Corso di Laurea in Ingegneria Informatica, Biomedica e delle Telecomunicazioni

Corso di Campi Elettromagnetici
a.a. 2017-2018

17 Maggio 2018

Extended Antennas

Extended antennas

$J(r)$

$$\nabla^2 \boldsymbol{A} + k^2 \boldsymbol{A} = -\mu \boldsymbol{J}$$ Vector Helmholtz equation

$$\mathbf{A}(\mathbf{r}) = \frac{\mu}{4\pi} \int \mathbf{J}(\mathbf{r}') \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}'$$

$$\boldsymbol{H} = \frac{1}{\mu} \nabla \times \boldsymbol{A} \quad \text{and} \quad \boldsymbol{E} = -j\omega \boldsymbol{A} + \frac{\nabla\nabla \cdot \boldsymbol{A}}{j\omega\varepsilon\mu}$$

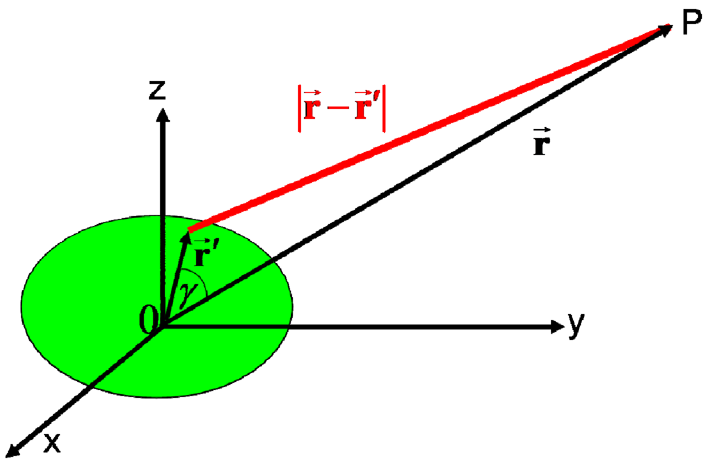
$E(r)$

$H(r)$

Is it possible to simplify the expressions of the fields, possibly via proper approximation of the vector potential ***A***?

Extended antennas

$$\mathbf{A}(\vec{\mathbf{r}}) = \frac{\mu}{4\pi} \int \mathbf{J}(\vec{\mathbf{r}}') \frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} d\vec{\mathbf{r}}' \qquad |\vec{\mathbf{r}}-\vec{\mathbf{r}}'| = r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + ...$$



$$\frac{1}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = \frac{1}{r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma \cdots}$$

$$e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = e^{-j\beta r} e^{j\beta r'\cos\gamma} e^{-j\beta\frac{(r')^2}{2r}\sin^2\gamma} \cdots$$

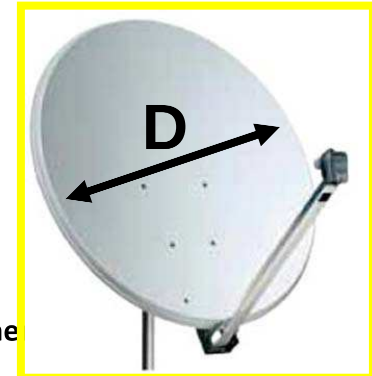
Extended antennas

$$\mathbf{A}(\vec{\mathbf{r}}) = \frac{\mu}{4\pi}\int \mathbf{J}(\vec{\mathbf{r}}')\frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}d\,\vec{\mathbf{r}}'$$

$$|\vec{\mathbf{r}}-\vec{\mathbf{r}}'| = r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots$$

$$\frac{1}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = \frac{1}{r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots} \approx \frac{1}{r} \quad \text{if} \quad r' << r$$

$$e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = e^{-j\beta r}e^{j\beta r'\cos\gamma}e^{-j\beta\frac{(r')^2}{2r}\sin^2\gamma}\cdots \approx e^{-j\beta r} \quad \text{if} \quad r' << \lambda$$



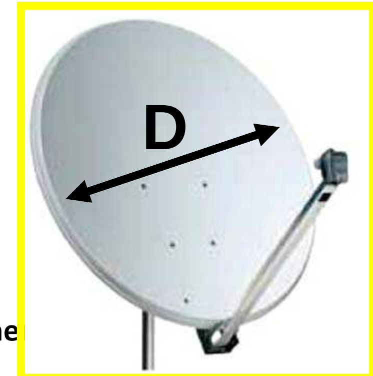
Extended antennas

$$\mathbf{A}(\vec{\mathbf{r}}) = \frac{\mu}{4\pi}\int \mathbf{J}(\vec{\mathbf{r}}')\frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}d\vec{\mathbf{r}}'$$

$$|\vec{\mathbf{r}}-\vec{\mathbf{r}}'| = r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots$$

$$\frac{1}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = \frac{1}{r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots} \approx \frac{1}{r} \quad \textit{if} \quad D << r$$

$$e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = e^{-j\beta r}e^{j\beta r'\cos\gamma}e^{-j\beta\frac{(r')^2}{2r}\sin^2\gamma}\cdots \approx e^{-j\beta r} \quad \textit{if} \quad D << \lambda$$



Extended antennas

$$\mathbf{A}(\vec{\mathbf{r}}) = \frac{\mu}{4\pi}\int \mathbf{J}(\vec{\mathbf{r}}') \frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} d\vec{\mathbf{r}}'$$

$$|\vec{\mathbf{r}}-\vec{\mathbf{r}}'| = r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots$$

$$\frac{1}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = \frac{1}{r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots} \approx \frac{1}{r} \quad \textit{if} \quad D << r$$

$$e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = e^{-j\beta r} e^{j\beta r'\cos\gamma} e^{-j\beta\frac{(r')^2}{2r}\sin^2\gamma} \cdots \approx e^{-j\beta r} \quad \textit{if} \quad D << \lambda$$

When the antennas are **small** with respect to the wavelength **and** to the distance from the observation point

$$\frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} \approx \frac{e^{-j\beta r}}{r} \quad \Rightarrow \quad \mathbf{A}(\vec{\mathbf{r}}) \approx \frac{\mu}{4\pi}\frac{e^{-j\beta r}}{r}\int \mathbf{J}(\vec{\mathbf{r}}') d\vec{\mathbf{r}}'$$

Extended antennas

$$\mathbf{A}(\vec{\mathbf{r}}) = \frac{\mu}{4\pi}\int \mathbf{J}(\vec{\mathbf{r}}')\frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}d\,\vec{\mathbf{r}}'$$

$$|\vec{\mathbf{r}}-\vec{\mathbf{r}}'| = r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots$$

$$\frac{1}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = \frac{1}{r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots} \approx \frac{1}{r} \quad \text{if} \quad D \ll r$$

$$e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = e^{-j\beta r}e^{j\beta r'\cos\gamma}e^{-j\beta\frac{(r')^2}{2r}\sin^2\gamma}\cdots \approx e^{-j\beta r}e^{j\beta\vec{\mathbf{r}}'\cdot\hat{\mathrm{i}}_r} \quad \text{if} \quad r > \frac{2D^2}{\lambda}$$

For <u>**all**</u> the antennas, if the distance from the observation point **is sufficiently large**

$$\frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} \approx \frac{e^{-j\beta r}e^{j\beta\vec{\mathbf{r}}'\cdot\hat{\mathrm{i}}_r}}{r} \quad \Rightarrow \quad \mathbf{A}(\vec{\mathbf{r}}) \approx \frac{\mu}{4\pi}\frac{e^{-j\beta r}}{r}\int \mathbf{J}(\vec{\mathbf{r}}')e^{j\beta\vec{\mathbf{r}}'\cdot\hat{\mathrm{i}}_r}d\,\vec{\mathbf{r}}'$$

Extended antennas

$$r >> D$$

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

- $\int \mathbf{J}(\vec{\mathbf{r}}')e^{j\beta\vec{\mathbf{r}}'\cdot\hat{i}_r}d\,\vec{\mathbf{r}}' = \mathbf{M}(\vartheta,\varphi)$

$$\Downarrow$$

$$\mathbf{A}(\vec{\mathbf{r}}) \approx \frac{\mu}{4\pi}\frac{e^{-j\beta r}}{r}\mathbf{M}(\vartheta,\varphi)$$

For **all** the antennas, if the distance from the observation point **is sufficiently large**

$$\frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} \approx \frac{e^{-j\beta r}e^{j\beta\vec{\mathbf{r}}'\cdot\hat{i}_r}}{r} \Rightarrow \mathbf{A}(\vec{\mathbf{r}}) \approx \frac{\mu}{4\pi}\frac{e^{-j\beta r}}{r}\int \mathbf{J}(\vec{\mathbf{r}}')e^{j\beta\vec{\mathbf{r}}'\cdot\hat{i}_r}d\,\vec{\mathbf{r}}'$$

Extended antennas

$$r >> D$$

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

$$r >> \lambda$$

Fraunhofer region

$$\mathbf{M}(\vartheta,\varphi) = \int \mathbf{J}(\vec{\mathbf{r}}')\, e^{j\beta\vec{\mathbf{r}}'\cdot\hat{\mathrm{i}}_r}\, d\,\vec{\mathbf{r}}'$$

$$\mathbf{A}(\vec{\mathbf{r}}) \approx \frac{\mu}{4\pi}\frac{e^{-j\beta r}}{r}\mathbf{M}(\vartheta,\varphi)$$

$$\Rightarrow \begin{cases} \nabla\nabla\cdot\mathbf{A}(\vec{\mathbf{r}}) \approx -\beta^2 A_r(\vec{\mathbf{r}})\,\hat{i}_r \\ \nabla\times\mathbf{A}(\vec{\mathbf{r}}) \approx -j\beta\,\hat{i}_r \times \mathbf{A}(\vec{\mathbf{r}}) \end{cases}$$

Radiation problem for extended antennas

$\downarrow$ $\boldsymbol{J}(\boldsymbol{r})$

$$\nabla^2 \boldsymbol{A} + k^2 \boldsymbol{A} = -\mu \boldsymbol{J}$$ **Vector Helmholtz equation**

$$\mathbf{A}(\mathbf{r}) = \frac{\mu}{4\pi} \int \mathbf{J}(\vec{\mathbf{r}}') \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} d\vec{\mathbf{r}}'$$

$$\mathbf{A}(\mathbf{r}) \approx \frac{\mu}{4\pi} \frac{e^{-j\beta r}}{r} \int \mathbf{J}(\vec{\mathbf{r}}') e^{j\beta \vec{\mathbf{r}}' \cdot \hat{i}_r} d\vec{\mathbf{r}}'$$

$$\boldsymbol{H} = \frac{1}{\mu} \nabla \times \boldsymbol{A} \quad \text{and} \quad \boldsymbol{E} = -j\omega \boldsymbol{A} + \frac{\nabla\nabla \cdot \boldsymbol{A}}{j\omega\varepsilon\mu}$$

$$-j\beta \hat{i}_r \times \mathbf{A}$$

$\downarrow$ $\boldsymbol{E}(\boldsymbol{r})$, $\boldsymbol{H}(\boldsymbol{r})$

$$-\beta^2 A_r \hat{i}_r$$

$$\nabla\nabla\cdot\mathbf{A}(\vec{\mathbf{r}})\approx-\beta^2 A_r(\vec{\mathbf{r}})\hat{i}_r$$

⬇

$$\mathbf{E}=-j\omega\mathbf{A}+\frac{\nabla\nabla\cdot\mathbf{A}}{j\omega\varepsilon\mu}\approx-j\omega\mathbf{A}-\frac{\beta^2 A_r\hat{i}_r}{j\omega\varepsilon\mu}=-j\omega\mathbf{A}+j\omega A_r\hat{i}_r=-j\omega\left[\mathbf{A}-A_r\hat{i}_r\right]$$

$$\boldsymbol{H}=\frac{1}{\mu}\nabla\times\boldsymbol{A}\quad\text{and}\quad\boldsymbol{E}=-j\omega\boldsymbol{A}+\frac{\nabla\nabla\cdot\boldsymbol{A}}{j\omega\varepsilon\mu}$$

$$\nabla\nabla\cdot\mathbf{A}(\vec{\mathbf{r}})\approx-\beta^2 A_r(\vec{\mathbf{r}})\hat{i}_r$$

$$\nabla\times\mathbf{A}(\vec{\mathbf{r}})\approx-j\beta\,\hat{i}_r\times\mathbf{A}(\vec{\mathbf{r}})$$

$$\mathbf{E}(\vec{\mathbf{r}}) = -j\omega\left[\mathbf{A}(\vec{\mathbf{r}}) - A_r(\vec{\mathbf{r}})\hat{i}_r\right]$$

$$\nabla\nabla\cdot\mathbf{A}(\vec{\mathbf{r}}) \approx -\beta^2 A_r(\vec{\mathbf{r}})\hat{i}_r$$

$$\Downarrow$$

$$\mathbf{E} = -j\omega\mathbf{A} + \frac{\nabla\nabla\cdot\mathbf{A}}{j\omega\varepsilon\mu} \approx -j\omega\mathbf{A} - \frac{\beta^2 A_r\hat{i}_r}{j\omega\varepsilon\mu} = -j\omega\mathbf{A} + j\omega A_r\hat{i}_r = -j\omega\left[\mathbf{A} - A_r\hat{i}_r\right]$$

$$\boldsymbol{H} = \frac{1}{\mu}\nabla\times\boldsymbol{A} \quad \text{and} \quad \boldsymbol{E} = -j\omega\boldsymbol{A} + \frac{\nabla\nabla\cdot\boldsymbol{A}}{j\omega\varepsilon\mu}$$

$$\nabla\nabla\cdot\mathbf{A}(\vec{\mathbf{r}}) \approx -\beta^2 A_r(\vec{\mathbf{r}})\hat{i}_r$$

$$\nabla\times\mathbf{A}(\vec{\mathbf{r}}) \approx -j\beta\,\hat{i}_r\times\mathbf{A}(\vec{\mathbf{r}})$$

$$\mathbf{E}(\vec{\mathbf{r}}) = -j\omega\left[\mathbf{A}(\vec{\mathbf{r}}) - A_r(\vec{\mathbf{r}})\hat{i}_r\right]$$

$$\nabla\times\mathbf{A}(\vec{\mathbf{r}}) \approx -j\beta\hat{i}_r\times\mathbf{A}(\vec{\mathbf{r}})$$

$$\Downarrow$$

$$\zeta\mathbf{H} = \frac{\zeta}{\mu}\nabla\times\mathbf{A} \approx \frac{\zeta}{\mu}(-j\beta)\hat{i}_r\times\mathbf{A} = \frac{\zeta\sqrt{\mu}\sqrt{\varepsilon}}{\mu}\hat{i}_r\times[-j\omega\mathbf{A}] =$$

$$= \hat{i}_r\times[-j\omega\mathbf{A}] = \hat{i}_r\times\left[-j\omega\left(\mathbf{A} - A_r\hat{i}_r\right)\right] = \hat{i}_r\times\mathbf{E}$$

$$\boldsymbol{H} = \frac{1}{\mu}\nabla\times\boldsymbol{A} \quad \text{and} \quad \boldsymbol{E} = -j\omega\boldsymbol{A} + \frac{\nabla\nabla\cdot\boldsymbol{A}}{j\omega\varepsilon\mu}$$

$$\nabla\nabla\cdot\mathbf{A}(\vec{\mathbf{r}}) \approx -\beta^2 A_r(\vec{\mathbf{r}})\hat{i}_r$$

$$\nabla\times\mathbf{A}(\vec{\mathbf{r}}) \approx -j\beta\hat{i}_r\times\mathbf{A}(\vec{\mathbf{r}})$$

$$\mathbf{E}(\vec{\mathbf{r}}) = -j\omega\left[\mathbf{A}(\vec{\mathbf{r}}) - A_r(\vec{\mathbf{r}})\hat{i}_r\right]$$

$$\zeta\mathbf{H}(\vec{\mathbf{r}}) = \hat{i}_r \times \mathbf{E}(\vec{\mathbf{r}})$$

$$\nabla \times \mathbf{A}(\vec{\mathbf{r}}) \approx -j\beta\hat{i}_r \times \mathbf{A}(\vec{\mathbf{r}})$$

$$\zeta\mathbf{H} = \frac{\zeta}{\mu}\nabla \times \mathbf{A} \approx \frac{\zeta}{\mu}(-j\beta)\hat{i}_r \times \mathbf{A} = \frac{\zeta\sqrt{\mu}\sqrt{\varepsilon}}{\mu}\hat{i}_r \times [-j\omega\mathbf{A}] =$$

$$= \hat{i}_r \times [-j\omega\mathbf{A}] = \hat{i}_r \times \left[-j\omega\left(\mathbf{A} - A_r\hat{i}_r\right)\right] = \hat{i}_r \times \mathbf{E}$$

$$\boldsymbol{H} = \frac{1}{\mu}\nabla \times \boldsymbol{A} \quad \text{and} \quad \boldsymbol{E} = -j\omega\boldsymbol{A} + \frac{\nabla\nabla \cdot \boldsymbol{A}}{j\omega\varepsilon\mu}$$

$$\nabla\nabla \cdot \mathbf{A}(\vec{\mathbf{r}}) \approx -\beta^2 A_r(\vec{\mathbf{r}})\hat{i}_r$$

$$\nabla \times \mathbf{A}(\vec{\mathbf{r}}) \approx -j\beta\hat{i}_r \times \mathbf{A}(\vec{\mathbf{r}})$$

Extended antennas

$$r >> D$$

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

$$r >> \lambda$$

Fraunhofer region

$$\mathbf{M}(\vartheta,\varphi) = \int \mathbf{J}(\vec{\mathbf{r}}') e^{j\beta \vec{\mathbf{r}}' \cdot \hat{i}_r} d\vec{\mathbf{r}}'$$

$$\mathbf{A}(\vec{\mathbf{r}}) \approx \frac{\mu}{4\pi} \frac{e^{-j\beta r}}{r} \mathbf{M}(\vartheta,\varphi)$$

$$\begin{cases} \nabla\nabla \cdot \mathbf{A}(\vec{\mathbf{r}}) \approx -\beta^2 A_r(\vec{\mathbf{r}}) \hat{i}_r \\ \nabla \times \mathbf{A}(\vec{\mathbf{r}}) \approx -j\beta \hat{i}_r \times \mathbf{A}(\vec{\mathbf{r}}) \end{cases}$$

$$\begin{cases} \mathbf{E}(\vec{\mathbf{r}}) = -j\omega\left[\mathbf{A}(\vec{\mathbf{r}}) - A_r(\vec{\mathbf{r}}) \hat{i}_r\right] = \frac{-j\omega\mu}{4\pi} \frac{e^{-j\beta r}}{r} \left[\mathbf{M}(\vartheta,\varphi) - M_r(\vartheta,\varphi) \hat{i}_r\right] \\ \zeta \mathbf{H}(\vec{\mathbf{r}}) = \hat{i}_r \times \mathbf{E}(\vec{\mathbf{r}}) \end{cases}$$

Extended antennas & Fraunhofer region

$r >> D$

$r > \dfrac{2D^2}{\lambda}$

$r >> \lambda$

Fraunhofer region

- the e.m. field propagates along $\hat{i}_r$
- the e.m. field lies on the plane orthogonal to the propagation direction
- |E| and |H| exhibit the decaying factor 1/r
- |E| and |H| are proportional through ζ

$$\begin{cases} \mathbf{E}(\vec{\mathbf{r}}) = -j\omega\left[\mathbf{A}(\vec{\mathbf{r}}) - A_r(\vec{\mathbf{r}})\hat{i}_r\right] = \dfrac{-j\omega\mu}{4\pi}\dfrac{e^{-j\beta r}}{r}\left[\mathbf{M}(\vartheta,\varphi) - M_r(\vartheta,\varphi)\hat{i}_r\right] \\ \zeta\mathbf{H}(\vec{\mathbf{r}}) = \hat{i}_r \times \mathbf{E}(\vec{\mathbf{r}}) \end{cases}$$

Field regions

- *Far-field (Fraunhofer) region* is defined as "that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. If the antenna has a maximum overall dimension D (D>λ), the far-field region is commonly taken to exist at distances greater than $2D^2/\lambda$ from the antenna, λ being the wavelength".
- In this region, the field components are essentially transverse

Fraunhofer region

$$r >> D$$

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

$$r >> \lambda$$

$$\begin{cases} \mathbf{E}(\vec{\mathbf{r}}) = \dfrac{-j\omega\mu}{4\pi} \dfrac{e^{-j\beta r}}{r} \left[\mathbf{M}(\vartheta,\varphi) - M_r(\vartheta,\varphi)\hat{i}_r \right] \\ \zeta \mathbf{H}(\vec{\mathbf{r}}) = \hat{i}_r \times \mathbf{E}(\vec{\mathbf{r}}) \end{cases}$$

I) $$\mathbf{S} = \frac{1}{2\zeta} |\mathbf{E}|^2 \hat{i}_r$$

II) $$\mathbf{E}(\vec{\mathbf{r}}) = \mathbf{E}(r,\vartheta,\varphi) = \frac{j\zeta I}{2\lambda} \frac{e^{-j\beta r}}{r} \mathbf{l}(\vartheta,\varphi)$$

where

I is the input current at the antenna input terminals

$\mathbf{l}(\vartheta,\varphi) = l_\vartheta(\vartheta,\varphi)\hat{i}_\vartheta + l_\varphi(\vartheta,\varphi)\hat{i}_\varphi$ is said ***effective length*** of the antenna

Field regions

$$\mathbf{A}(\vec{\mathbf{r}}) = \frac{\mu}{4\pi}\int \mathbf{J}(\vec{\mathbf{r}}')\frac{e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|}d\vec{\mathbf{r}}'$$

$$|\vec{\mathbf{r}}-\vec{\mathbf{r}}'| = r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots$$

$$\frac{1}{|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = \frac{1}{r - r'\cos\gamma + \frac{(r')^2}{2r}\sin^2\gamma + \cdots} \approx \frac{1}{r}$$

$if \quad D << r$

$$e^{-j\beta|\vec{\mathbf{r}}-\vec{\mathbf{r}}'|} = e^{-j\beta r}e^{j\beta r'\cos\gamma}e^{-j\beta\frac{(r')^2}{2r}\sin^2\gamma}e^{-j\beta\frac{(r')^3}{2r^2}\cos\gamma\sin^2\gamma}\cdots$$

$$\approx e^{-j\beta r}e^{j\beta\vec{\mathbf{r}}'\cdot\hat{i}_r}e^{-j\beta\frac{(r')^2}{2r}\sin^2\gamma}$$

$if \quad r > 0.62\sqrt{\frac{D^3}{\lambda}}$

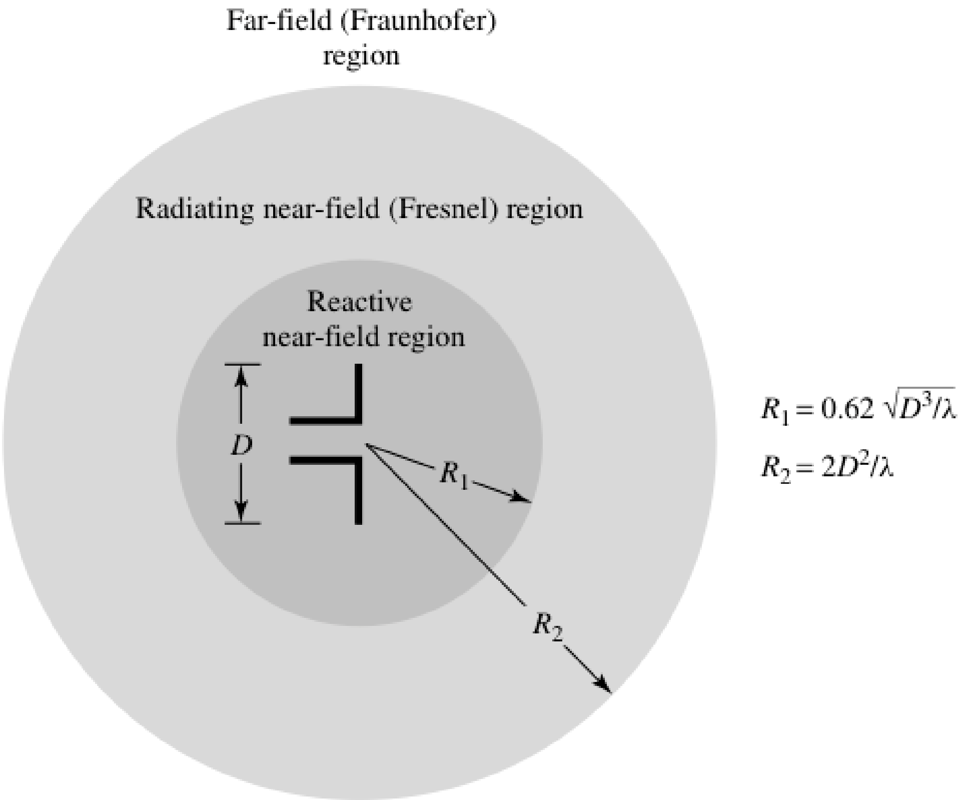
Fresnel region

Fresnel region

- *Radiating near-field (Fresnel) region* is defined as "that region of the field of an antenna between the reactive near-field region and the far-field region."
- The inner boundary is taken to be the distance $R \geq 0.62\ \mathrm{sqrt}(D^3/\lambda)$ and the outer boundary the distance $R < 2D^2/\lambda$ where D is the largest dimension of the antenna. (D is meant to be greater then λ)

Field regions

The space surrounding an antenna is usually subdivided into three regions: (a) reactive near-field, (b) radiating near-field (*Fresnel*) and (c) far-field (*Fraunhofer*) regions as shown in Figure.



Field regions of an antenna.