Propagación y Transmisión Inalámbrica

Dpto. Teoría de la Señal y Comunicaciones
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Fundamentos y conceptos básicos de radiación

- Introduction to electromagnetic radiation
- The short dipole
- Antenna parameters
- Friis equation

Algunos tipos de antenas

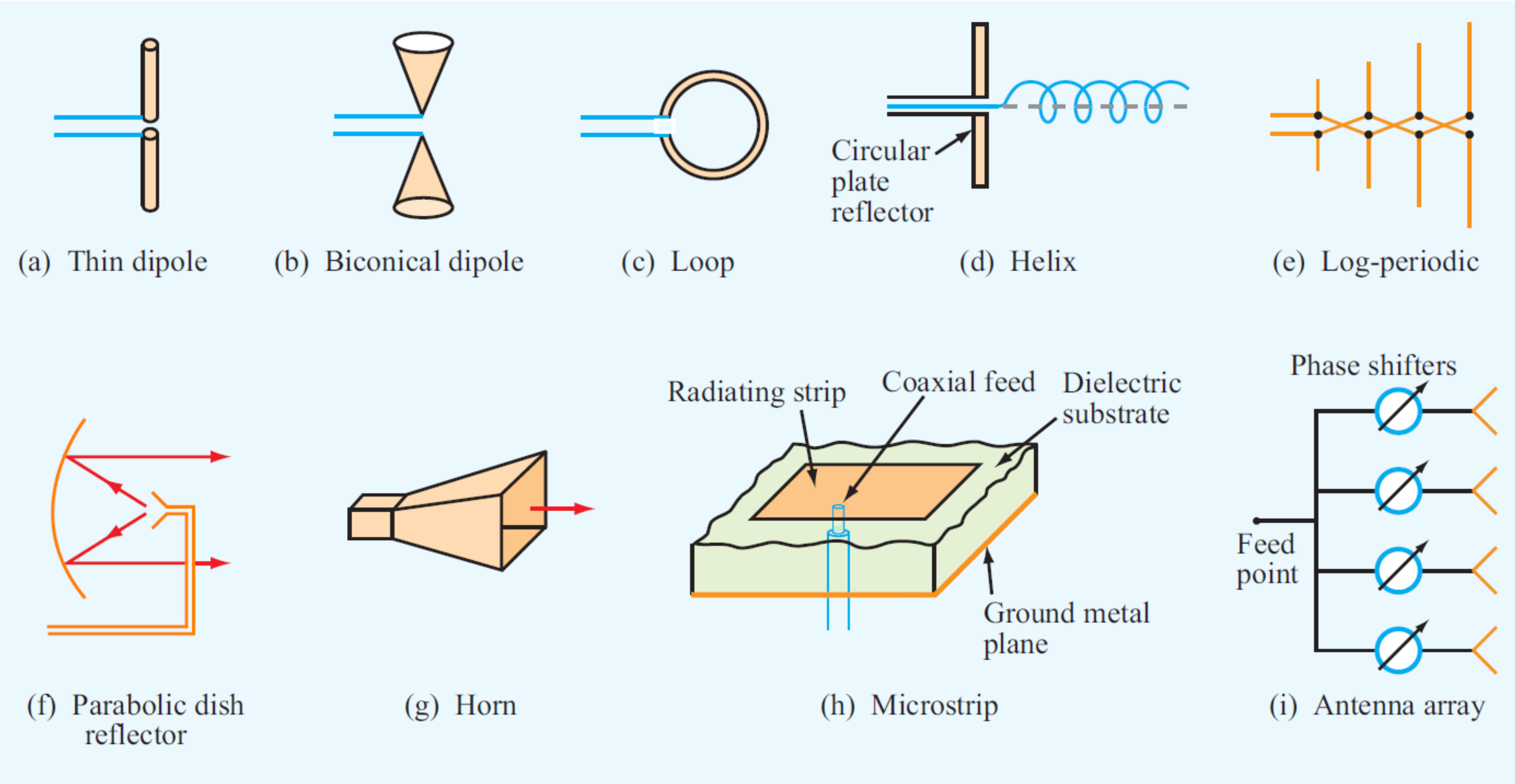
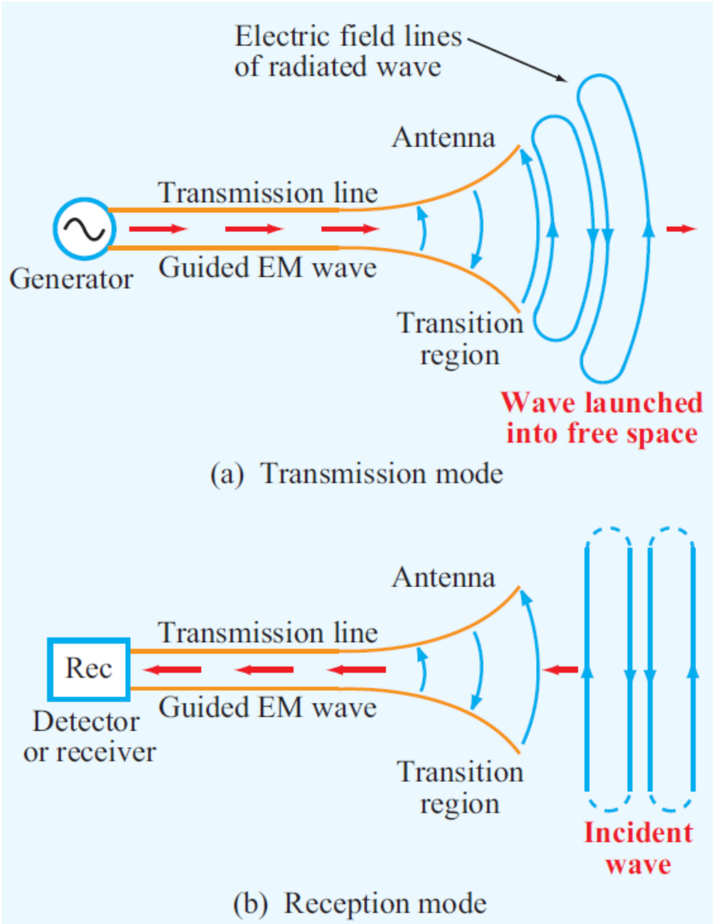
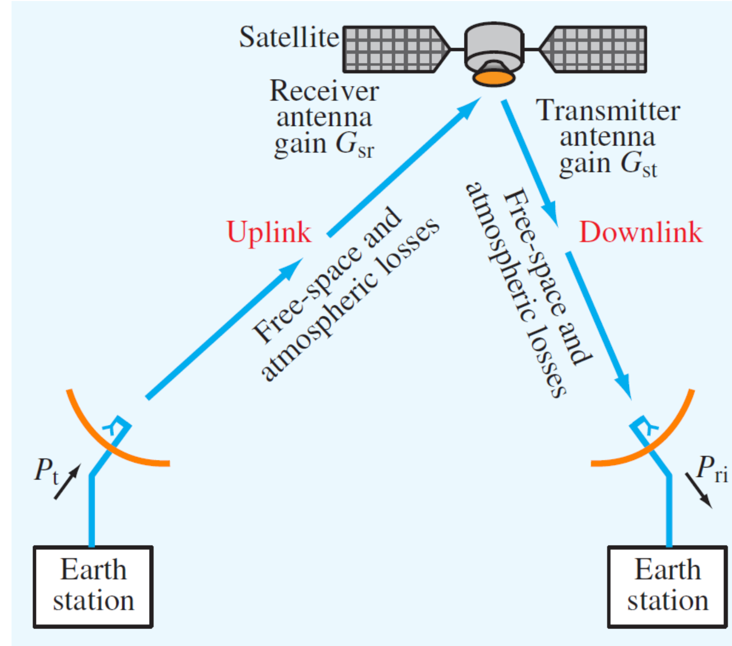
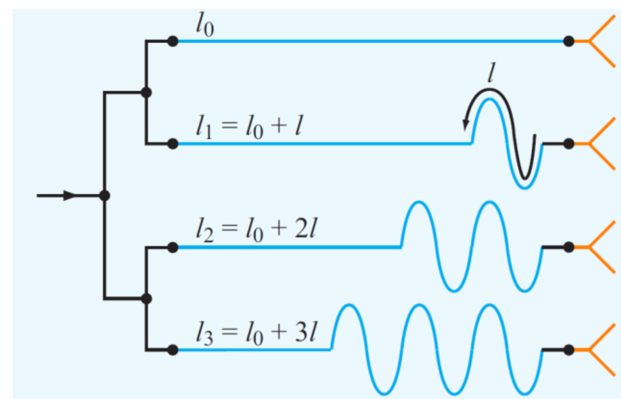


Figura del libro de Ulaby:
F.T.Ulaby , U.Ravaioli: “Fundamentals of Applied Electromagnetics”, Pearson (7th Edition)
Applied Electromagnetics 7e Textbook Website
http://em7e.eecs.umich.edu/ulaby_modules_choice.html







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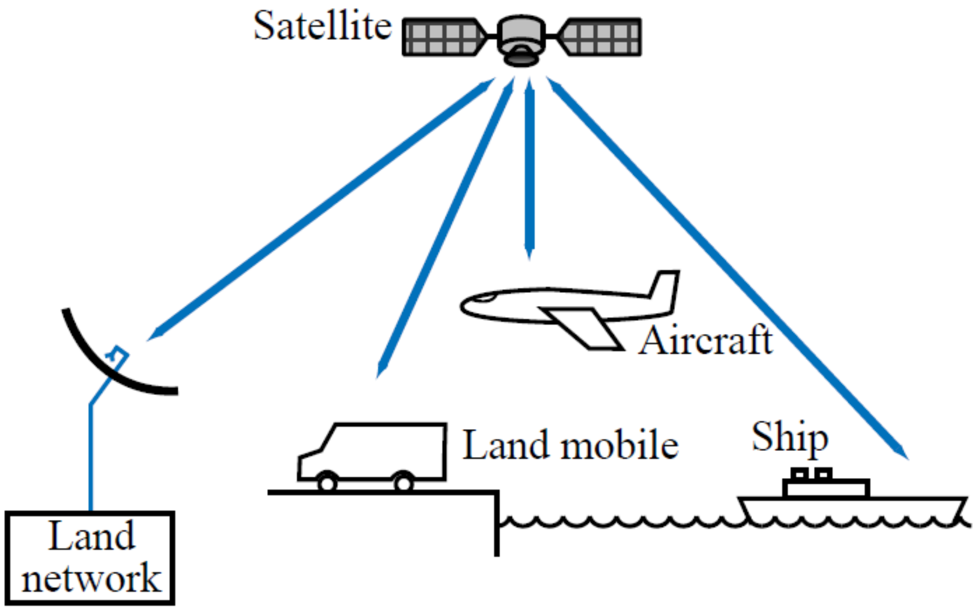
Why do we need antennas? Motivation I

- Satellite Communication Systems



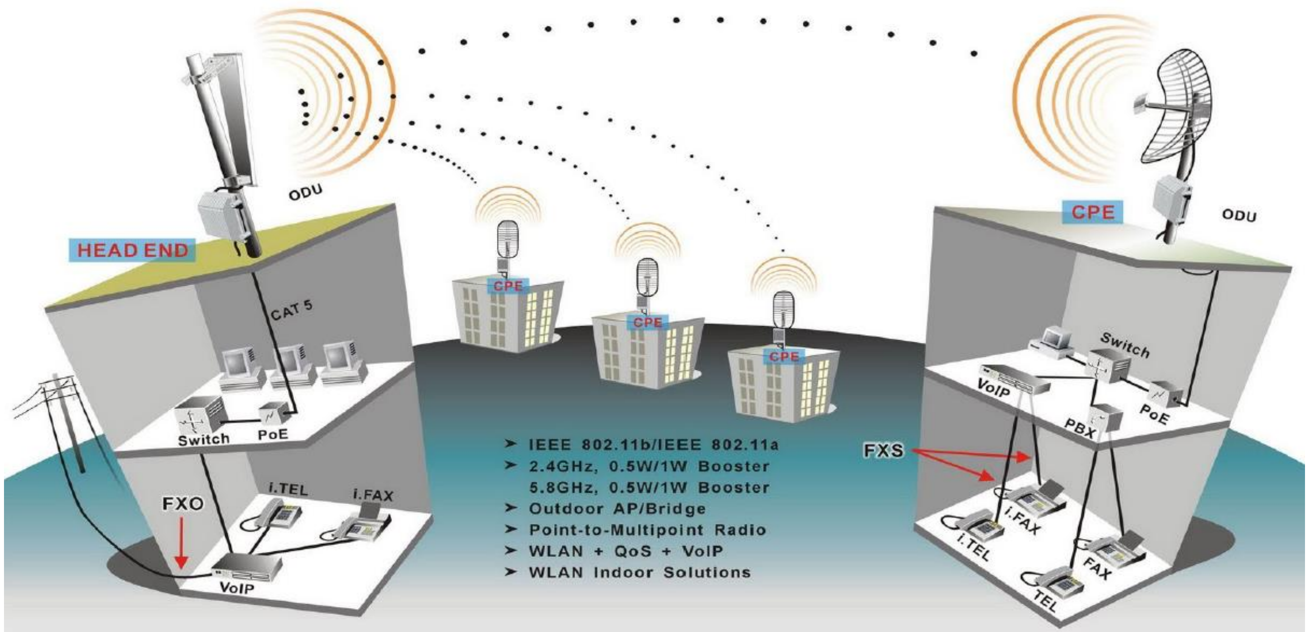
http://www.esa.int/spaceinimages/Images/2014/03/Artist_s_impression_of_Sentinel-1A

Vast communication network…voice, data, video services….

The viability and effectiveness of the network are attributed in large measure to the use of orbiting satellite systems that function as a relay stations with wide area coverage of Earth's surface

Why do we need antennas? Motivation II

- Wireless systems….mobile terminals



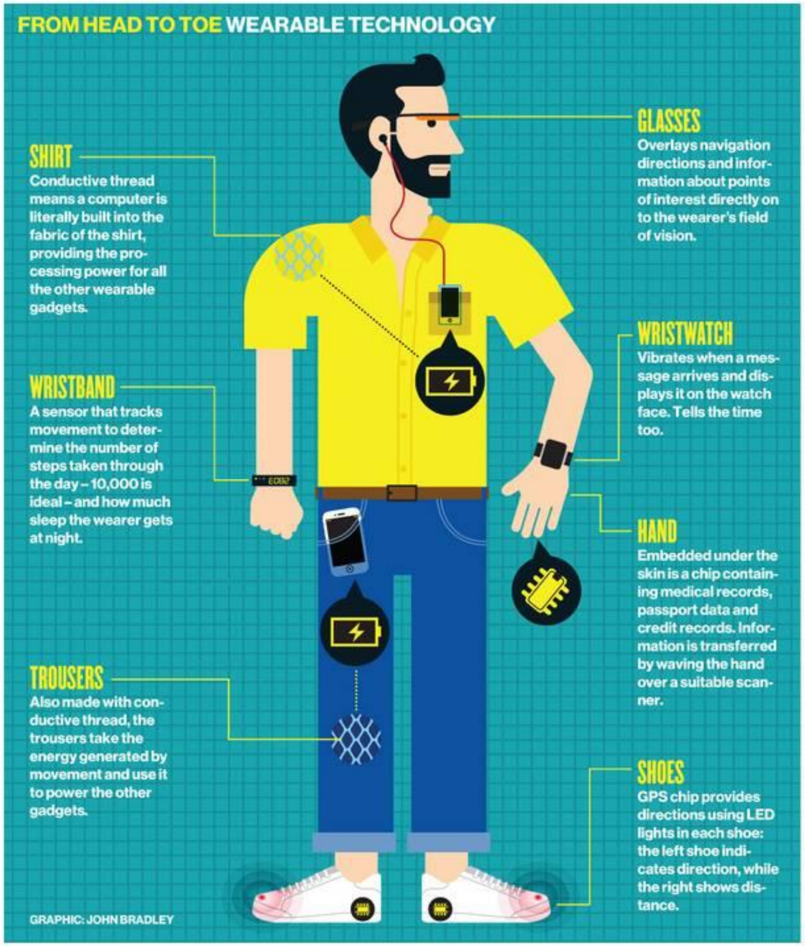
Antennas are needed and used in wireless systems…

Wireless ground-based telecommunication systems
Point-to-point radio links
Local area networks

Smart Cities

Geolocation and location-based services
Sensors

Why do we need antennas? Motivation III



Galileo is Europe's own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control

http://www.esa.int/Our_Activities/Navigation/

http://dazeinfo.com/2014/06/03/wearable-device-market-growth-will-decline-2015-healthcare-china-main-drivers/

❑ What is an antenna?

- All oscilating electric and magnetic fields propagate
- All circuit that create AC electric field and currents will radiate to some extent
- Antennas are devices to optimize and control the emitted radiation so you can couple electrical energy from a circuit to free space and back again

Antenna Design factor

❑The strength of the radiated field in different direction (antenna pattern)
❑The total power radiated compared to the driving power
❑The impedance of the antenna to match it to transmission lines
❑The radiation as a function of frequency (bandwidth)
❑The voltage or current spatial distribution on the antenna to avoid heating or breackdown

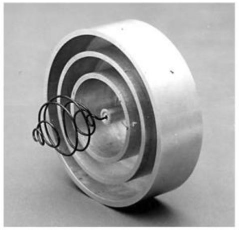
- Potentially any conducting or dielectric structure can serve as an antenna…
- An antenna is designed to radiate or receive electromagnetic energy

But it is necessary

  - To design the antenna with **directional and polarization** properties suitable for the intended **application**
  - To **minimize energy reflection** in the transmission line-antenna juncture (to match the antenna impedance to the line Z_0)
  - The approppiate properties for the antenna are governed by its **shape and size** and the **material** of which it is made

- Key design factor
  - Radiation Pattern
  - Directivity
  - Efficiency/ Gain
  - Bandwidht
  - Polarization

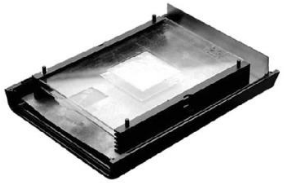
Reflector antenna with dipole-disk feed



Spiral wire antenna on corrugated disk

Waveguide slot antenna array

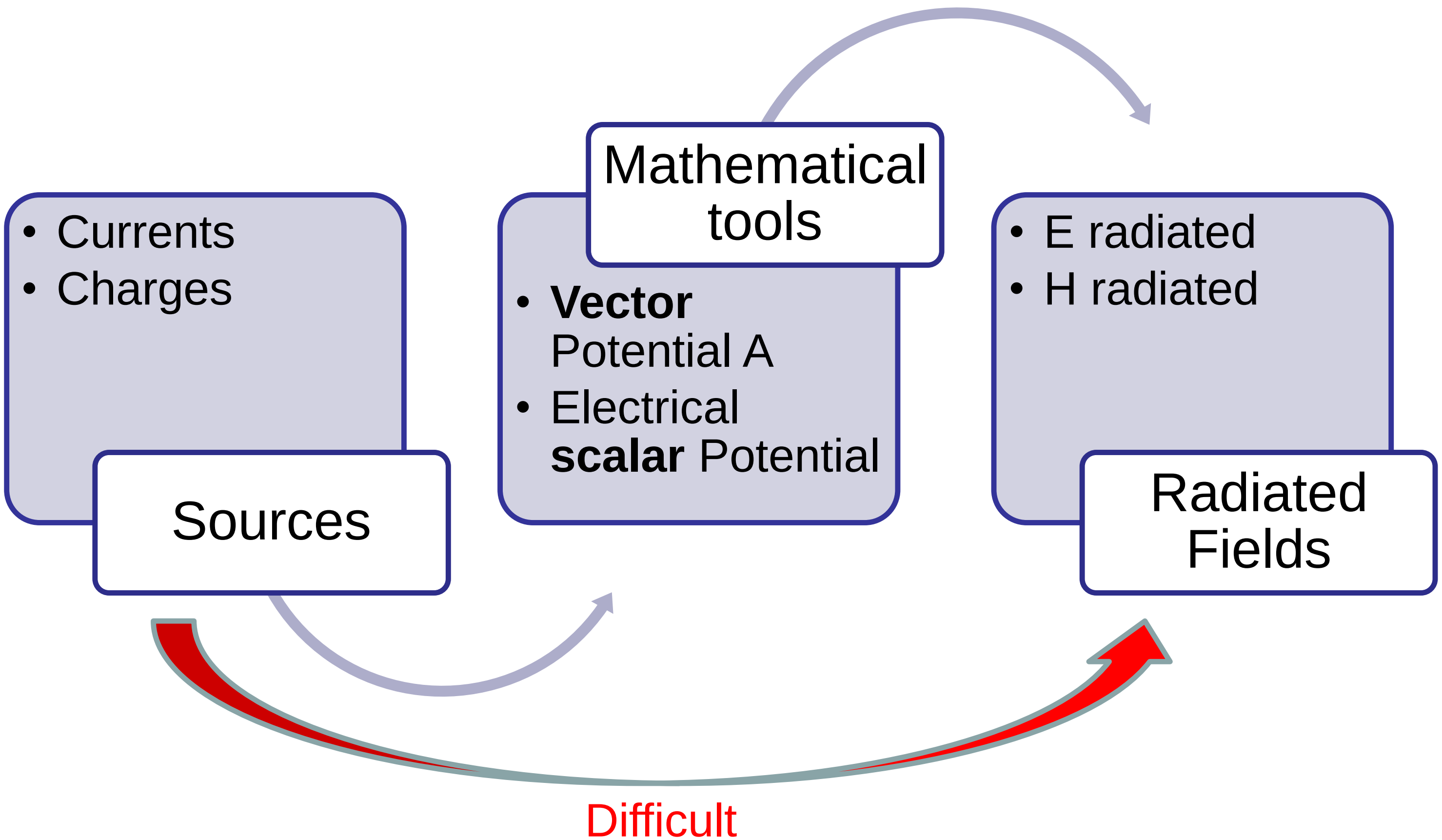
Corrugated horn antenna



Aperture-coupled stacked microstrip antenna (model for tuning)

- How we can obtain the radiated field?
  - Not easy to solve (no simple wave equation)
  - It is necessary to take into account the sources
- Firs solution of Maxwell equations with sources:

Radiated waves



The vector potential **A** for an electric current source **J**

We start from the Maxwell equation $\nabla \cdot \vec{B} = 0$

Therefore, it can be represented as the curl of another vector $\nabla \cdot \nabla \times \vec{A} = 0$

$$\vec{B} = \nabla \times \vec{A} \quad \text{or} \quad \vec{H_A} = \frac{1}{\mu} \nabla \times \vec{A}$$

A indicates the field due to **A** potencial

Substituting into Faraday's equation $\nabla \times \vec{E_A} = -j\omega\mu\vec{H_A}$

$$\nabla \times [\vec{E_A} + j\omega\vec{A}] = 0$$

$$\nabla \times [-\nabla\Phi] = 0$$

$$\vec{E_A} + j\omega\vec{A} = -\nabla\Phi$$

Scalar function that represents an arbitrary **electric scalar potential**

$$\vec{E_A} = -\nabla\Phi - j\omega\vec{A}$$
$$\vec{B} = \nabla \times \vec{A}$$

$\vec{E_A}$ **Electric field due to the A potential**

How **A** is related to the sources?

$$\vec{E}_A = -\nabla\Phi - j\omega\vec{A}$$
$$\vec{B} = \nabla \times \vec{A}$$

$$\nabla \times \vec{H}_A = \vec{J} + j\omega\vec{E}_A$$

By replacing E and H in Maxweel equations by the former expressions,

…and using $\nabla \times \nabla \times \vec{A} = \nabla(\nabla \cdot \vec{A}) - \nabla^2\vec{A}$

we obtain:

$$\Rightarrow \quad \nabla^2\vec{A} + \omega^2\mu\epsilon\vec{A} = -\mu\vec{J} + \nabla\left(\mu\epsilon j\omega\Phi + \nabla \cdot \vec{A}\right)$$

We need now to impose a condition to have a particular solution

$$\boxed{j\omega\mu\epsilon\Phi + \nabla \cdot \vec{A} = 0}$$

LORENTZ's condition or radiation condition

Finally

$$\boxed{\nabla^2\vec{A} + k^2\vec{A} = -\mu\vec{J}}$$

Vectors

Inhomogeneous

Inhomogeneous vector potential
Wave equation

How **ϕ** is related to the sources?

In the same way we can obtain for the potential **ϕ**

$$\nabla^2 \Phi + k^2 \Phi = -\frac{\rho}{\epsilon}$$

$$\nabla^2 \vec{A} + k^2 \vec{A} = -\mu \vec{J}$$

How are the solutions for these differential equations?

$$\vec{J} = J_z \qquad \nabla^2 A_z + k^2 A_z = 0$$

homogeneous potential
Wave equation

$$\frac{d^2 A_z(r)}{dr^2} + \frac{2}{r}\frac{dA_z(r)}{dr} + k^2 A_z(r) = 0$$

Since in the limit the source is a point, **A_z** is not a function of direction (**θ** and **ϕ**)

Has two independent solutions

$$A_{z1} = C_1 \frac{e^{-jkr}}{4\pi r}$$

outward wave

traveling waves
solutions

$$e^{j\omega t}$$

$$A_{z2} = C_2 \frac{e^{+jkr}}{4\pi r}$$

inward wave

Relation between sources and potentials

Electric current with harmonic time variation…

with sources… $$\nabla^2 \vec{A} + k^2 \vec{A} = -\mu \vec{J}$$

inhomogeneous
Wave equation

$$\vec{J} = J_z \qquad \nabla^2 A_z + k^2 A_z = -\mu J_z$$

$$A_z = \frac{\mu}{4\pi} \int_V J_z \frac{e^{-jkr}}{r} \, dv'$$

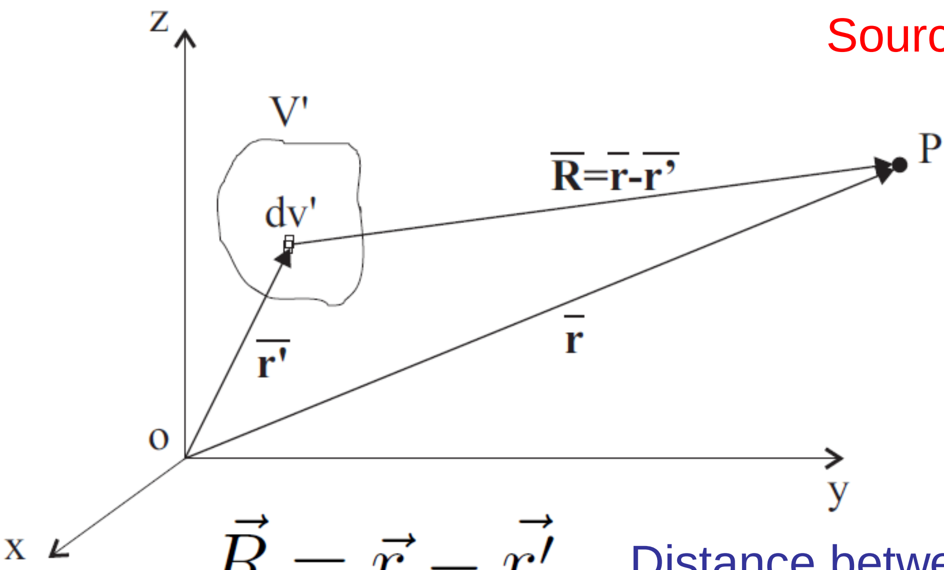
The sum of contribution of incremental **Jz** sources to the potential

$$\left.\begin{array}{l} \nabla^2 A_x + k^2 A_x = -\mu J_x \\ \nabla^2 A_y + k^2 A_y = -\mu J_y \\ \nabla^2 A_z + k^2 A_z = -\mu J_z \end{array}\right\} \quad \nabla^2 \vec{A} + k^2 \vec{A} = -\mu \vec{J}$$

we assume the solution to the vector wave equation as….

$$\vec{A} = \frac{\mu}{4\pi} \int_V \vec{J}(\vec{r}) \frac{e^{-jkr}}{r} \, dv'$$

ELECTROMAGNETIC RADIATION



Source not at origin, located in a volume V'

$\vec{J}$ Electric courrent source

$\vec{r'}$ Position of the source from the origin

$\vec{r}$ Position of point P from the origin

$\vec{R} = \vec{r} - \vec{r'}$ Distance between the observation point and the source

$$\vec{A} = \frac{\mu}{4\pi} \int_{V'} \vec{J}(\vec{r'}) \frac{e^{-jkR}}{R} \quad dv'$$

We must integrate…. The contribution of the J with their directions and amplitudes and the…

$$\frac{e^{-jkR}}{R}$$

…spherical propagation factor

$\frac{1}{R}$ decay of the magnitude with distance….

e^{-jkR} phase change with distance

In …SUMMARY

we obtain the radiated fields in 3 steps….

1 *Specify the sources J*

$$\vec{J}$$

2 *Find vector potential A*

$$\vec{A} = \frac{\mu}{4\pi}\int_{V'} \vec{J}(\vec{r'})\frac{e^{-jkR}}{R} \quad dv'$$

3 *Find the fields from the potential*

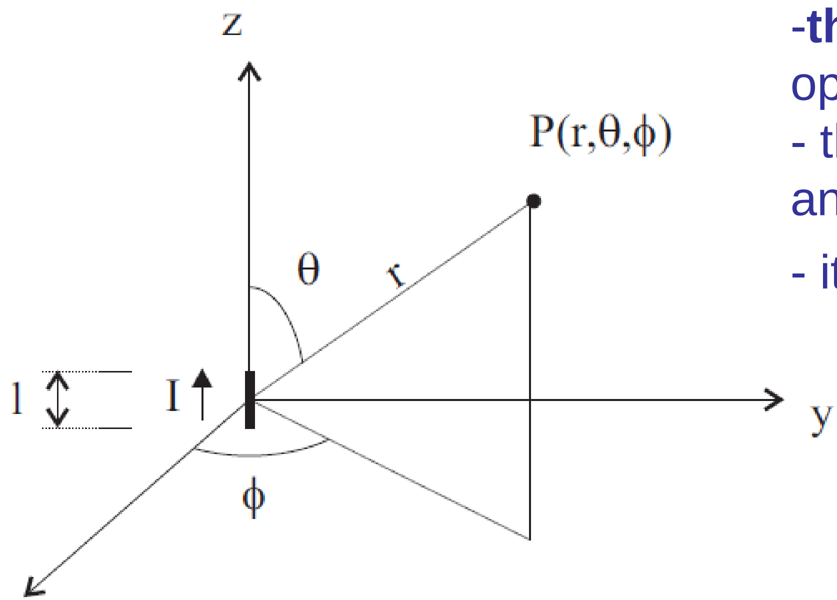
$$\vec{E_A} = -j\omega\vec{A} - j\frac{\nabla(\nabla\cdot\vec{A})}{\omega\mu\epsilon}$$

$$\vec{H} = \frac{1}{\mu}\nabla\times\vec{A}$$

$$\vec{E} = \frac{1}{j\omega\epsilon}\nabla\times\vec{H}$$

CALCULATION OF THE RADIATED FIELDS FROM A SHORT DIPOLE

The Ideal dipole or Hertzian dipole



-**the dipole** a is very short compared to the operating wavelenght

- the element of current is along the z-axis and centered on the coordinate origin

- it is of constant amplitude I_0

$$\vec{A} = \frac{\mu}{4\pi}\int_{V'} \vec{J}\frac{e^{-jkR}}{R}dv' = \frac{\mu}{4\pi}\int_{C} \vec{I}\frac{e^{-jkR}}{R}dl' = \hat{z}\frac{\mu I_o}{4\pi}\frac{e^{-jkr}}{r}\int_{-l/2}^{l/2} dz' = \hat{z}\frac{\mu I_o l}{4\pi r}e^{-jkr}$$

Changing the coordinate system….

Transformations Between Coordinate Systems

$$x = r\sin\theta\cos\phi \qquad \hat{\mathbf{r}} = \hat{\mathbf{x}}\cos\phi\sin\theta + \hat{\mathbf{y}}\sin\phi\sin\theta + \hat{\mathbf{z}}\cos\theta$$
$$y = r\sin\theta\sin\phi \qquad \hat{\boldsymbol{\theta}} = \hat{\mathbf{x}}\cos\phi\cos\theta + \hat{\mathbf{y}}\sin\phi\cos\theta - \hat{\mathbf{z}}\sin\theta$$
$$z = r\cos\theta \qquad \hat{\boldsymbol{\phi}} = -\hat{\mathbf{x}}\sin\phi + \hat{\mathbf{y}}\cos\phi$$

Unit vectors

$$\hat{\mathbf{x}} = \hat{\mathbf{r}}\sin\theta\cos\phi + \hat{\boldsymbol{\theta}}\cos\theta\cos\phi - \hat{\boldsymbol{\phi}}\sin\phi$$
$$\hat{\mathbf{y}} = \hat{\mathbf{r}}\sin\theta\sin\phi + \hat{\boldsymbol{\theta}}\cos\theta\sin\phi + \hat{\boldsymbol{\phi}}\cos\phi$$
$$\hat{\mathbf{z}} = \hat{\mathbf{r}}\cos\theta - \hat{\boldsymbol{\theta}}\sin\theta$$

For example, to express the spherical components A_θ, A_ϕ in terms of the cartesian components, we proceed as follows:

$$A_\theta = \hat{\boldsymbol{\theta}}\cdot\mathbf{A} = \hat{\boldsymbol{\theta}}\cdot(\hat{\mathbf{x}}A_x + \hat{\mathbf{y}}A_y + \hat{\mathbf{z}}A_z) = (\hat{\boldsymbol{\theta}}\cdot\hat{\mathbf{x}})A_x + (\hat{\boldsymbol{\theta}}\cdot\hat{\mathbf{y}})A_y + (\hat{\boldsymbol{\theta}}\cdot\hat{\mathbf{z}})A_z$$

$$A_\phi = \hat{\boldsymbol{\phi}}\cdot\mathbf{A} = \hat{\boldsymbol{\phi}}\cdot(\hat{\mathbf{x}}A_x + \hat{\mathbf{y}}A_y + \hat{\mathbf{z}}A_z) = (\hat{\boldsymbol{\phi}}\cdot\hat{\mathbf{x}})A_x + (\hat{\boldsymbol{\phi}}\cdot\hat{\mathbf{y}})A_y + (\hat{\boldsymbol{\phi}}\cdot\hat{\mathbf{z}})A_z$$

The dot products can be read off

resulting in:

$$A_\theta = \cos\phi\cos\theta A_x + \sin\phi\cos\theta A_y - \sin\theta A_z$$
$$A_\phi = -\sin\phi A_x + \cos\phi A_y$$

RADIATED FIELDS FOR THE INFINITESIMAL DIPOLE (II)

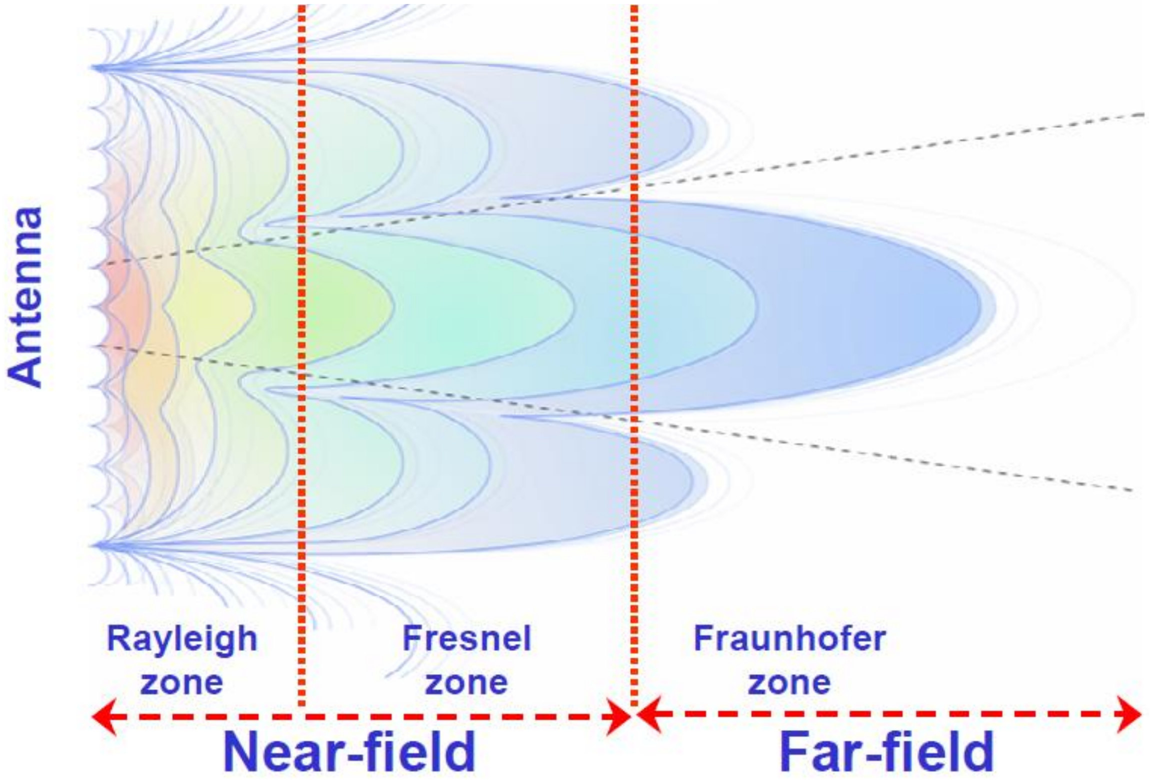
$$E_r = \eta \frac{I_o l \cos\theta}{2\pi r^2}\left[1+\frac{1}{jkr}\right]e^{-jkr}$$

$$E_\theta = j\eta \frac{k I_o l \sin\theta}{4\pi r}\left[1+\frac{1}{jkr}-\frac{1}{(kr)^2}\right]e^{-jkr}$$

$$E_\phi = 0$$

$$H_r = H_\theta = 0$$

$$H_\phi = j\frac{k I_o l \sin\theta}{4\pi r}\left[1+\frac{1}{jkr}\right]e^{-jkr}$$



RADIATED FIELDS FOR THE INFINITESIMAL DIPOLE (III)

$$r << \lambda$$

We could neglect the terms depending of $\frac{r}{\lambda}$

$$E_r = -j\eta \frac{I_o l \cos\theta e^{-jkr}}{2\pi k r^3}$$

$$E_\theta = -j\eta \frac{I_o l e^{-jkr} \sin\theta}{4\pi k r^3}$$

$$E_\phi = 0$$

Near Field

$$H_r = H_\theta = 0$$

$$H_\phi = \frac{I_o l e^{-jkr} \sin\theta}{4\pi r^2}$$

If $r >> \lambda$ the predominant terms are $\frac{1}{r}$ (The other terms can be neglected)

$$E_r = 0$$

$$E_\theta = j\eta \frac{k I_o l \sin\theta e^{-jkr}}{4\pi r}$$

$$E_\phi = 0$$

Far Field zone

$$H_r = 0$$

$$H_\theta = 0$$

$$H_\phi = j \frac{k I_o l \sin\theta e^{-jkr}}{4\pi r}$$

Main remarks

In the Far-Field

- The **E** and **H** field component **are perpendicular** to each other and **transverse to the** radial **direction of propagation**
- The **E** and **H** field component are in **time phase**
- The E and H field component are both varying **inversely with the distance** to the dipole
- The **spherical wave** can be <u>locally</u> considered as a **plane wave**

with $$\vec{H} = \frac{\hat{r} \times \vec{E}}{\eta}$$ in practice we can assume $$\frac{E_\theta}{H_\phi} \approx \eta$$

We can compute the Poynting vector for this field…

$$\vec{W}_{av} = \frac{1}{2} Re(\vec{E} \times \vec{H}^*) = \hat{r} \frac{1}{2\eta} |E_\theta|^2 = \hat{r} \frac{\eta}{2} \left| \frac{k I_o l}{4\pi} \right|^2 \frac{\sin^2 \theta}{r^2}$$

We obtain the real power radiated by the dipole

- Infinitesimal Dipole (short dipole)
- How we can represented the radiated power?
  - It's a function of spatial variables (θ,ϕ)
  - 3D or 2D plots in specific planes
  - No energy is radiated by the dipole along the direction of the dipole axis
  - Maximum radiation occurs in θ=90º (broadside direction)