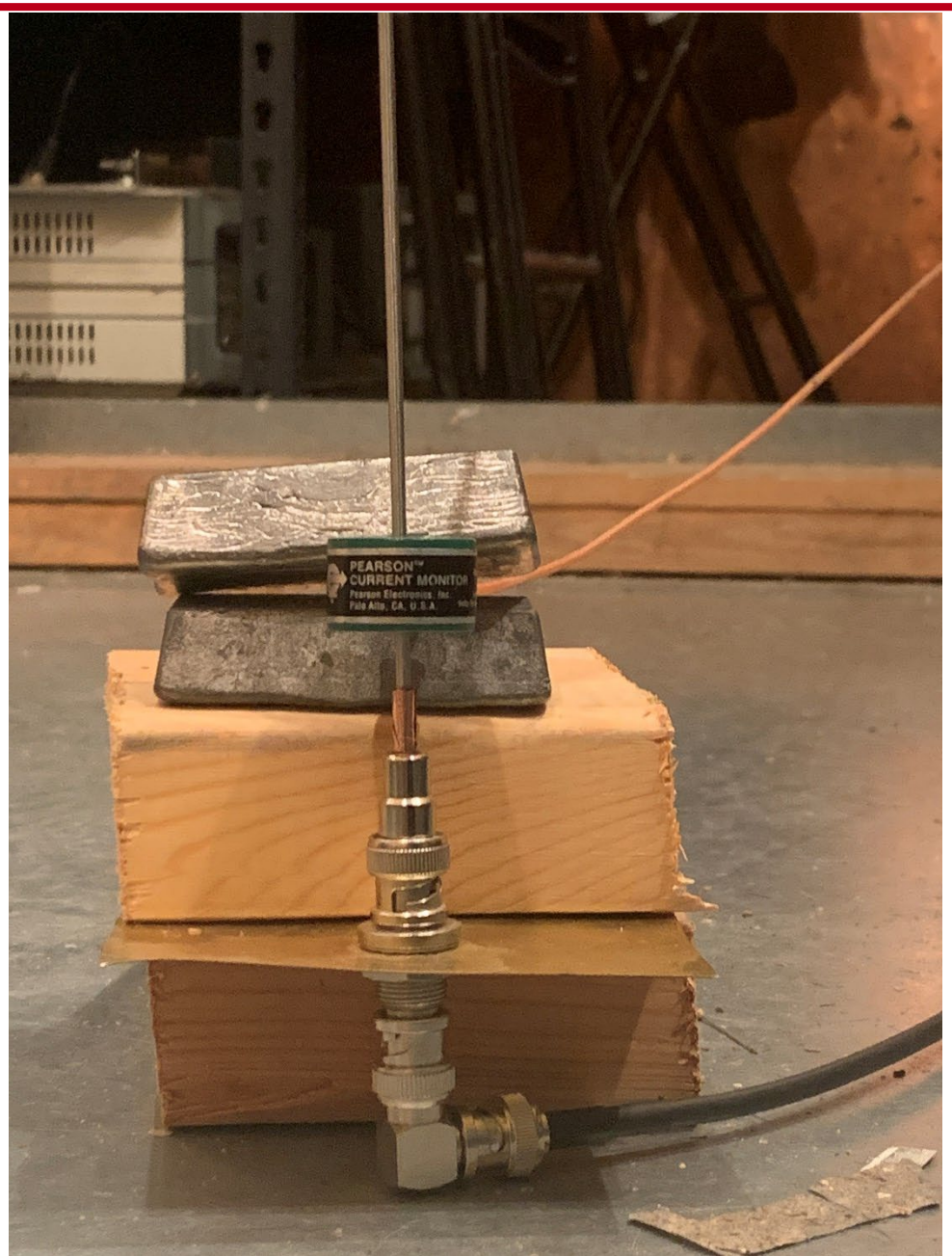
Working against test chamber floor (brass bond strap to floor)

Pearson Model 2877 current monitor around 41” rod base
1 V/A open circuit 300 Hz to 200 MHz
-6 dBΩ transfer impedance connected to HP 4195A analyzer test input (light colored coax)



Driving Point Close-up

Lead weights are to hold Model 2877 in place so that rod goes through window center without touching sides



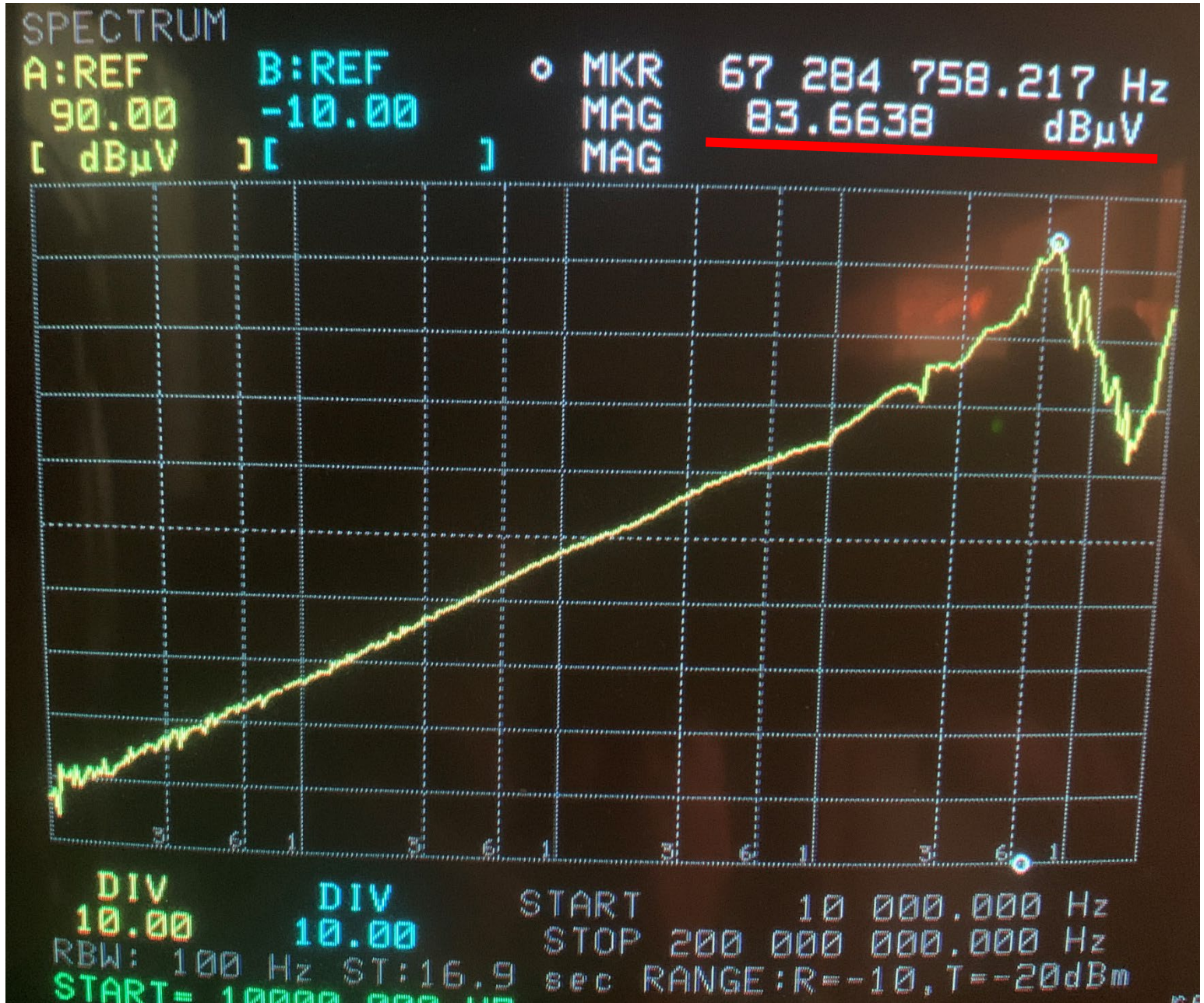
Measured Data - Magnitude

HP 4195A network analyzer set up as a spectrum analyzer with tracking generator
Source drives antenna base against ground; test input is connected to Pearson current monitor output

15 dBm drive into 36 Ω yields 29 mA = 89 dBμA (ignoring reflections at load)

89 dBμA + (-6 dBΩ Z_T) = 83 dBuV (expected value)

Good agreement for magnitude…

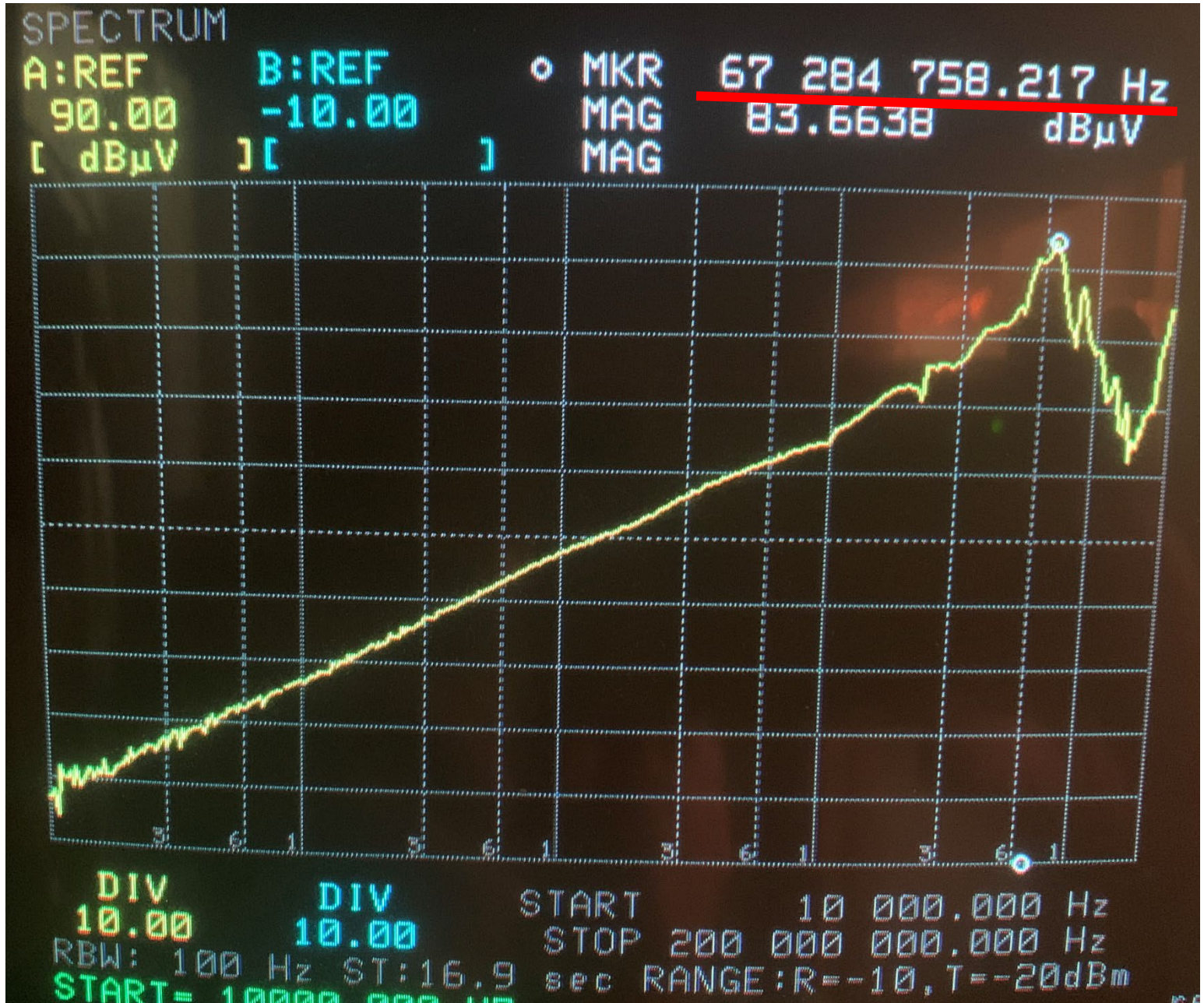


Measured Data - Frequency

Expected frequency of resonance is when rod (monopole) is a quarter-wavelength (λ/4)

41” = 1.04 meter
λ/4 at 72 MHz

Measured resonance ~7% low…



Stub Capacity Assessment, Part the First

LCR-45 measuring female-to-female BNC feedthrough capacity at 2.6 pF



Stub Capacity Assessment, Part the Second

LCR-45 measuring female-to-female BNC feedthrough capacity plus that of BNC male to RCA female adapter at 7 pF



Stub Capacity Assessment, Part the Third

LCR-45 measuring capacity of both adapters plus the rod at 18.5 pF

This makes the rod itself:

C_{rod} = 18.5 pF – 7 pF = 11.5 pF

→ *in the ballpark*



Stub Capacity Assessment, Part the Last

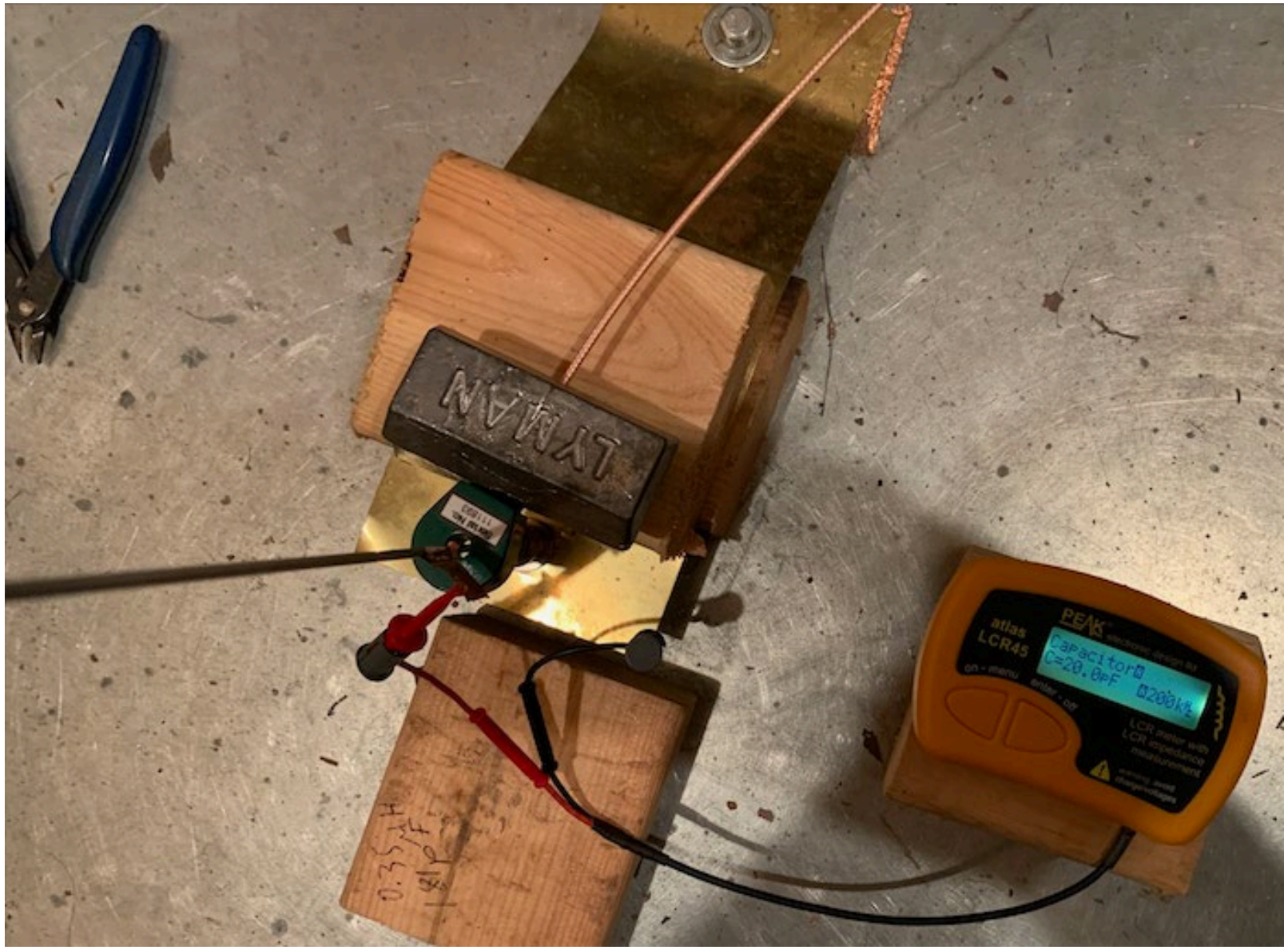
LCR-45 measuring capacity of both adapters plus the rod and the effect of the Pearson Model 2877 current monitor acting as a coaxial capacitor with a crummy inductive ground at 20 pF

The difference between the rod capacity at around 11.5 pF and the added capacity of:

20 pF – 18.5 pF = 1.5 pF

means the current monitor added over 10% extra capacity

This is why the current resonance was lower than calculated for just a 41” rod.



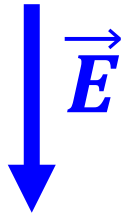
Reciprocity

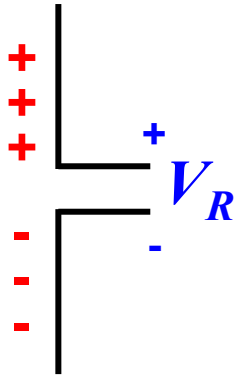
- **Up to this point, discussions have addressed transmitting antennas**
- **Reciprocity states that the following are identical whether antenna is transmitting or receiving:**
  - Radiation pattern
  - Directivity (gain)
  - Beamwidth
  - Impedance
- **Proof is beyond scope of this presentation; see references for gory details**
  - Balanis, Schelkunoff/Friis, and Kraus in particular

Receiving Antennas

Incident electric field

$E\ (V/m)$





...induces potential difference between pair of separated conductors (intentional or unintentional)

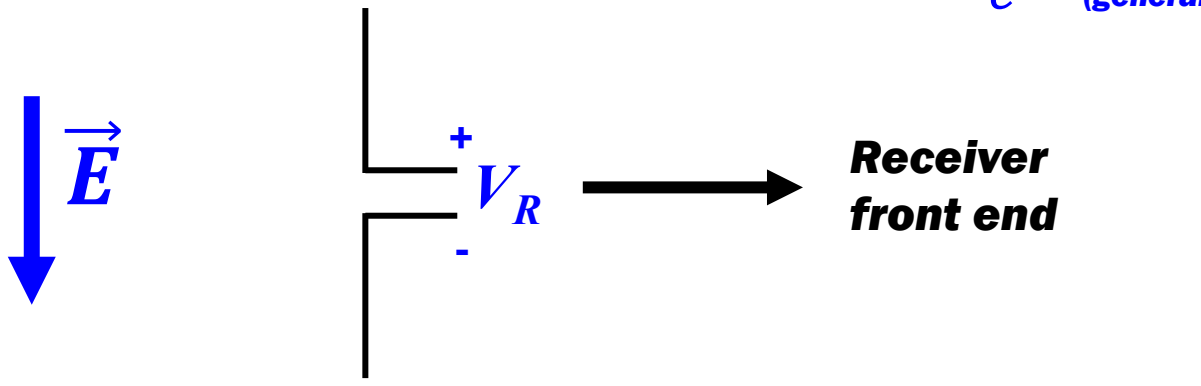
Effective Height & Antenna Factor

Antenna factor $AF = \frac{1}{h_e}$

Used by measurement equipment to convert measured potential back to incident electric field (generally in dB/m)

For uniform plane wave:

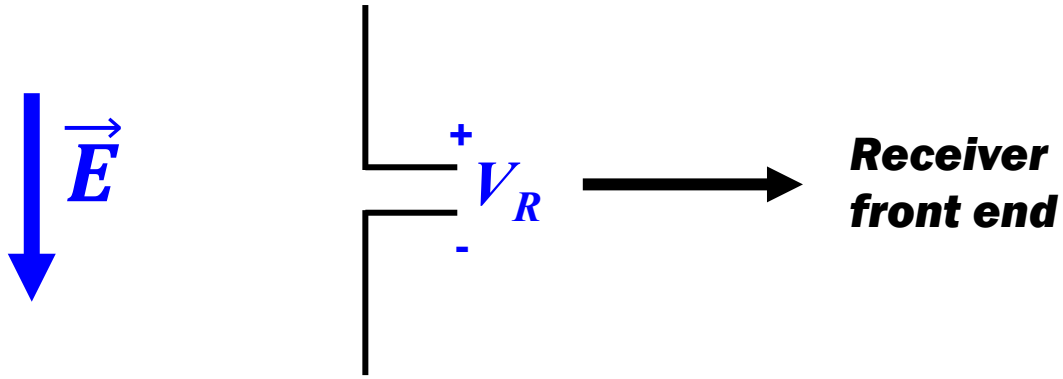
$$P_d = \frac{E^2}{120\pi}$$



Incident electric field	***Effective height***	***Potential delivered to receiver***
E ***(V/m)***	h_e ***(m)***	V_R ***(volts)***

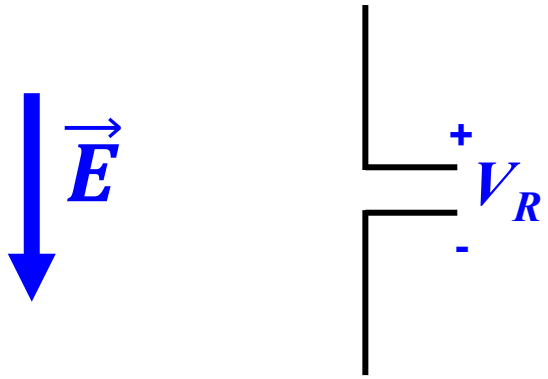
$$E(V/m) \times h_e(m) = V_R\ (volts)$$

Effective Height of Half-Wave Dipole



For half-wave dipole: $h_e(m) = \frac{\lambda}{2\pi}$ ***Into matched load (intentional receiver)***

Effective Height of Half-Wave Dipole



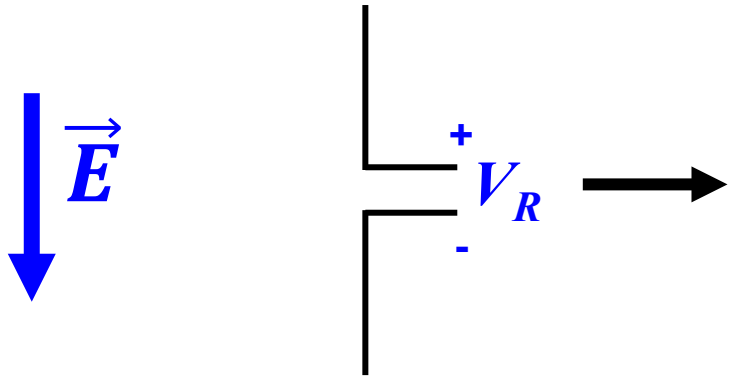
Useful for calculating worst-case coupled (common mode) potential from incident electric field

For half-wave dipole:

$$h_e(m) = \frac{\lambda}{\pi}$$

Into open circuit

Worst-Case Coupled Current



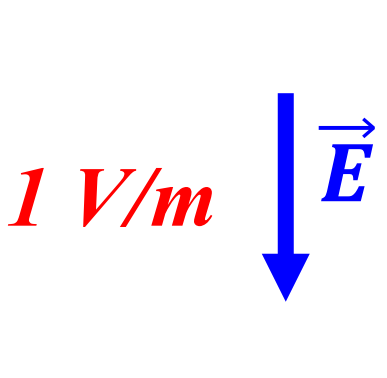
$$h_e(m) = \frac{\lambda}{\pi}$$

Worst-case coupled (common mode) current may be calculated using impedance of half-wave dipole or quarter-wave monopole

$$I_{CM} = \frac{V_R}{73\ \Omega}$$ ***Half-wave dipole***

$$I_{CM} = \frac{V_R}{36.5\ \Omega}$$ ***Quarter-wave monopole***

Worst-Case Coupled Current Example



$$V_R\ (volts) = E(V/m) \times h_e(m)$$

$$(V_R)_{MAX} = (1\ V/m)(0.16\ m) = 160\ mV$$

$$h_e(m) = \frac{\lambda}{\pi}$$

$$I_{CM} = \frac{V_R}{73\ \Omega}$$

Half-wave dipole

$$(I_{CM})_{MAX} = \frac{0.16\ V}{73\ \Omega} = 2\ mA$$

Coupling decreases with frequency

600 MHz:

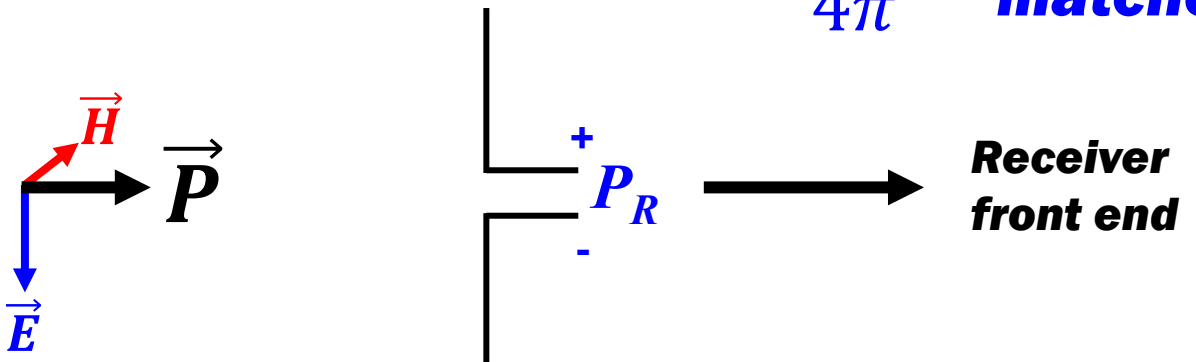
$\lambda = 50\ cm$

$h_e = 16\ cm$

Effective Aperture (Area)

$$A_e = \frac{G\lambda^2}{4\pi}$$

Maximum into matched load



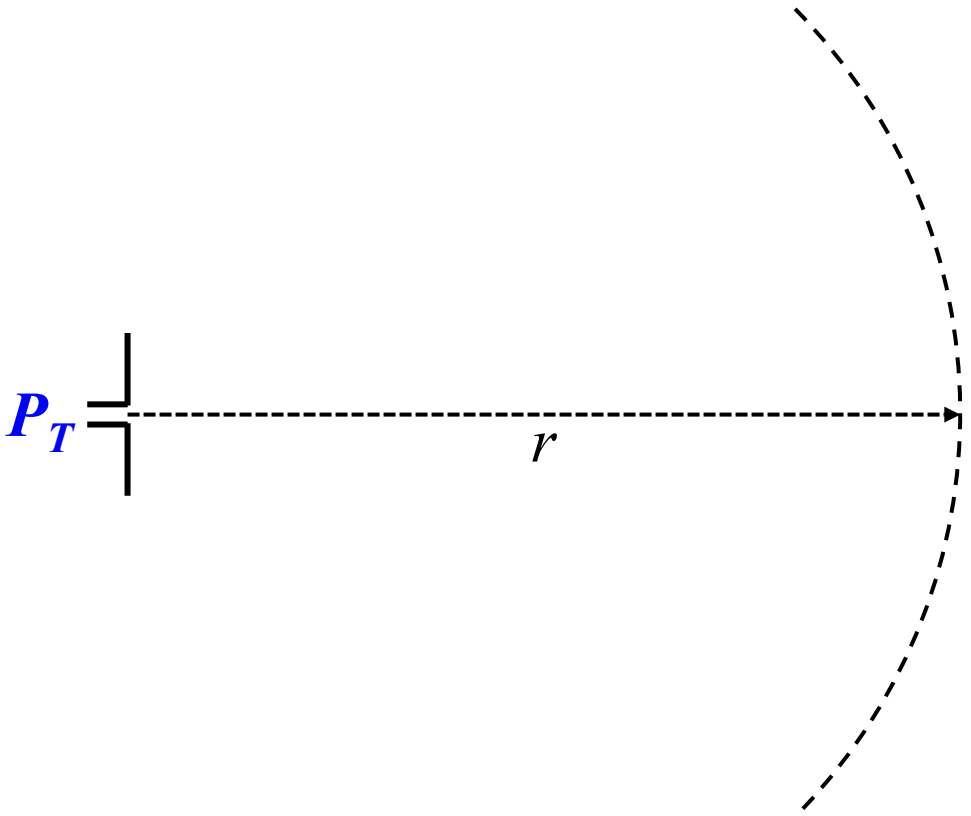
Incident power density $P_d\,(W/m^2)$

Effective aperture $A_e\,(m^2)$

Power delivered to receiver $P_R\,(W)$

$$P_d(W/m^2) \times A_e(m^2) = P_R\,(W)$$

Intentional Transmit/Receive Systems

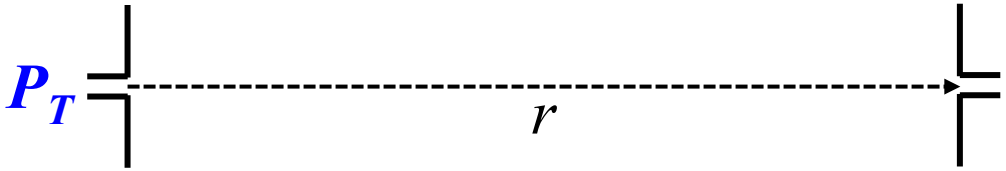


Power density at distance r from transmit antenna:

$$P_d = \frac{P_T}{4\pi r^2} G_T$$

Transmit antenna gain

Intentional Transmit/Receive Systems (cont.)



$$P_d = \frac{P_T}{4\pi r^2} G_T$$

$$P_R = P_d A_e$$

$$A_e = \frac{G_R \lambda^2}{4\pi}$$

G_R = ***receive antenna gain***

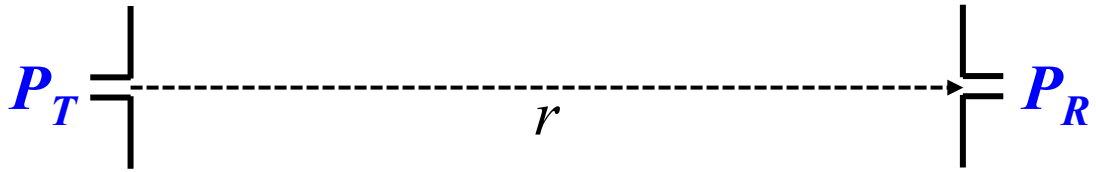
Intentional Transmit/Receive Systems (cont.)

Friis Transmission equation:

$$\frac{P_R}{P_T} = G_T G_R \frac{\lambda^2}{(4\pi r)^2}$$

Friis Transmission equation (dB):

$$\left(\frac{P_R}{P_T}\right)_{dB} = 10\log_{10}\left[G_T G_R \frac{\lambda^2}{(4\pi r)^2}\right]$$



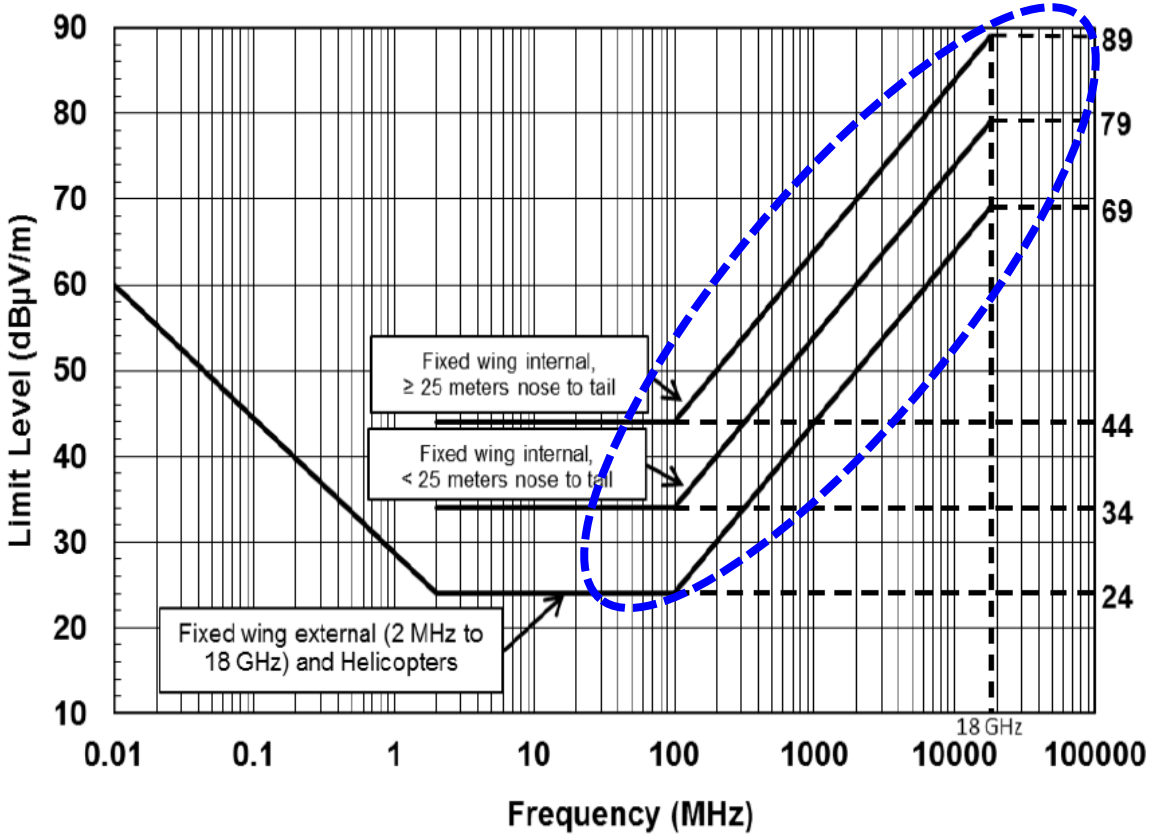
For intentional transmit/receive systems ONLY (large r)

Unintentional coupling between conductors in close proximity (small r) best addressed using capacitive or inductive crosstalk analysis techniques discussed in electric field and magnetic field sessions

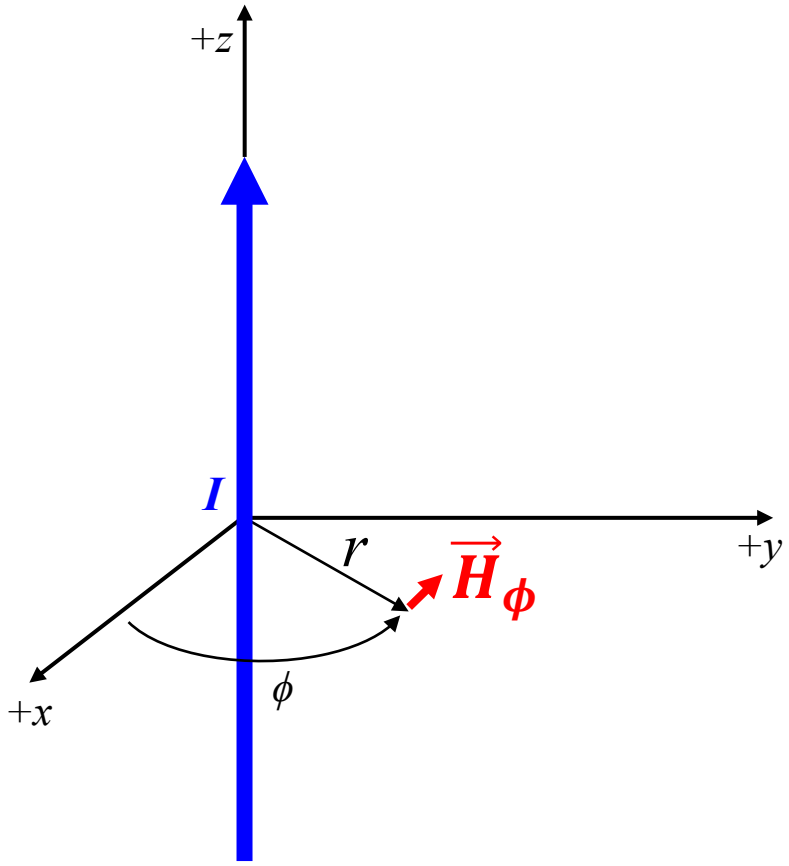
MIL-STD-461G Default RE102 Limits

A.5.18 (5.18) RE102, radiated emissions, electric field

The 20 dB/decade increase in the limit above 100 MHz is due to the aperture size of a tuned antenna ($G\lambda^2/4\pi$) decreasing with frequency. The coupled power level from an isotropic tuned antenna will remain constant. The curve breaks at 100 MHz because of difficulty with maintaining a tuned antenna due to increasing physical size and the lower likelihood of coupling to the antenna with longer wavelengths.



Recall: Magnetic Field Near Long Current-Carrying Wire



From Ampère's Law:

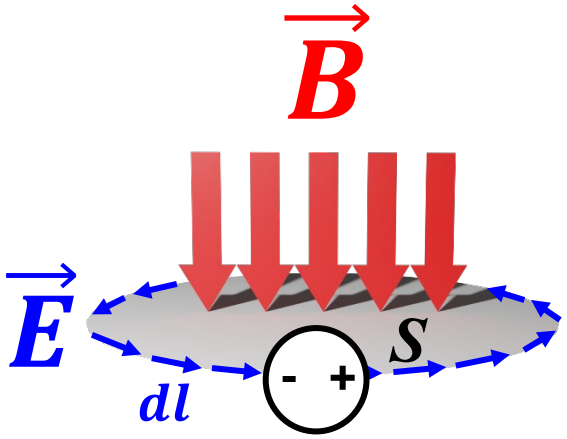
$$\oint \vec{H} \cdot d\vec{l} = I$$

$$H_\phi = \frac{I}{2\pi r} \qquad \left(B_\phi = \frac{\mu I}{2\pi r} \right)$$

VERY accurate in near field

Current probes employ this very principle

Recall: Faraday's Law of Electromagnetic Induction



Faraday's Law of Electromagnetic Induction

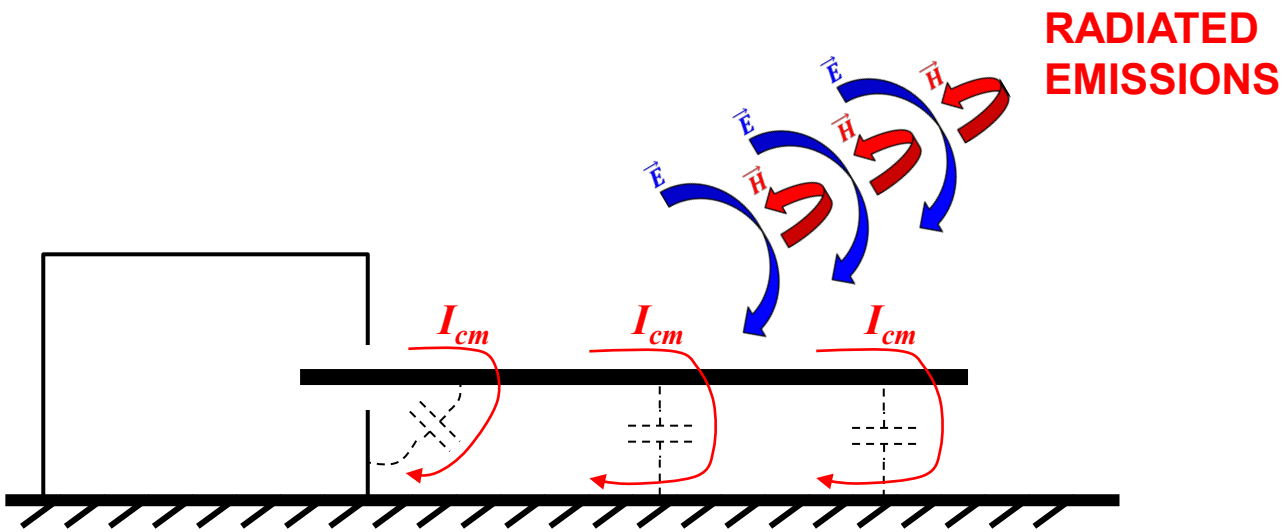
$$\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \iint \vec{B} \cdot d\vec{s}$$

$$V_{emf} = -\frac{d\Phi}{dt}$$

Ampère's Law and Faraday's Law are more effective tools to address crosstalk between circuits in close proximity than any attempts at near-field analysis

Recall: Unintentional Radiators, a.k.a. Antennas

- If any part of your equipment radiates or is susceptible to radio frequency (RF) energy, you have created an antenna, whether or not you call it one
- These can be any two conductors, e.g. cable and chassis, cable and ground plane (structure), PC board trace and chassis, poorly bonded connector and chassis (seams on chassis)
- Radiated fields directly related to <u>CURRENT</u>
- **Control current → control radiated fields**

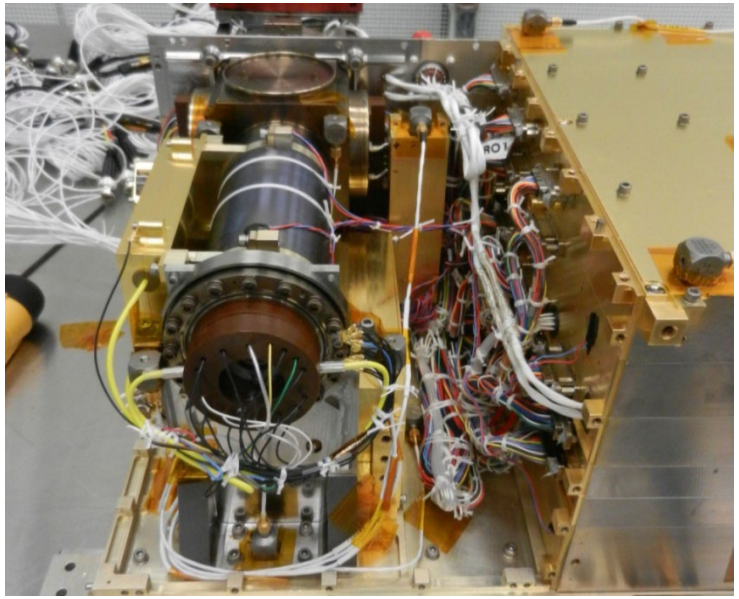


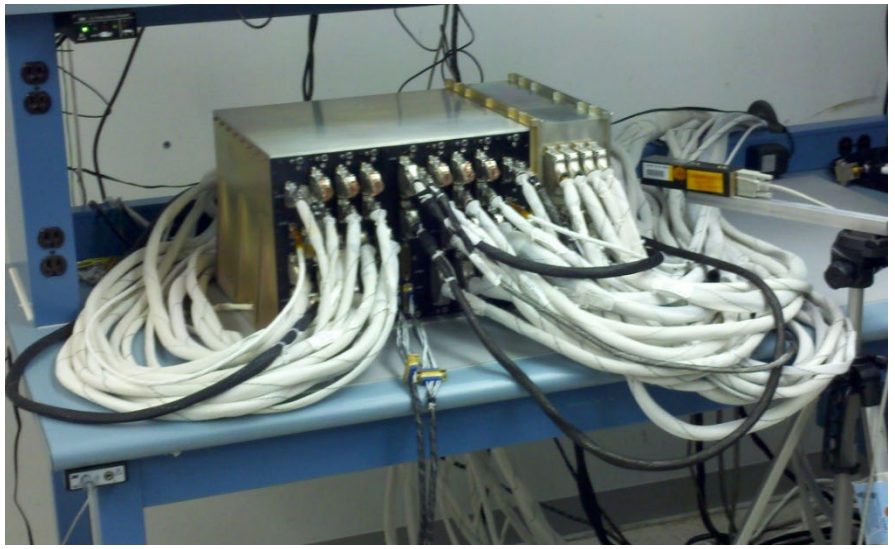


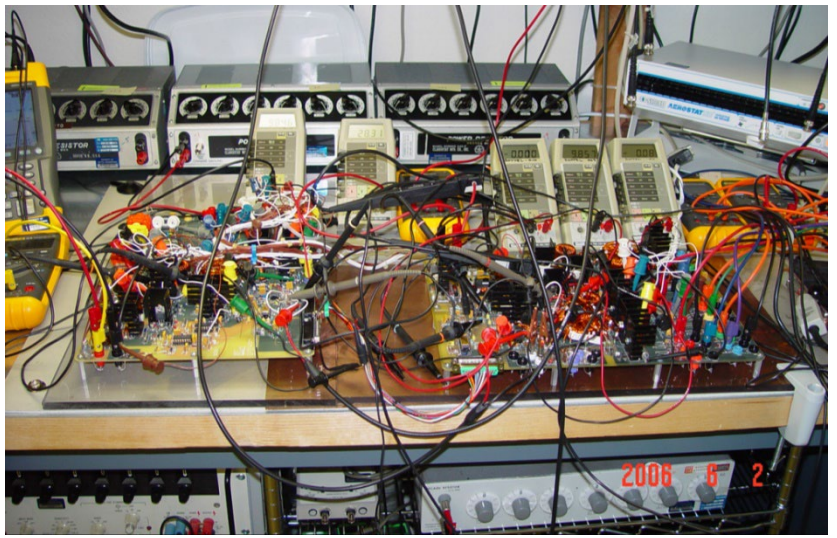
Summary

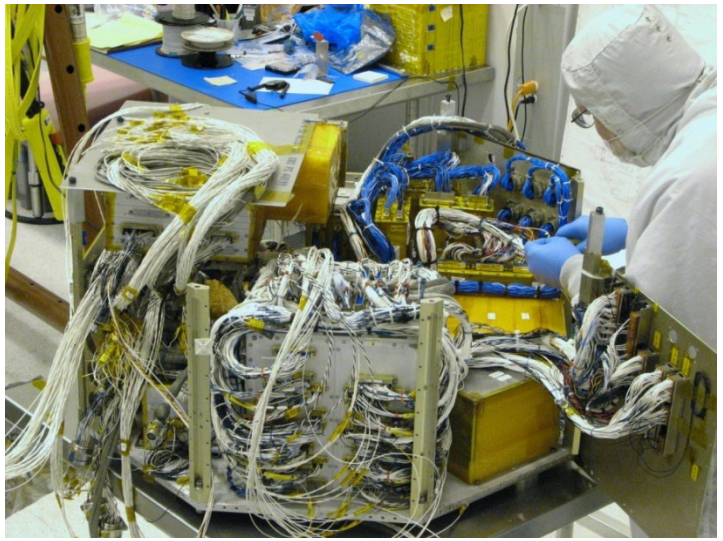
- An antenna is made by establishing an RF potential between any two conductors
- “Crux of the biscuit” for understanding the relationship between conducted and radiated EMI issues
- Control current → control radiated emissions and susceptibility
- Most basic type of antenna is the dipole, which is a good model for understanding how circuit elements (especially cables) can act as unintentional antennas
- Antenna model is most effective for addressing radiated energy away from source (far field)
- Near field issues (“reactive” region) best addressed using crosstalk models discussed in earlier sessions (e.g. Ampère’s Law and Faraday’s Law for inductive crosstalk)
- Much has been written about antennas by many great minds for many decades
- Recommendations for further reading provided on “References” slide

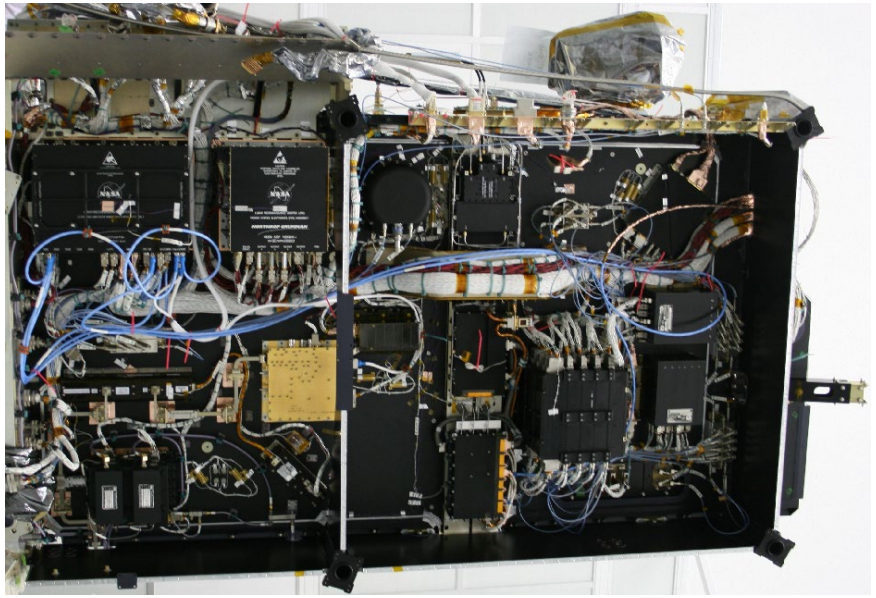
Can You Find the Dipoles in These Pictures?

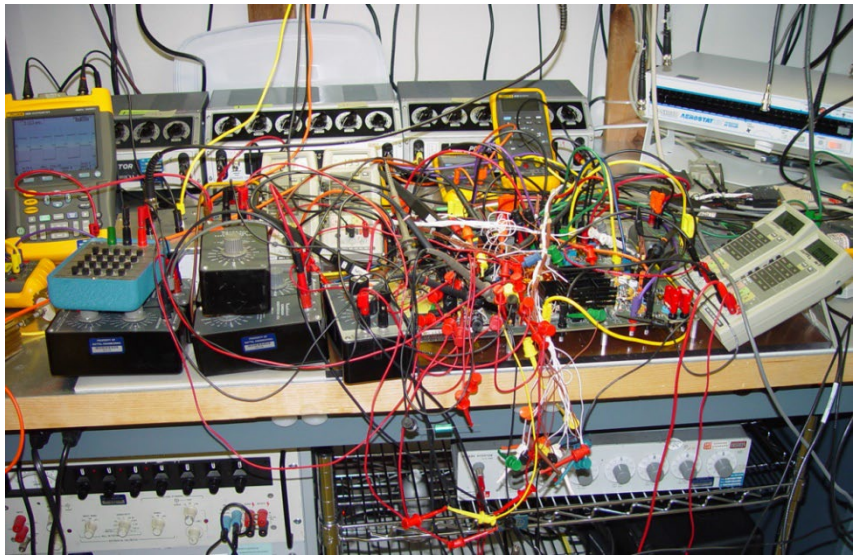












References

- Balanis, Constantine: Antenna Theory - Analysis and Design
- Cheng, David: Field and Wave Electromagnetics
- Kraus: Antennas
- Ott, Henry: Electromagnetic Compatibility Engineering (Appendix D: “Dipoles for Dummies”)
- Paul, Clayton: Introduction to Electromagnetic Compatibility
- Schelkunoff, Sergei, and Friis, Harald: Antennas, Theory and Practice

