Introduction to antennas

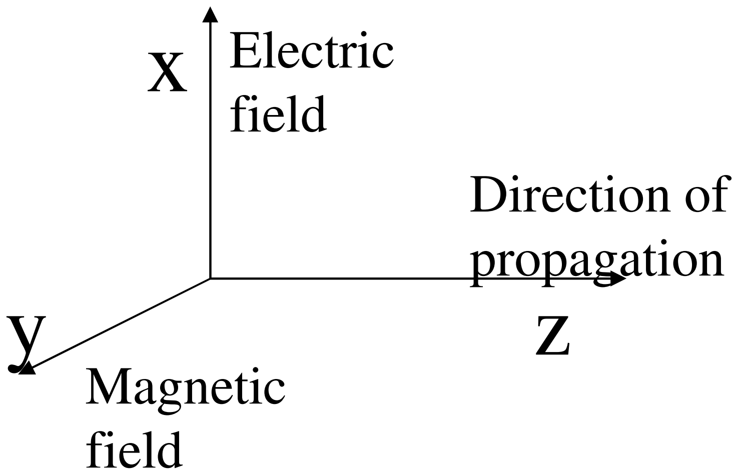
Outline

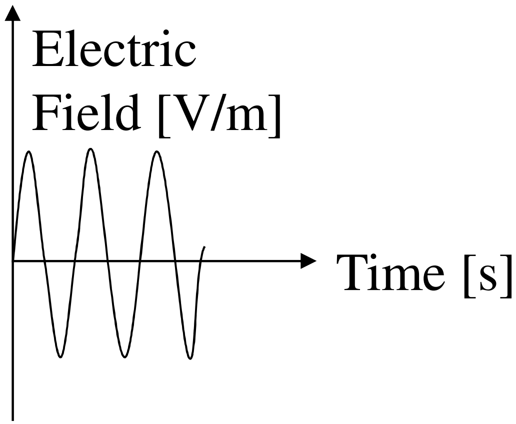
- What is an antenna?
- Review of EM wave
- Fundamental Parameters of antennas
- Types of antennas

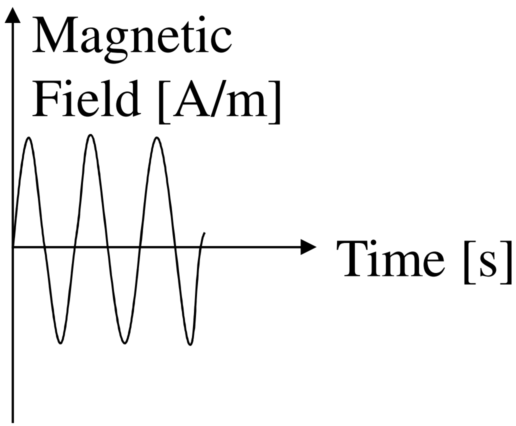
What is an antenna?

- Region of transition between guided and free space propagation
- Concentrates incoming wave onto a sensor (receiving case)
- Launches waves from a guiding structure into space or air (transmitting case)
- Often part of a signal transmitting system over some distance
- Not limited to electromagnetic waves (e.g. acoustic waves)

Free space electromagnetic wave







- Disturbance of EM field
- Velocity of light (~300 000 000 m/s)
- E and H fields are orthogonal
- E and H fields are in phase
- Impedance, Z_0: 377 ohms

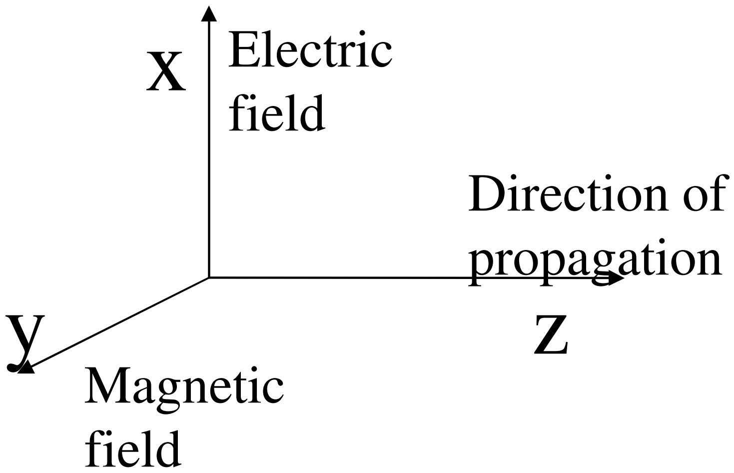
EM wave in free space

$$\frac{\partial^2 E_x}{\partial t^2} = \frac{1}{\mu_0 \varepsilon_0} \frac{\partial^2 E_x}{\partial z^2}$$

$$\frac{\partial^2 H_y}{\partial t^2} = \frac{1}{\mu_0 \varepsilon_0} \frac{\partial^2 H_y}{\partial z^2}$$

$$E_x = E_0 e^{j(\omega t \pm \beta z)}$$

$$H_y = H_0 e^{j(\omega t \pm \beta z)}$$



frequency $f = \frac{\omega}{2\pi}$

wavelength $\lambda = \frac{1}{\sqrt{\mu_0 \varepsilon_0} f}$

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

$$Z_0 = \frac{E_0}{H_0} \qquad Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

Wave in lossy medium

$$E_x = E_0 e^{-\gamma z} e^{j\omega t} = E_0 \cdot e^{-\alpha z} \cdot e^{-j\beta z} \cdot e^{j\omega t}$$

Attenuation increases with z

Phase varies with z

Periodic time variation

$\gamma = \alpha + j\beta$ Propagation constant

α Attenuation constant

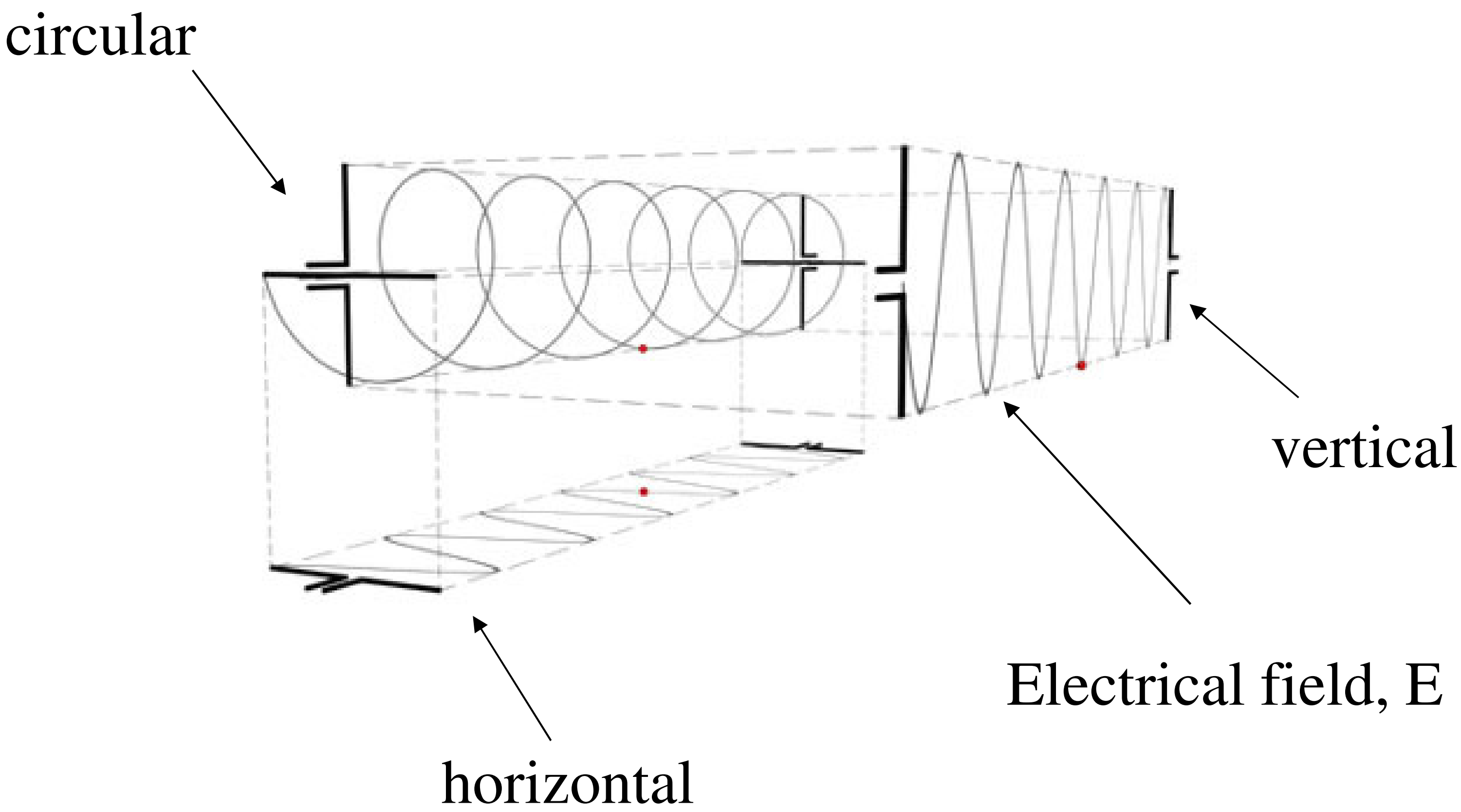
β Phase constant

Power flow

Poynting vector $\vec{S} = \vec{E} \times \vec{H}$

Average power density $S_{av} = \frac{1}{2}\left|E_x\right|^2 \frac{1}{Z_0} = \frac{1}{2}\left|H_y\right|^2 Z_0$

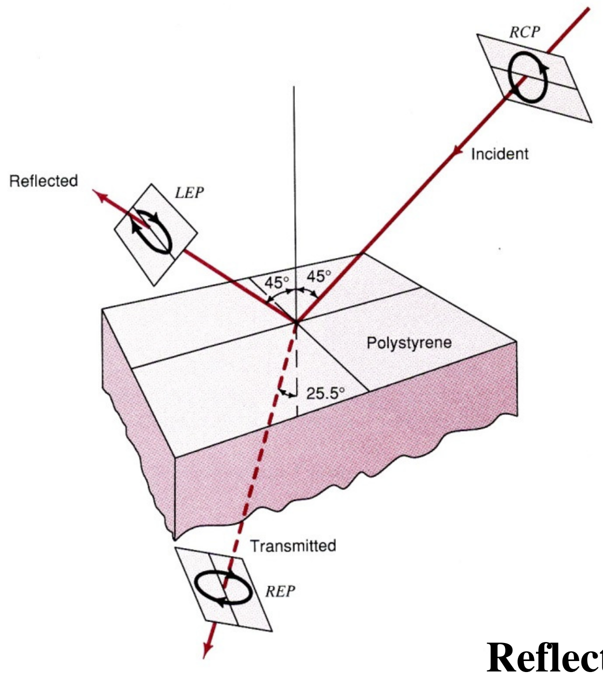
Polarization of EM wave



Reflection, refraction

Reflection $\theta_r = \theta_i$

Reflection coefficient: $\rho = \dfrac{E_r}{E_i}$ Depends on media, polarisation of incident wave and angle of incidence.



Refraction $\sin(\theta_t) = \dfrac{\eta_1}{\eta_2}\sin(\theta_i)$

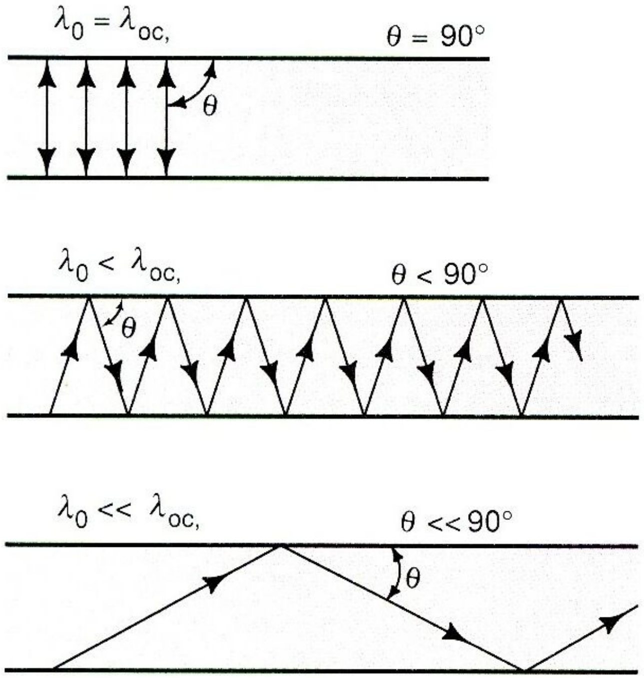
if both media are lossless $\sin(\theta_t) = \sqrt{\frac{\mu_1\varepsilon_1}{\mu_2\varepsilon_2}}\sin(\theta_i)$

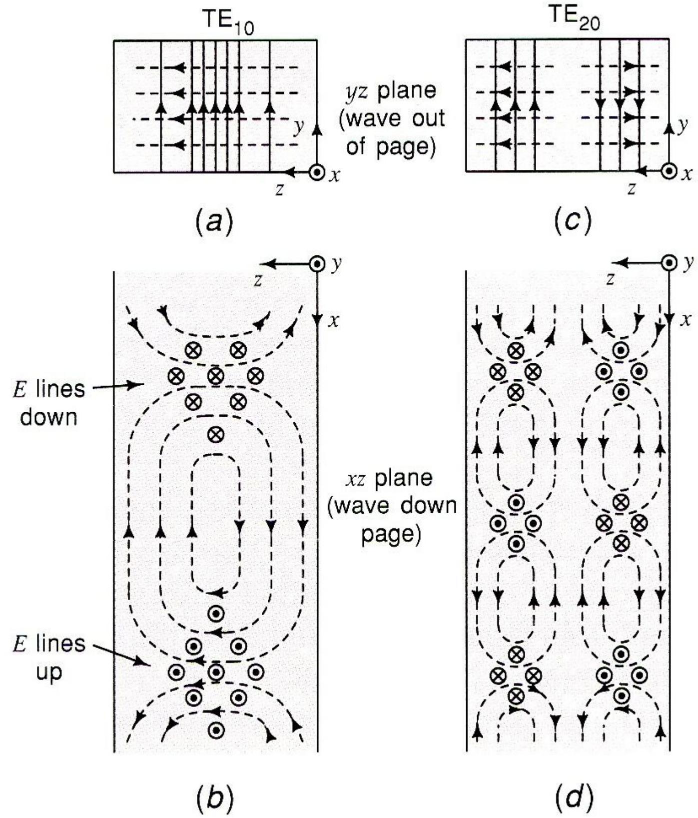
Reflection and refraction affect polarisation

Guided electromagnetic wave

- Cables
  - Used at frequencies below 35 GHz
- Waveguides
  - Used between 0.4 GHz to 350 GHz
- Quasi-optical system
  - Used above 30 GHz
- TEM wave in cables and quasi-optical systems (same as free space)
- TH,TE and combinations in waveguides
  - E or H field component in the direction of propagation
  - Wave bounces on the inner walls of the guide
  - Lower and upper frequency limits
  - Cross section dimensions proportional to wavelength

Rectangular waveguide





Launching of EM wave

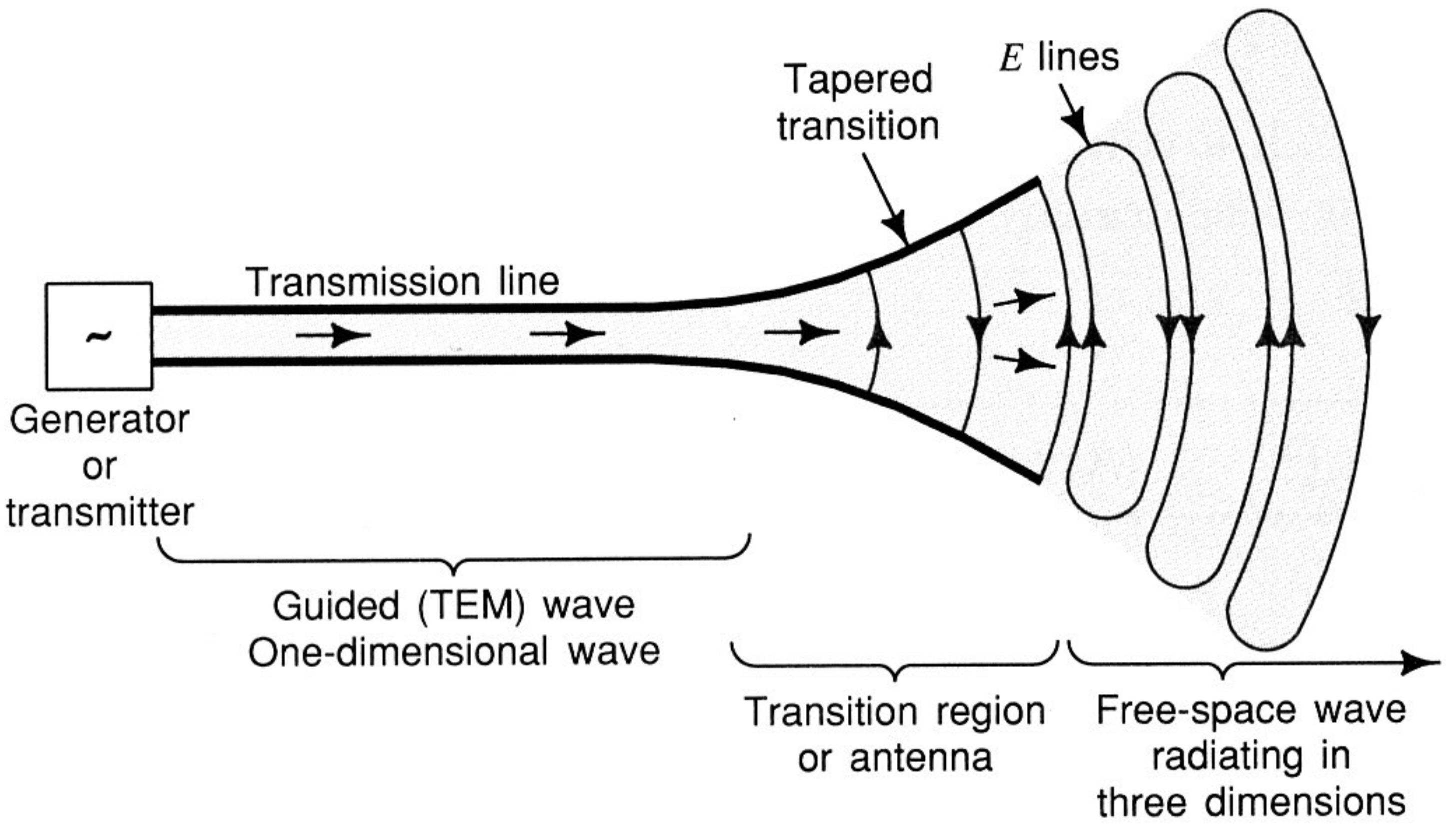
Open up the cable and separate wires

Dipole antenna

Open and flare up waveguide

Horn antenna

Transition from guided wave to free space wave



Reciprocity

- Transmission and reception antennas can be used interchangeably
- Medium must be linear, passive and isotropic
- Caveat: Antennas are usually optimised for reception or transmission not both !

Basic antenna parameters

- Radiation pattern
- Beam area and beam efficiency
- Effective aperture and aperture efficiency
- Directivity and gain
- Radiation resistance

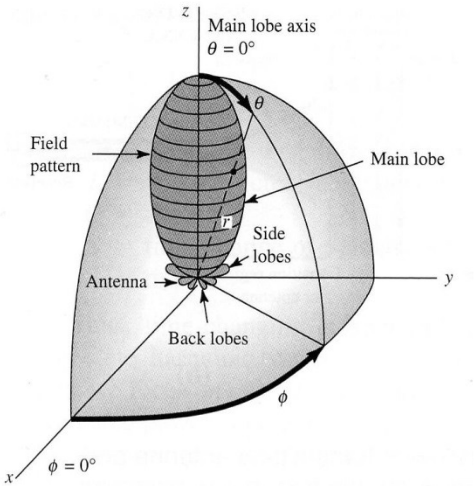
Radiation pattern

- Far field patterns
- Field intensity decreases with increasing distance, as 1/r
- Radiated power density decreases as $1/r^2$
- Pattern (shape) independent on distance
- Usually shown only in principal planes

$$\text{Far field: } r > 2\frac{D^2}{\lambda}$$

D : largest dimension of the antenna

Radiation pattern (2)

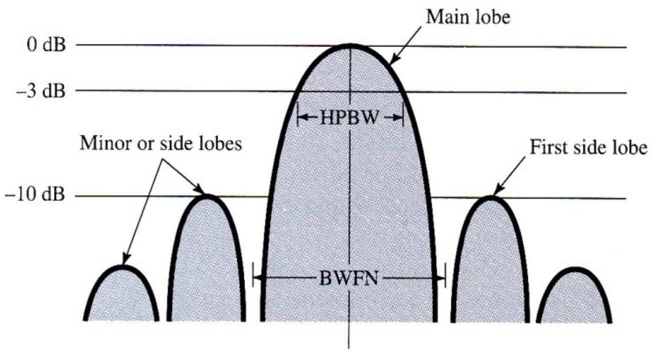


Field patterns

$$E_\theta(\theta,\phi) \qquad E_\phi(\theta,\phi)$$

+ phase patterns

$$\varphi_\theta(\theta,\phi) \qquad \varphi_\phi(\theta,\phi)$$



HPBW: half power beam width

$$P(\theta,\phi) = \frac{E_\theta^2(\theta,\phi) + E_\phi^2(\theta,\phi)}{Z_0} r^2$$

$$P_n(\theta,\phi) = \frac{P(\theta,\phi)}{P(\theta,\phi)_{\max}}$$

Beam area and beam efficiency

Beam area $$\Omega_A = \int_0^{2\pi}\int_0^{\pi} P_n(\theta,\phi)\cdot\sin(\theta)\,d\theta\, d\phi = \iint_{4\pi} P_n(\theta,\phi)\,d\Omega$$

Main beam area $$\Omega_M = \iint_{\substack{Main\\ beam}} P_n(\theta,\phi)\,d\Omega$$

Minor lobes area $$\Omega_m = \iint_{\substack{\min or\\ lobes}} P_n(\theta,\phi)\,d\Omega$$

$$\Omega_A = \Omega_M + \Omega_m$$

Main beam efficiency $$\varepsilon_M = \frac{\Omega_M}{\Omega_A}$$

Effective aperture and aperture efficiency

Receiving antenna extracts power from incident wave

$$P_{rec} = S_{in} \cdot A_e$$

Aperture and beam area are linked: $$A_e = \frac{\lambda^2}{\Omega_A}$$

For some antennas, there is a clear physical aperture and an aperture efficiency can be defined

$$\varepsilon_{ap} = \frac{A_e}{A_p}$$

Directivity and gain

Directivity $$D = \frac{P(\theta,\phi)_{\max}}{P(\theta,\phi)_{average}}$$

From pattern $$D = \frac{4\pi}{\iint\limits_{4\pi} P_n(\theta,\phi)\,d\Omega} = \frac{4\pi}{\Omega_A}$$

From aperture $$D = 4\pi \frac{A_e}{\lambda^2}$$

Isotropic antenna: $\Omega_A = 4\pi \quad D = 1$

Gain $G = k_g\ D$

$k_g =$ efficiency factor $(0 < k_g < 1)$

G is lower than D due to ohmic losses only

Radiation resistance

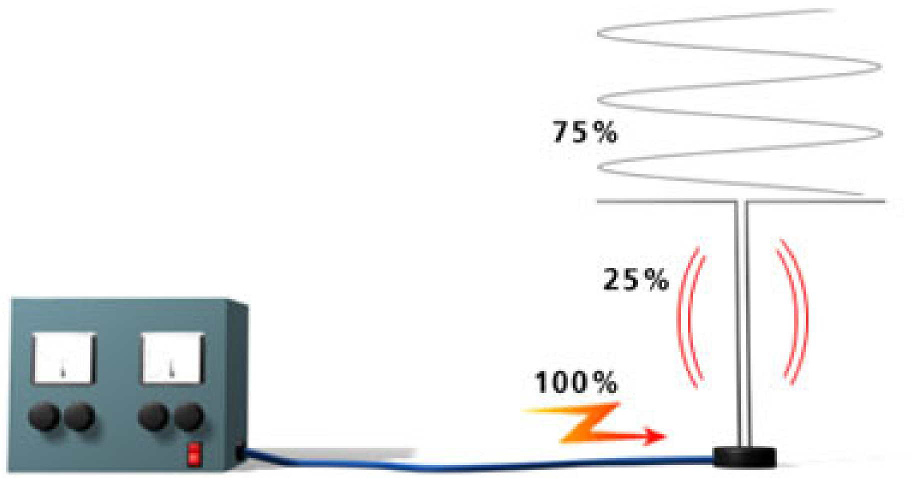
- Antenna presents an impedance at its terminals

$$Z_A = R_A + jX_A$$

- Resistive part is radiation resistance plus loss resistance

$$R_A = R_R + R_L$$

The radiation resistance does not correspond to a real resistor present in the antenna but to the resistance of space coupled via the beam to the antenna terminals.

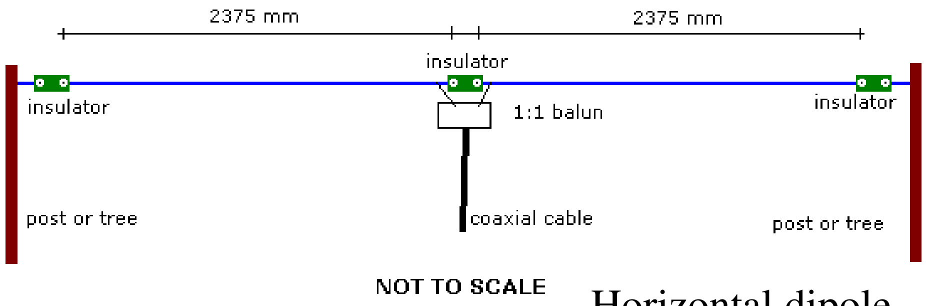


Types of Antenna

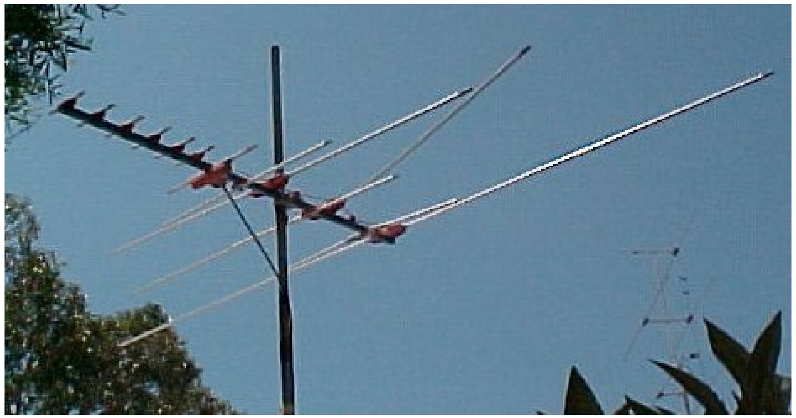
- Wire
- Aperture
- Arrays

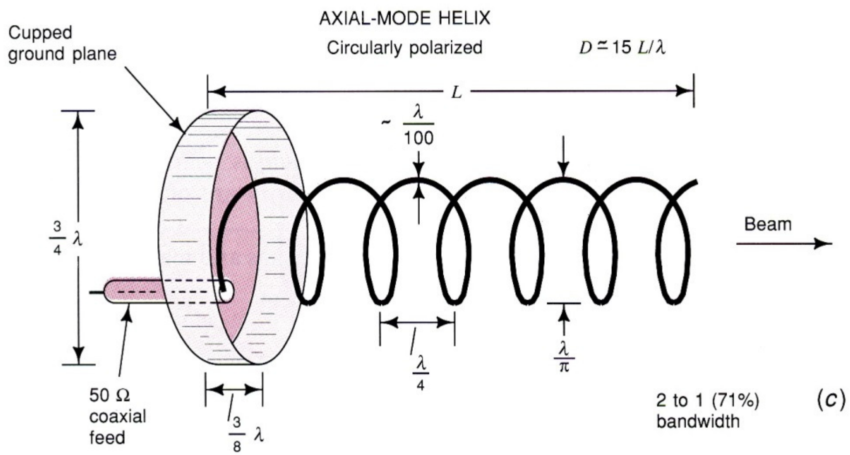
Wire antenna

- Dipole
- Loop
- Folded dipoles
- Helical antenna
- Yagi (array of dipoles)
- Corner reflector
- Many more types



Horizontal dipole

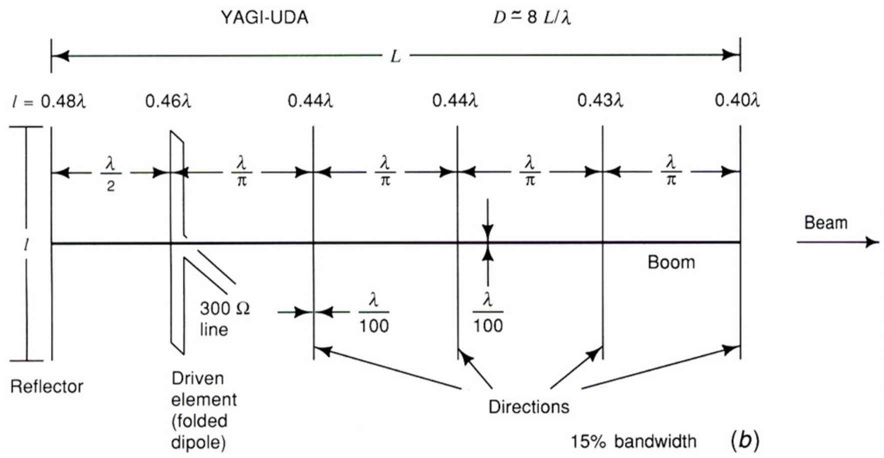


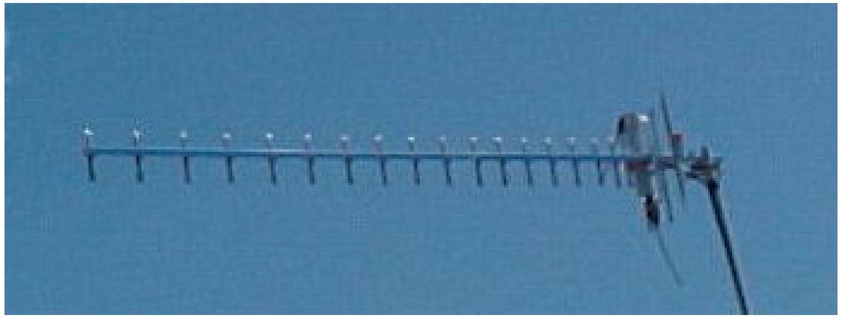


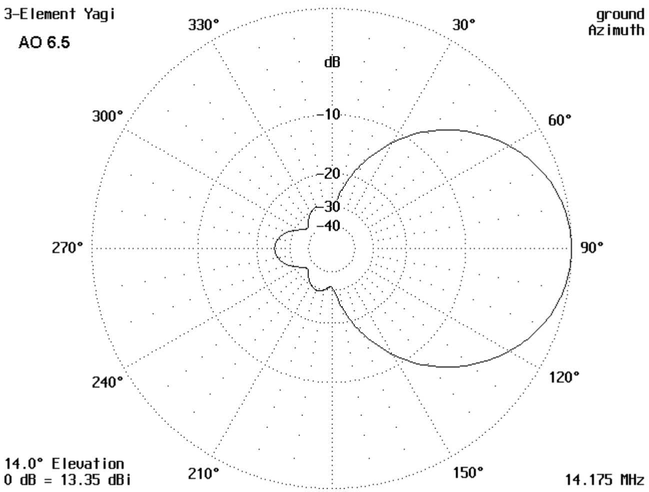
Wire antenna - resonance

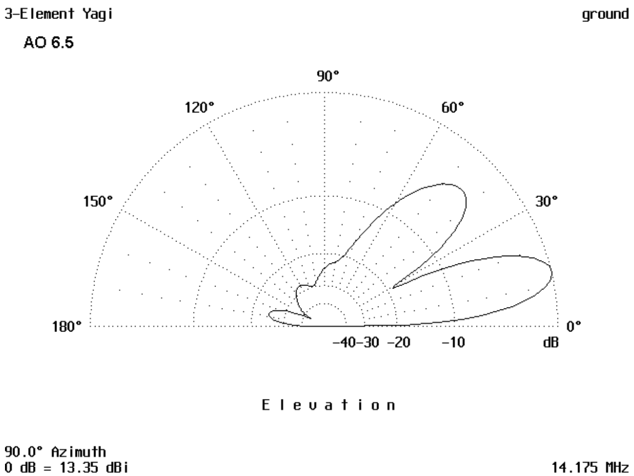
- Many wire antennas (but not all) are used at or near resonance
- Some times it is not practical to built the whole resonant length
- The physical length can be shortened using loading techniques
  - Inductive load: e.g. center, base or top coil (usually adjustable)
  - Capacitive load: e.g. capacitance “hats” (flat top at one or both ends)

Yagi-Uda









Elements	Gain dBi	Gain dBd
3	7.5	5.5
4	8.5	6.5
5	10	8
6	11.5	9.5
7	12.5	10.5
8	13.5	11.5

Aperture antenna

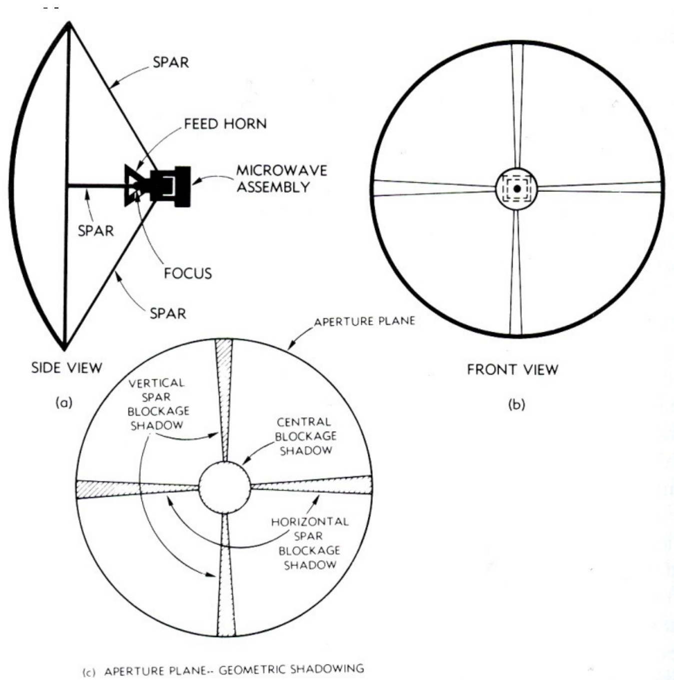
- Collect power over a well defined aperture
- Large compared to wavelength
- Various types:
  - Reflector antenna
  - Horn antenna
  - Lens

Reflector antenna

- Shaped reflector: parabolic dish, cylindrical antenna …
  - Reflector acts as a large collecting area and concentrates power onto a focal region where the feed is located
- Combined optical systems: Cassegrain, Nasmyth …
  - Two (Cassegrain) or three (Nasmyth) mirrors are used to bring the focus

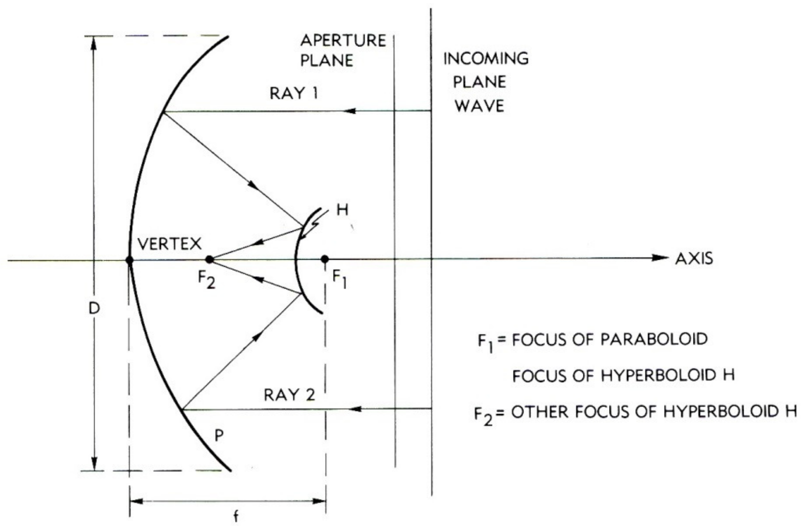
    to a location where the feed including the transmitter/receiver can be

    installed more



Cassegrain antenna

- Less prone to back scatter than simple parabolic antenna
- Greater beam steering possibility: secondary mirror motion amplified by optical system
- Much more compact for a given f/D ratio



Cassegrain antenna (2)

- Gain depends on diameter, wavelength, illumination
- Effective aperture is limited by surface accuracy, blockage
- Scale plate depends on equivalent focal length
- Loss in aperture efficiency due to:
  - Tapered illumination
  - Spillover (illumination does not stop at the edge of the dish)
  - Blockage of secondary mirror, support legs
  - Surface irregularities (effect depends on wavelength)

$$K_g = \cos\left(4\pi\frac{\delta}{\lambda}\right)^2 \qquad \delta = \text{rms of surface deviation}$$

At the SEST:

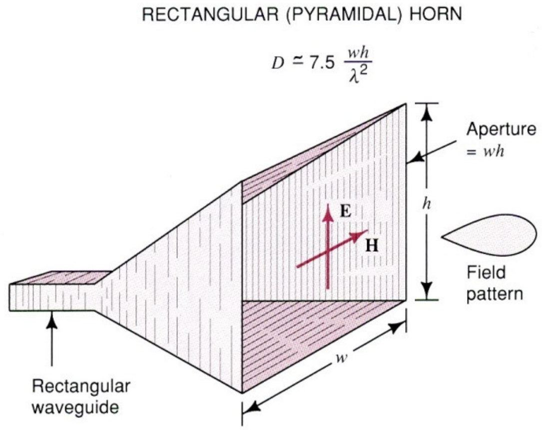
$$\text{taper efficiency}: \ \varepsilon_{\text{t}} = 0.87$$

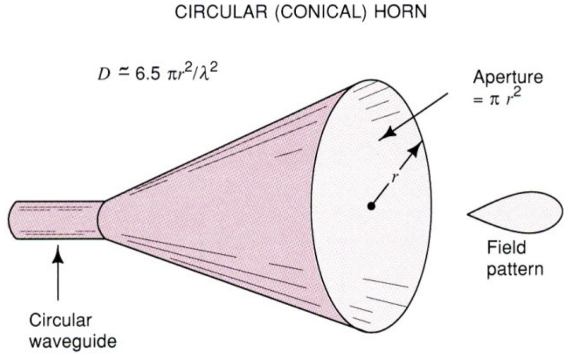
$$\text{spillover efficiency}: \ \varepsilon_{\text{s}} = 0.94$$

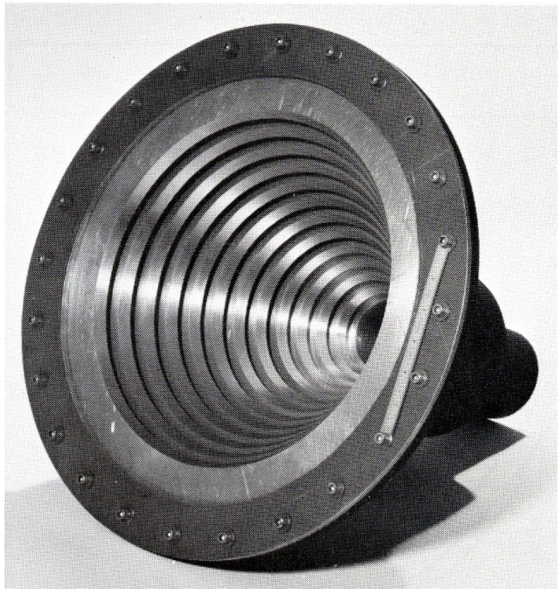
$$\text{blockage efficiency}: \ \varepsilon_{\text{b}} = 0.96$$

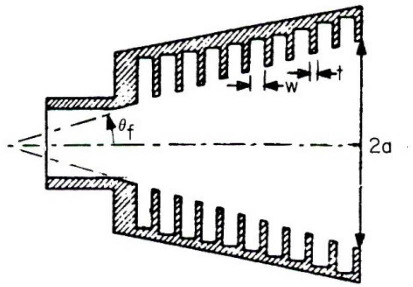
Horn antenna

- Rectangular or circular waveguide flared up
- Spherical wave fronts from phase centre
- Flare angle and aperture determine gain

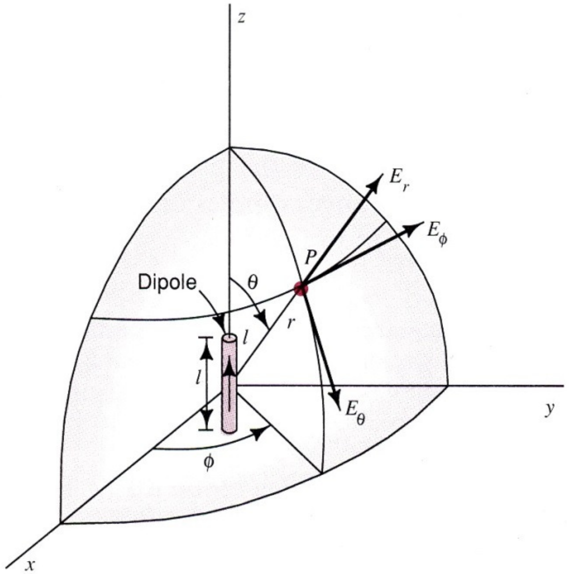








Short dipole



$$E_r = \frac{I_0 l e^{j(\omega t - \beta r)} \cos(\theta)}{2\pi\varepsilon_0}\left(\frac{1}{cr^2} + \frac{1}{j\omega r^3}\right)$$

$$E_\theta = \frac{I_0 l e^{j(\omega t - \beta r)} \sin(\theta)}{4\pi\varepsilon_0}\left(\frac{j\omega}{c^2 r} + \frac{1}{cr^2} + \frac{1}{j\omega r^3}\right)$$

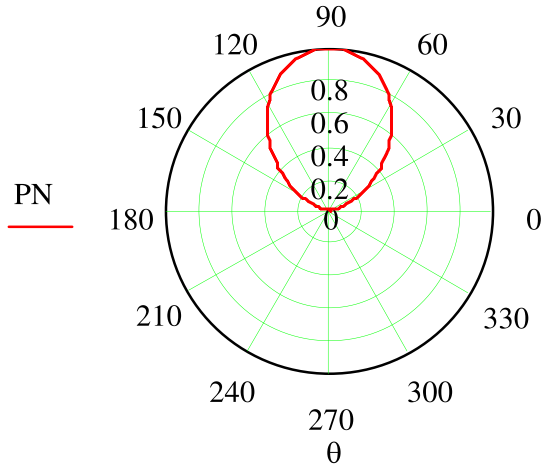
$$H_\phi = \frac{I_0 l e^{j(\omega t - \beta r)} \sin(\theta)}{4\pi}\left(\frac{j\omega}{cr} + \frac{1}{r^2}\right)$$

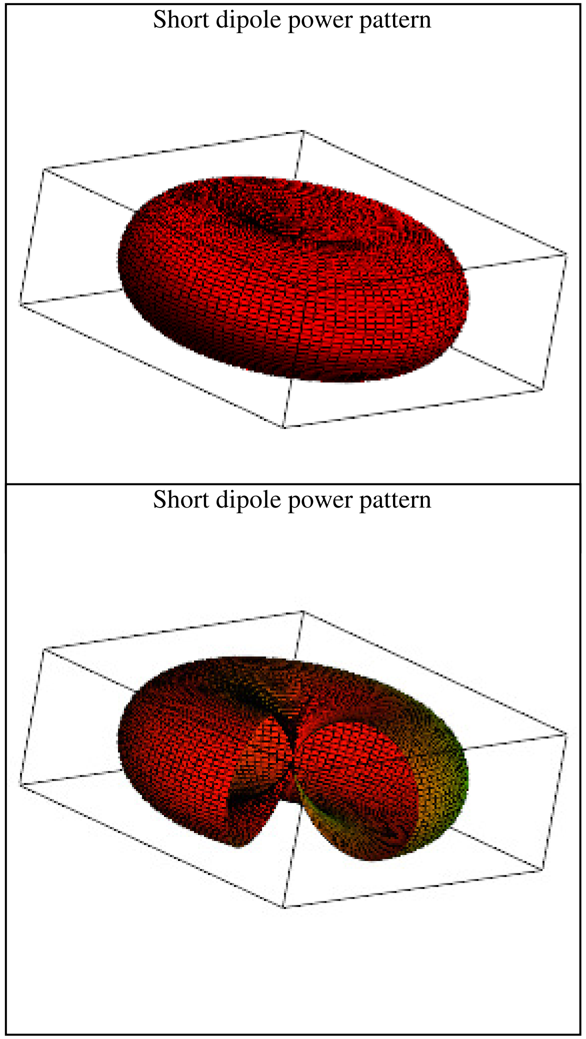
- Length much shorter than wavelength
- Current constant along the length
- Near dipole power is mostly reactive
- As r increases E_r vanishes, E and H gradually become in phase

$$for\ r >> \frac{\lambda}{2\pi}, \qquad \mathrm{E}_\theta\ and\ \mathrm{H}_\phi \text{ vary as } \frac{1}{\mathrm{r}} \longrightarrow E_\theta = \frac{j60\pi I_0 e^{j(\omega t - \beta r)} \sin(\theta)}{r}\frac{l}{\lambda}$$

$$\text{P varies as } \frac{1}{\mathrm{r}^2}$$

Short dipole pattern





(X,Y,Z)

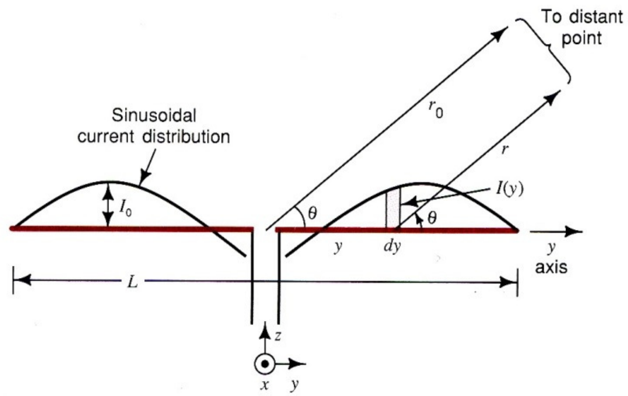
$$\Omega_A = \frac{8\pi}{3}$$

$$R_r = 80\pi^2 \left(\frac{l}{\lambda}\right)^2$$

$$D = 1.5$$

Thin wire antenna

- Wire diameter is small compared to wavelength
- Current distribution along the wire is no longer constant



$$\text{e.g.}\quad I(y) = I_0 \sin\left(\frac{2\pi}{\lambda}\left(\frac{L}{2} \pm y\right)\right)$$

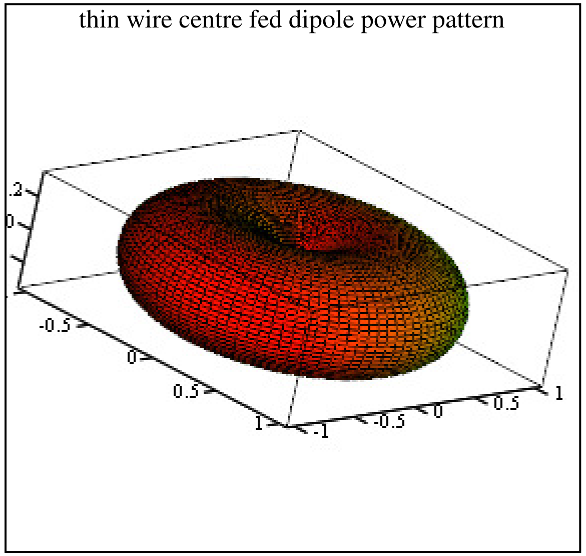
centre - fed dipole

- Using field equation for short dipole, replace the constant current with actual distribution

$$E_\theta = \frac{j60 I_0 e^{j(\omega t - \beta r)}}{r}\left(\frac{\cos\left(\frac{\beta L \cos(\theta)}{2}\right) - \cos\left(\frac{\beta L}{2}\right)}{\sin(\theta)}\right)$$

centre - fed dipole, I_0 = current at feed point

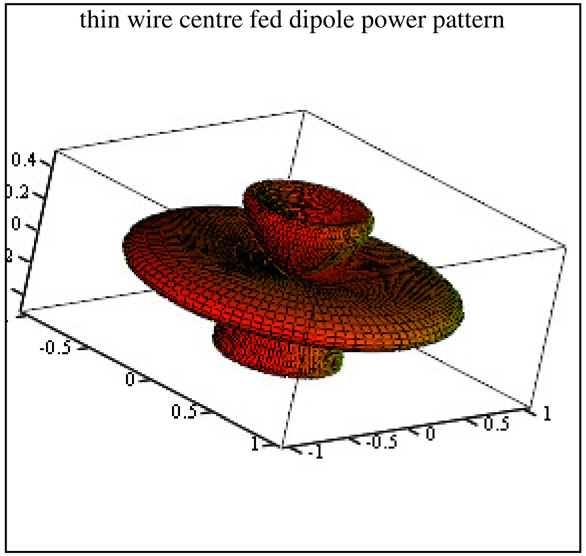
Thin wire pattern



(X, Y, Z)

$$l = 1\frac{\lambda}{2}$$

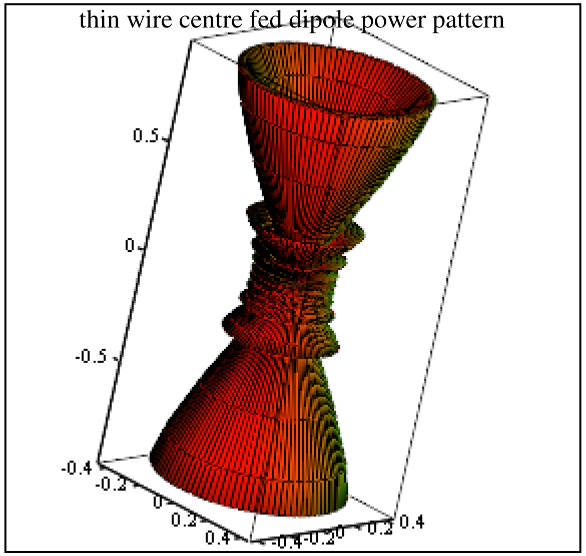
$\Omega_A = 7.735$ $D = 1.625$



(X, Y, Z)

$$l = 1.395\lambda$$

$\Omega_A = 5.097$ $D = 2.466$



(X, Y, Z)

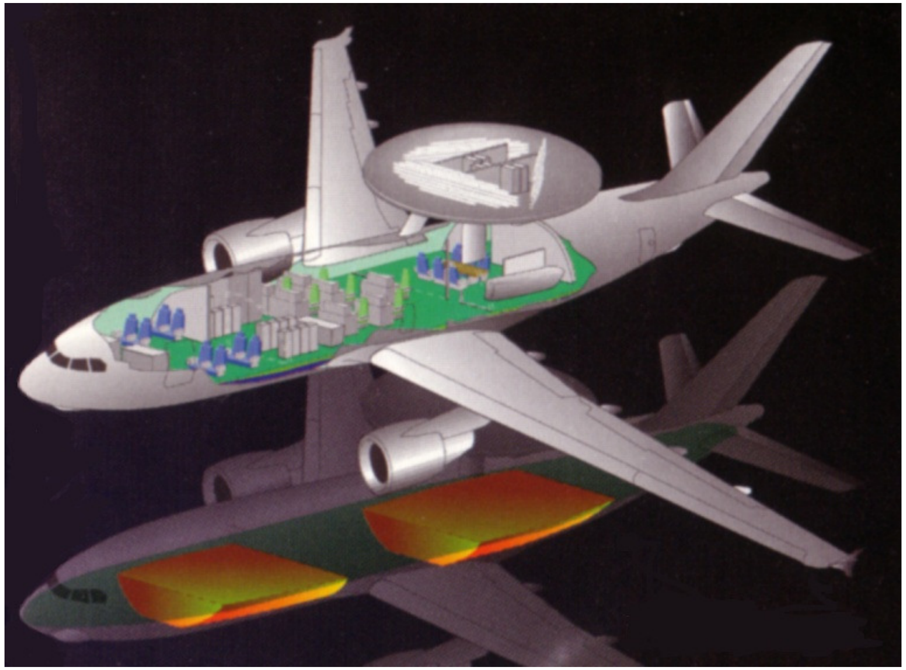
$$l = 10\lambda$$

$\Omega_A = 1.958$ $D = 6.417$

Antenna Array Examples

Very Large Antenna (VLA)

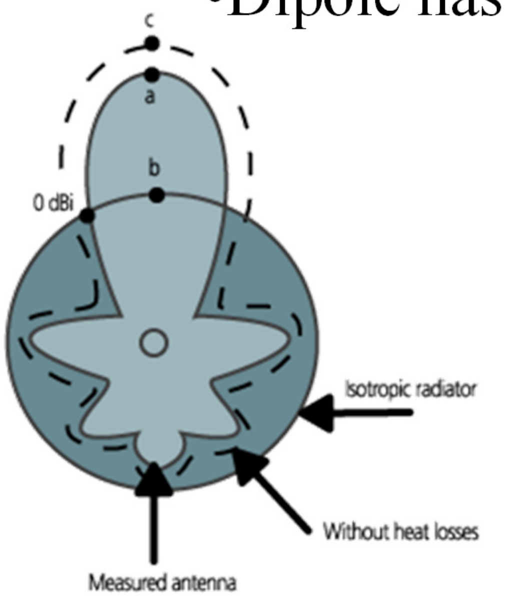
Airborne Warning and Control
System (AWACS)



dBi versus dBd

- **dBi** indicates gain vs. isotropic antenna
  - Isotropic antenna radiates equally well in all directions, spherical pattern

- **dBd** indicates gain vs. reference half-wavelength dipole
  - Dipole has a doughnut shaped pattern with a gain of 2.15 dBi



$$dBi = dBd + 2.15\,dB$$

Feed and line matching

- The antenna impedance must be matched by the line feeding it if maximum power transfer is to be achieved
- The line impedance should then be the complex conjugate of that of the antenna
- Most feed line are essentially resistive

Signal transmission, radar echo

- Transmitting antenna $A_{et}, P_t, G_t, \lambda$
- Receiving antenna A_{er}, P_r, G_r

$$P_r = \underbrace{\frac{G_t P_t}{4\pi \cdot r^2}}_{\text{S, power density}} \underbrace{\frac{\lambda^2 G_r}{4\pi}}_{\text{Effective receiving area}} = \left(\frac{\lambda}{4\pi \cdot r}\right)^2 G_t G_r P_t$$

Radar return

$$P_r = \underbrace{\frac{G_t P_t}{4\pi \cdot r^2}}_{\text{S, power density}} \underbrace{\frac{\sigma}{4\pi \cdot r^2}}_{\text{Reflected power density}} \underbrace{\frac{G_r \lambda^2}{4\pi}}_{\text{Effective receiving area}} = P_t G_t G_r \frac{\lambda^2}{(4\pi)^3 r^4} \sigma$$

$\sigma =$ radar cross section (area)