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微波工程講義

Microwave Engineering Notes

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國立臺灣大學電機工程學系

中華民國90年2月

Microwave Engineering

1. Class: Fri. 9:10-12:00 am, Room 225
2. Textbook: Principles of Microwave Technology, S.C. Harsany, Prentice Hall, 1997, (全華代理)
3. Scopes: microwave basics, principles of passive and active microwave components, microwave measurements and microwave communication applications.
4. Contents:

   Ch.1 Electromagnetic fundamentals

   Ch.2 Transmission fundamentals

   Ch.3 Smith chart analysis

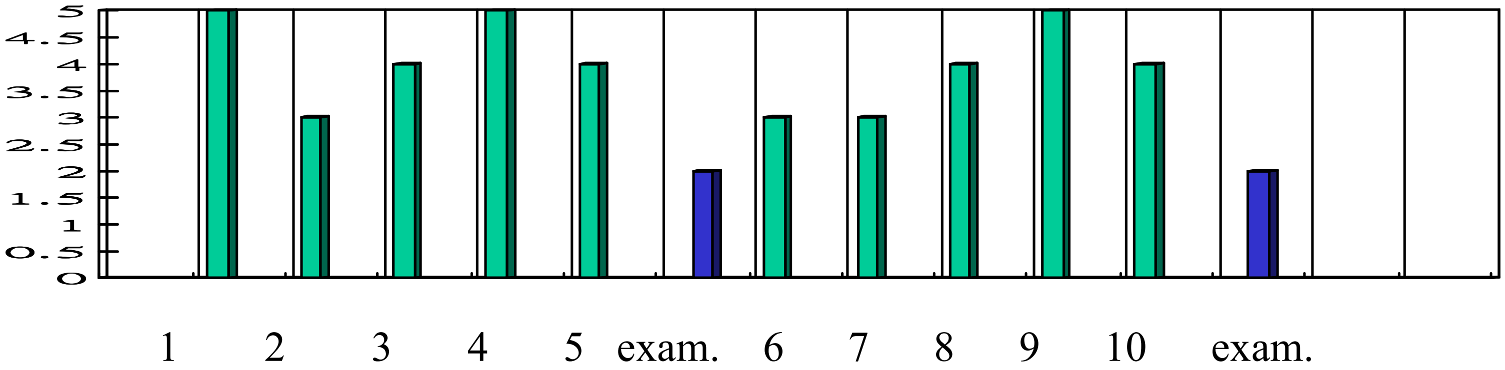
   Ch.4 Microwave transmission lines

   Ch.5 Passive microwave components

   Ch.6 Active microwave devices (thermionic)

Ch.7 Active microwave devices (solid-state)
Ch.8 Antennas
Ch.9 Microwave measurements
Ch.10 Microwave communication applications

5. Estimated time table: 45 hours



6. Grades: Homework 20%, Midterm exam. (Ch.1-Ch.5) 40%
Final exam. (Ch.6-Ch.10) 40%

7. Office hour: Mon. 2:00-3:00, room 541

8. Reference books:

(1) Foundations for Microwave Engineering, R.E. Collin, John Wiley &Sons, 1992.

(2) Microwave Engineering, D.M. Pozar, John Wiley &Sons, 1998.

(3) Microwave Engineering, T.K. Ishii, Harcourt Brace Jovanovich, 1989.

(4) Microwave Engineering passive circuits, P.A. Rizzi, Printice-Hall, 1988.

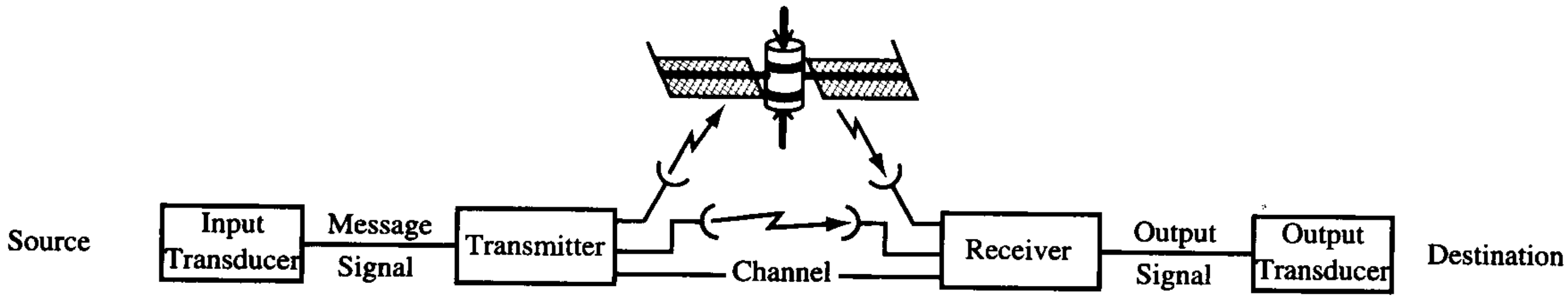
9. Notes are available at http://cc.ee.ntu.edu.tw/~thc or under the web of EE/faculty/Tah-Hsiung Chu/more

Chapter 1 Electromagnetic fundamentals

1.1 Introduction
   microwave applications, microwave history
1.2 Units and physical constants
1.3 What are microwave?
   definition, spectrum, frequency bands
1.4 Microwave technology
   unique characteristics
1.5 Velocity, frequency and wavelength
   definition, relations
1.6 The electromagnetic wave
   Maxwell's equation, antenna characteristics, TEM wave, polarization
1.7 Propagation
   inverse square law
1.8 Propagation paths
   ground wave, sky wave, space wave, line-of-sight, atmospheric effects

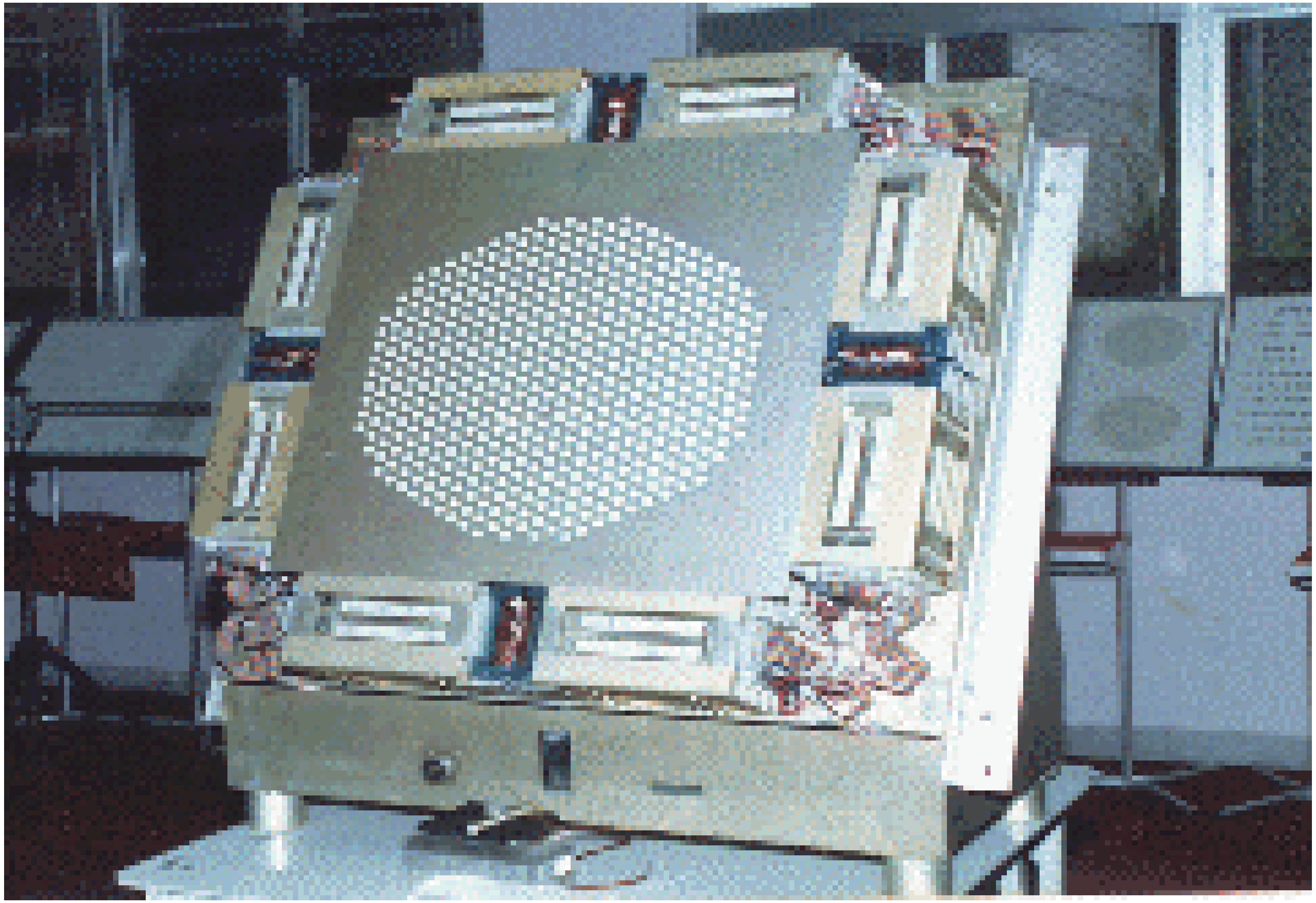
1.1 Introduction

1. Microwave applications: communication, radar, medical, remote sensing, heating, radio astronomy, industrial quality control, navigation (GPS), power transmission,….
2. Typical communication system (not restricted to microwaves)



Voice	Microphone	AM Commercial	Cable	AM Radio	Speaker	Ear
Tape	Tape Deck	FM Commercial	Wires	FM Radio	Telephone	Eye
Record	Telephone	SSB Military	Space	SSB Radio	TV Screen	Computer
Video	Camera	Radar	Optical Fiber	Radar	Modem	Next System
Computer	Modem	Laser Diode	Waveguide	Photo Transistor		
Telex	Electrodes	Light-Emitting Diode	Ionosphere	Diode		
Medical		Antennas	Ocean	Antennas		
Dispatcher		Mobile Radio		Mobile Radio		

3. Radar application (phased array)



4. Medical application (hyperthermia)

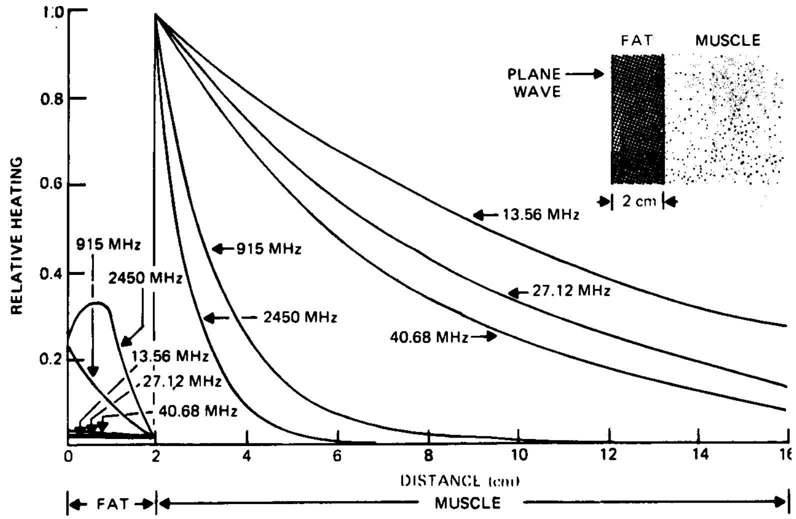


Fig. 1 Calculated relative heating in fat and muscle as a function of distance for five different ISM frequencies.

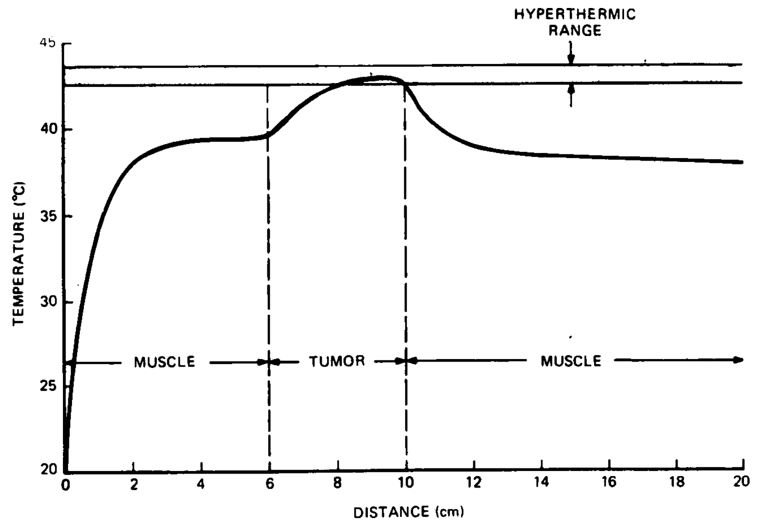
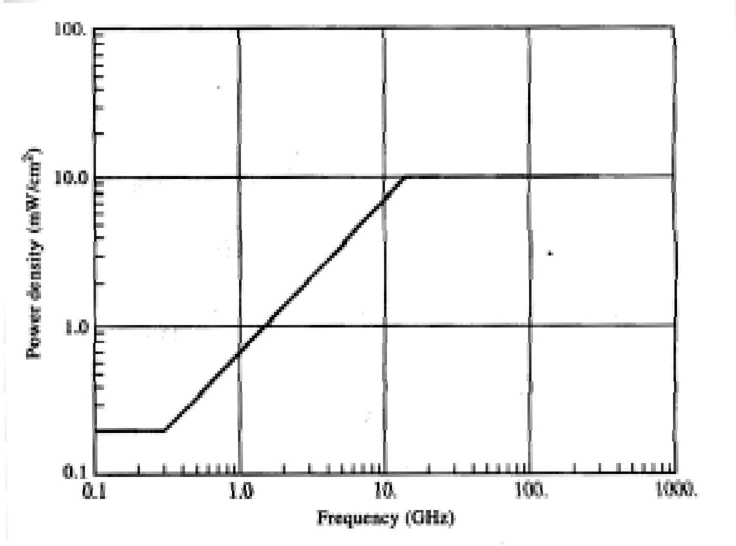


Fig. 10 Calculated temperature distribution in a layered one-dimensional structure of muscle-tumor-muscle when heated with RF power at a power density of 0.25 W/cm² at 17 MHz and the surface of the muscle is maintained at 20°C by active cooling. [λ (muscle) = 1. λ (muscle) = 1. λ (tumor) = 0.325 cm⁻².]

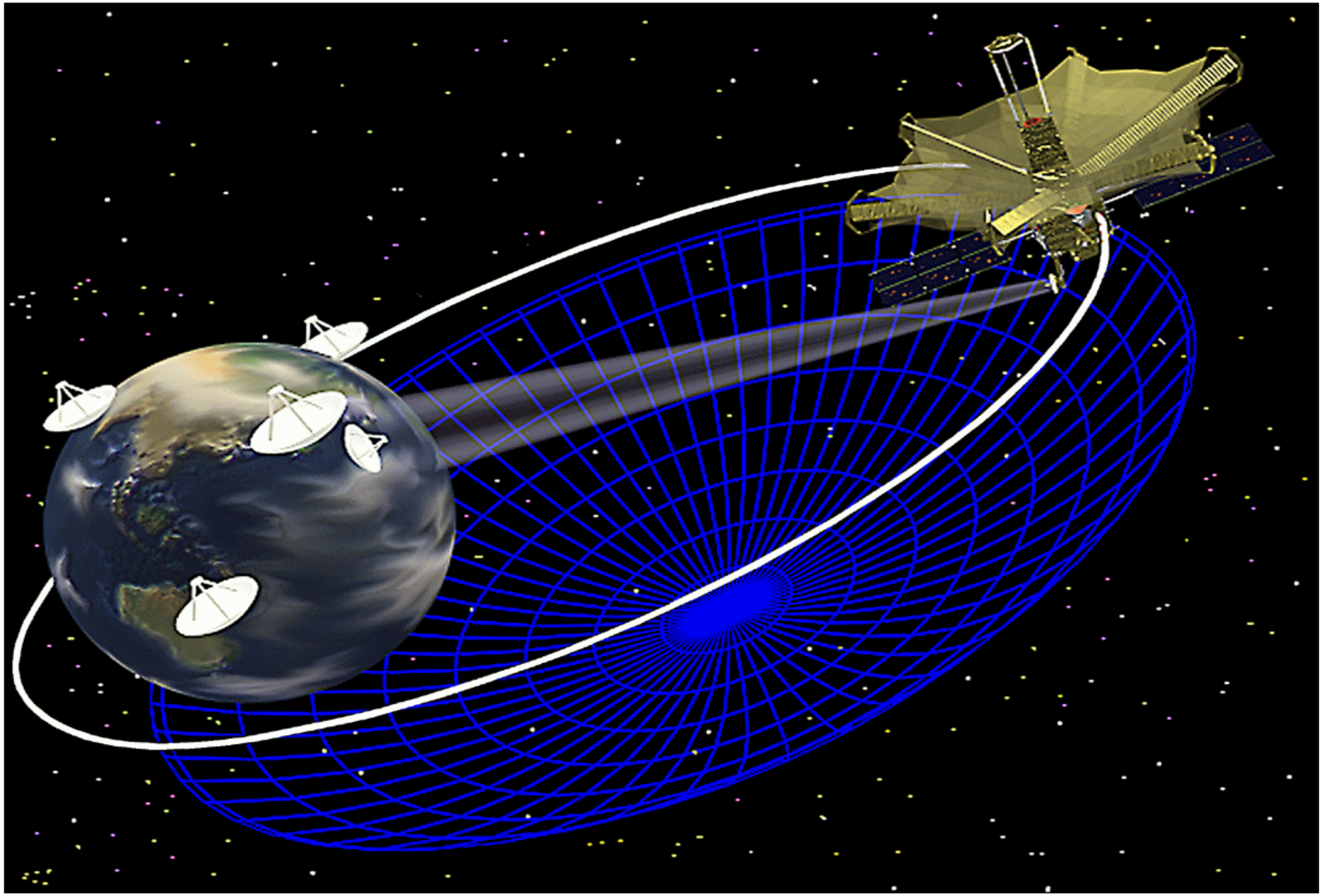


IEEE Standard C95.1-1991 recommended power density for human exposure to microwaves

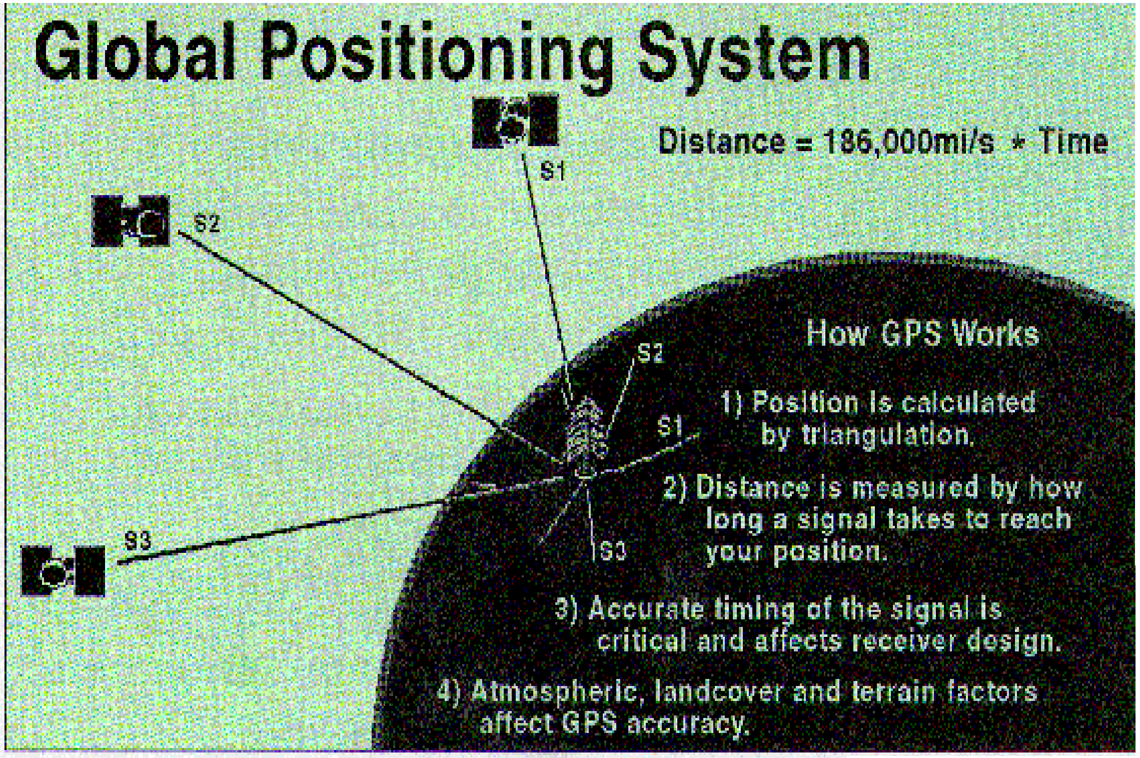
websites: http://www.mcw.edu/gcrc/cop/cell-phone-health-FAQ/toc.html

http://www.mcw.edu/gcrc/cop/powerlines-cancer-FAQ/toc.html

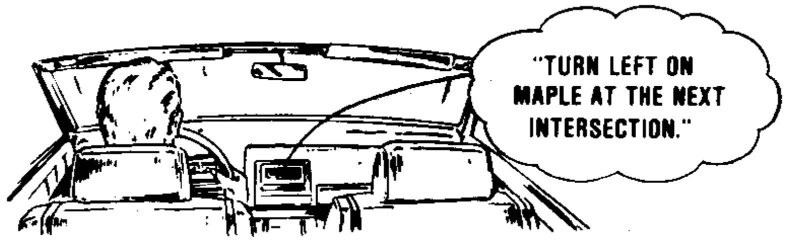
5. Radio astronomy application (interferometer)



6. GPS application (21 satellites)

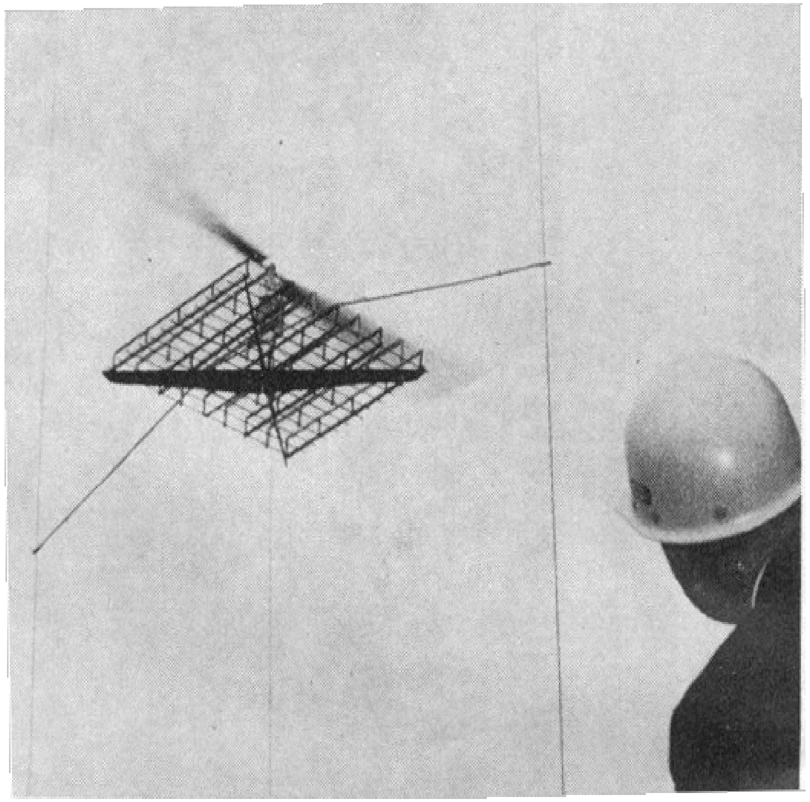


The basic elements of the Global Positioning System

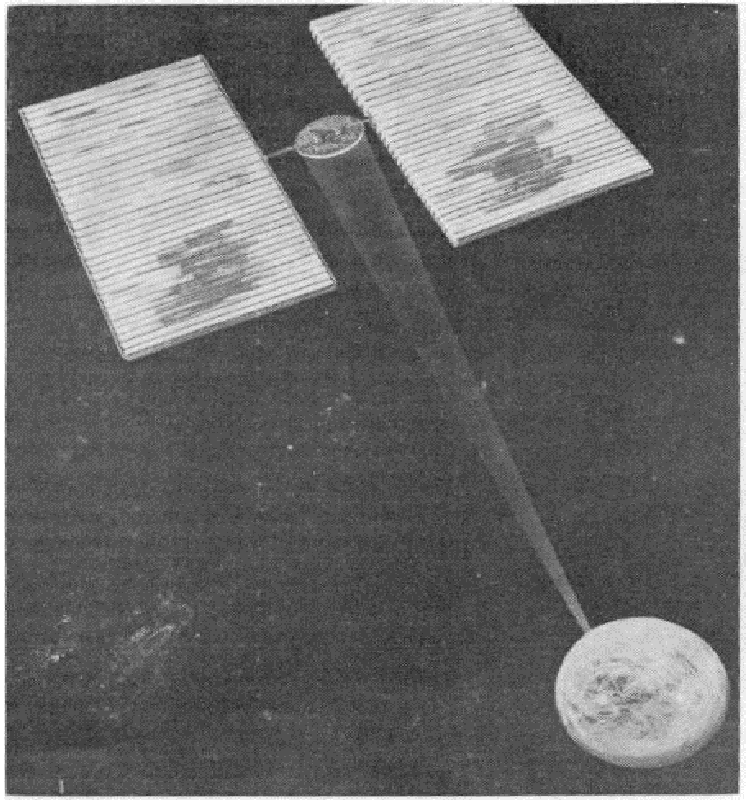


7. Remote sensing application (SIC-C/X-SAR, microwave imaging)

8. Power transmission application



Microwave-powered helicopter



Satellite space power station

9 History of microwaves

(1) 19th century

- Michael Faraday (1791-1867), “Thoughts on ray vibrations,” - 1846, earliest talk on EM wave
- James Clark Maxwell (1831-1879), “Maxwell’s equations,” 1864,
- Heinrich Rudolf Hertz (1857-1894), “electric spark at λ~10cm induces at a distant wire loop,” 1886-1888 - first microwave-like experiment
- Gugliemo Marconi (1874-1937), “wireless telegraphic communication,” 1895

(2) 20th century

- H. Barkhausenand K. Kurz, “BKO vacuum tube for high frequency” 1920
- A. W. Hull, “magnetron”, 1921
- George C. Southworth, “wave propagation in waveguide”, 1930
- Russell Varian, Sigurd Varian and William Hansen, “klystron,” 1937

- MIT Radiation Laboratory, “radar,” World War II-
- coaxial cables for radio communication, 1950s- satellite communication, 1960 -
- remote sensing satellite, DBS (direct broadcast satellite) 1980 -
- PCN/PCS (personal communications network/personal communication services), GPS (global positioning system), VSAT (very small aperture terminals), 1990 -
- Digital DBS, WLL (wireless local loop), GII (global information initiative), using mobile satellite network, fibers, cables and wireless, 2000 -

1.2 Units and physical constants

1. Physical constants

Constant	Value	Symbol
Boltzmann's constant	1.38×10^{-23} J/K	K
Electric charge (e-)	1.6×10^{-19} C	q
Electron (volt)	1.6×10^{-19} J	eV
Electron (mass)	9.12×10^{-31} kg	m
Permeability of free space	$4\pi \times 10^{-7}$ H/m	μ_o
Permittivity of free space	8.85×10^{-12} F/m	ϵ_o
Planck's constant	6.626×10^{-34} J · s	h
Velocity of electromagnetic waves	3.0×10^{8} m/s	c
Pi (π)	3.1416	π

2. Units conversion factors see Table 1.3

1in = 1000mil

1neper = 10log$e$ dB = 8.686dB

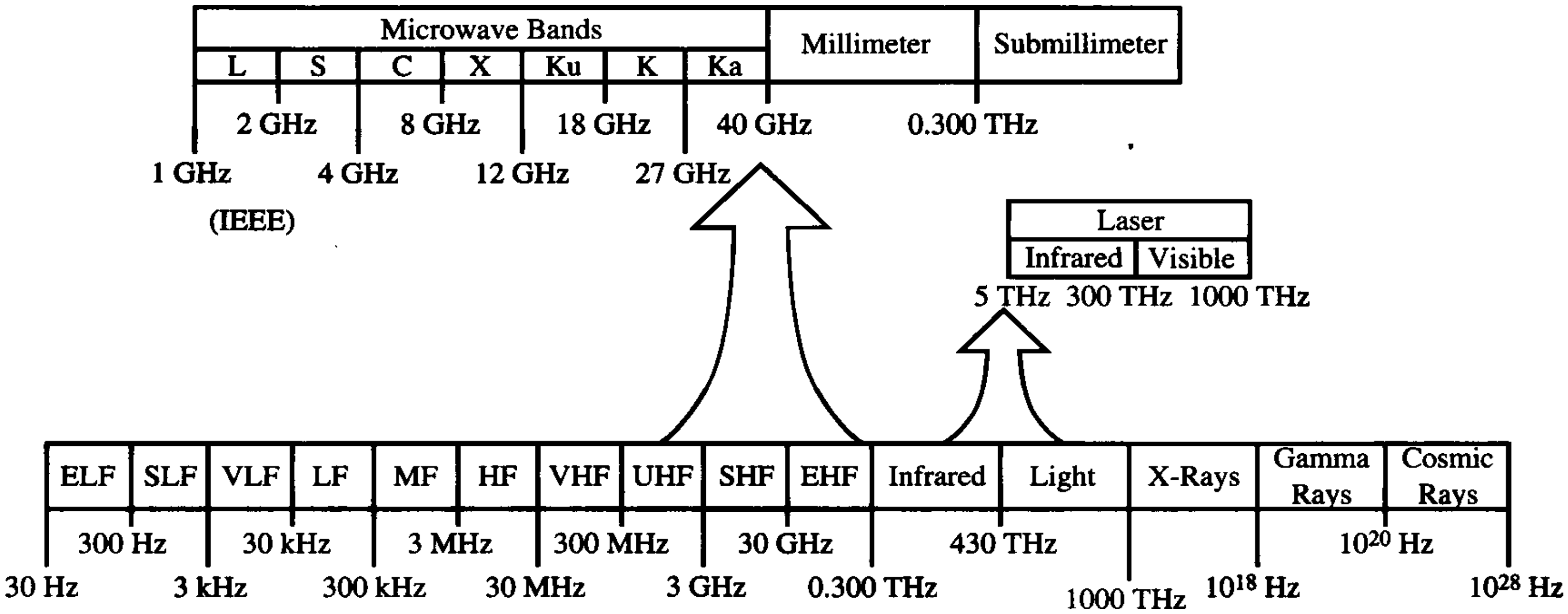
$$dB = 10\log_{10}\frac{P_2}{P_1} = 20\log_{10}\frac{V_2}{V_1}$$

$$20dBm = 10\log_{10}\frac{P}{1mW} \rightarrow P = 100mW$$

$$20dBmV = 20\log_{10}\frac{V}{1mV} \rightarrow V = 10mV$$

1.3 What are microwaves?

1. EM wave spectrum



2. Microwave: designating or of that part of the electromagnetic spectrum between the far infrared and some lower frequency limit: commonly regarded as extending from 300,000 to 300 megahertz. (from Webster's dictionary)

f: 300MHz - 300GHz $\Rightarrow$ λ : 100cm - 0.1cm

3. Microwave frequency bands

Band	Frequency Range, (GHz)
HF	0.003–0.030
VHF	0.030–0.300
UHF	0.300–1.00
L	1.00–2.00
S	2.00–4.00
C	4.00–8.00
X	8.00–12.0
Ku	12.0–18.0
K	18.0–27.0
Ka	27.0–40.0
Millimeter	40.0–300.0
Submillimeter	greater than 300

4. f ↗ ⇨ available bandwidth ↗

e.g., audio BW=10KHz

1% BW of AM radio @1MHz gives 1channel

1% BW of X-band satellite communication @10GHz gives 10000 channels

1.4 Microwave technology

Unique characteristics

1. wavelength ≈ circuit size

   ⇒ phase shift in signal, $\Delta\theta = \beta\Delta l = \dfrac{2\pi\Delta l}{\lambda}$

   ⇒ (1) incident wave reflected from an impedance mismatch

   → standing wave → not optimal for energy transfer

   ⇒ (2) mesurement difficulty

2. component lead effect becomes important

   ⇒ use distributed L, C i.e., equivalent transmission lines

   e.g. resonator @ 10GHz ⇒ L<1nH, C<1pF

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.5\times10^{-9}\times0.5\times10^{-12}}} \approx 10\,GHz \ \rightarrow \lambda = 3cm$$

A 3cm short-circuited transmission line becomes a series resonator.

1.5 Velocity, frequency and wavelength

- velocity $$v = \frac{1}{\sqrt{u\varepsilon}} = \frac{c}{\sqrt{\varepsilon_r}}$$
- frequency $$f = \frac{1}{T}$$
- wavelength $$\lambda = \frac{v}{f}$$

1. lossless medium $$\varepsilon = \varepsilon_o \varepsilon_r$$

   lossy medium $$\varepsilon = \varepsilon' - j\varepsilon'', \ \tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

2. Frequency remains constant as the signal travels through different medium.
3. Electrical length θ (rad. or deg.) = $\beta \times$ physical length
   = $2\pi \times$ physical length in wavelength

4. Ex. 1.1 $\varepsilon_r = 2 \rightarrow v = \dfrac{c}{\sqrt{2}} = 2.12 \times 10^8 m/s$

Ex. 1.2 $f = 5GHz \rightarrow T = 0.2ns$

Ex. 1.3 $T = 500ps \rightarrow f = 2GHz$

Ex. 1.4 $f = 200MHz, 2G\text{Hz} \rightarrow \lambda = 1.5m, 15cm$

Ex. 1.5 $f = 50G\text{Hz}$ in medium $\varepsilon_\text{r} = 3$

$$\rightarrow \lambda = \frac{c}{f\sqrt{\varepsilon_r}} = 0.35cm$$

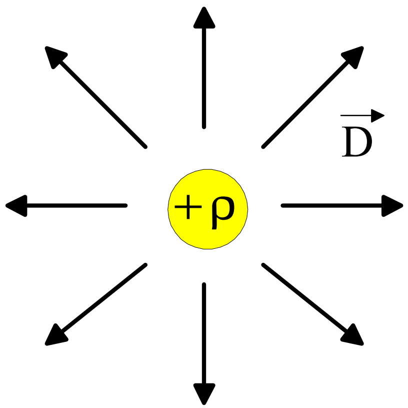
1.6 The electromagnetic waves

1. Maxwell's equation

static case ($\vec{E}$, $\vec{H}$ decoupled)

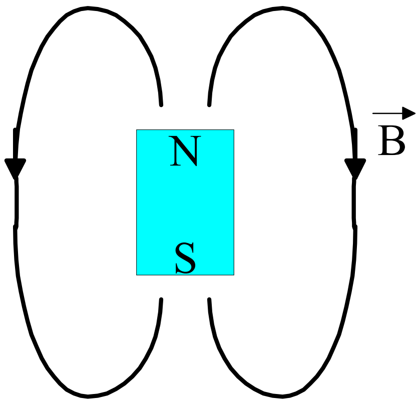
electric charge ρ $\rightarrow \vec{D}$

$$\nabla \bullet \vec{D} = \rho$$

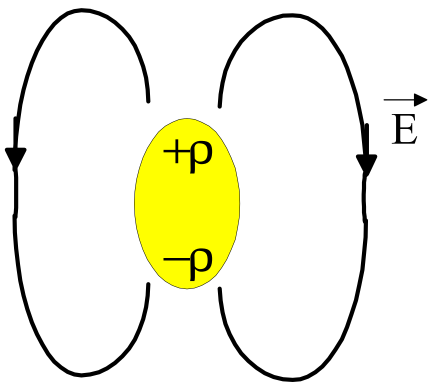


magnet $\rightarrow \vec{B}$

$$\nabla \bullet \vec{B} = 0$$

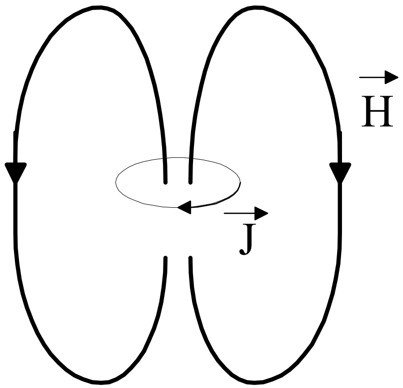


$$\nabla \times \vec{E} = 0$$



magnet $\rightarrow \vec{B} \quad \Leftrightarrow \quad \vec{J} \rightarrow \vec{H}$

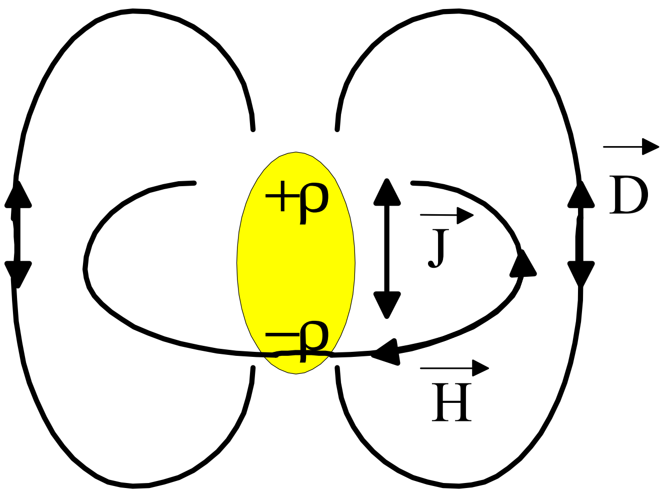
$$\nabla \times \vec{H} = \vec{J}$$

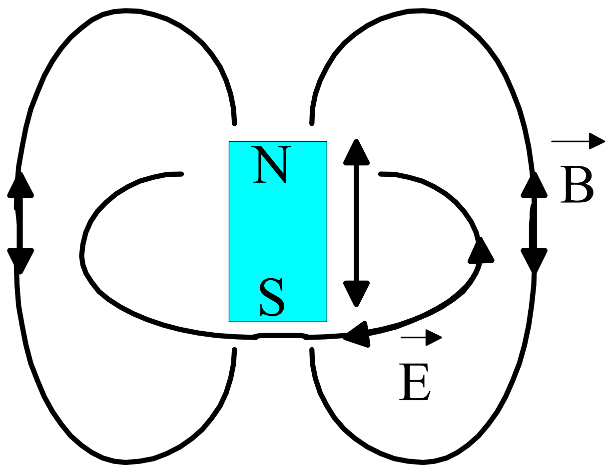


dynamic case ($\vec{E}, \vec{H}$ coupled)

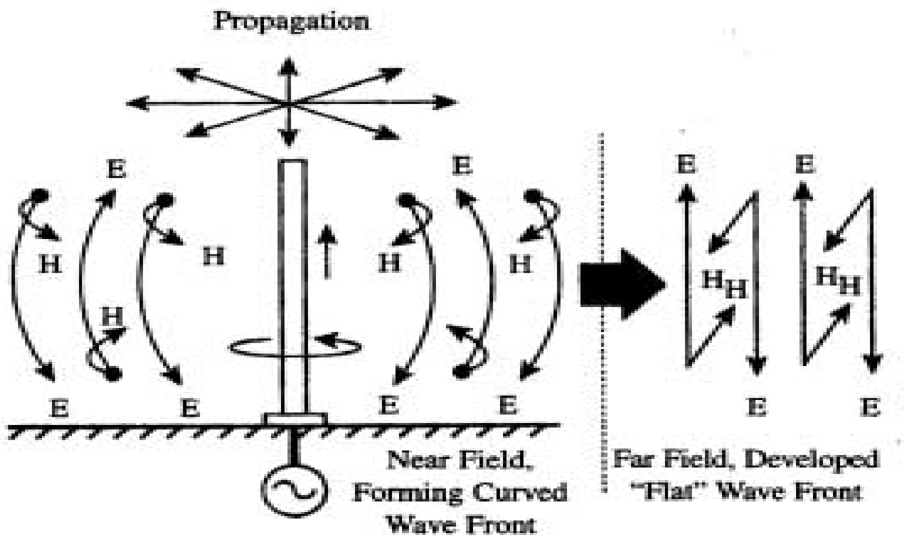
$\nabla \bullet \vec{D} = \rho$ Gauss's law　　$\nabla \bullet \vec{B} = 0$ no isolated magnetic charge

$\nabla \times \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t}$ Ampere's law　　$\nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t}$ Faraday's law





2. Antenna characteristics



radiation pattern $$P(\theta,\phi) \equiv r^2 \left| \vec{E}(\theta,\phi) \times \vec{H}^*(\theta,\phi) \right| = r^2 S(\theta,\phi)$$

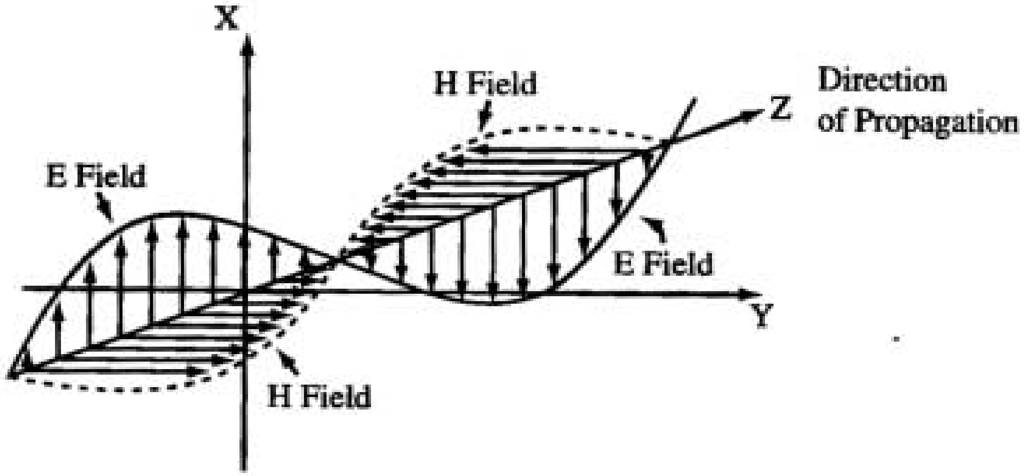
directivity $$D \equiv \frac{4\pi P_{\max}}{P_{rad}} = \frac{4\pi P_{\max}}{\iint P(\theta,\phi)\sin\theta d\theta d\phi} = \frac{4\pi A_e}{\lambda^2}$$

efficiency $$\eta \equiv \frac{P_{rad}}{P_{in}}$$

$$A_e \equiv \frac{P_l}{S}$$

gain $$G = \eta D$$

3. TEM (transverse electromagnetic) wave $\hat{k} \perp \vec{E} \perp \vec{H}$



$$\vec{E}\,(x, y, z, t) = \vec{E}(\vec{r},t) = \mathrm{Re}\,[\vec{E}(\vec{r})e^{jwt}\,] = \mathrm{Re}\,[\,\left|\vec{E}(\vec{r})\right|e^{j\angle\vec{E}(\vec{r})+jwt}\,]$$

a uniform plane wave (with E_x and H_y) propagates in z - driecion $\vec{k} = k_o\hat{z}$

$$\vec{E}(z,t) = \mathrm{Re}\,[E_{ox}e^{j(wt-k_oz)}\hat{x}] = \left|E_{ox}\right|\cos\,[wt - kz + \angle E_{ox}]\hat{x}$$

$$\vec{H}(z,t) = \mathrm{Re}\,[\,\frac{E_{ox}}{\eta_o}e^{j(wt-k_oz)}\hat{y}] = \left|\frac{E_{ox}}{\eta_o}\right|\cos\,[wt - kz + \angle E_{ox}]\hat{y}$$

4. Polarization: direction of $\vec{E}(\vec{r},t)$ at $\vec{r}$

general TEM wave

$$\vec{E}(\vec{r}) = \vec{E}_o e^{-j\vec{k}\bullet\vec{r}},\ \vec{H}(\vec{r}) = \frac{1}{\eta}\hat{k}\times\vec{E}_o e^{-j\vec{k}\bullet\vec{r}}$$

$$\vec{E}_o = E_{ox}\hat{x} + E_{oy}\hat{y} + E_{oz}\hat{z}, \vec{k} = k_x\hat{x} + k_y\hat{y} + k_z\hat{z}, \vec{r} = x\hat{x} + y\hat{y} + z\hat{z}$$

if $\vec{k} = k\hat{z}, \vec{E} = (E_{ox}\hat{x} + E_{oy}\hat{y})e^{-jkz}$ and $k = w\sqrt{\mu\varepsilon}$

linear polarization

$$\angle E_{ox} = \angle E_{oy} \text{ or } \angle E_{ox} = \angle E_{oy} \pm \pi \rightarrow$$

$$\vec{E}(0) = E_{ox}(\hat{x} + a\hat{y}), LP \text{ at } \angle\alpha = \tan^{-1} a = \tan^{-1}\frac{|E_{oy}|}{|E_{ox}|}$$

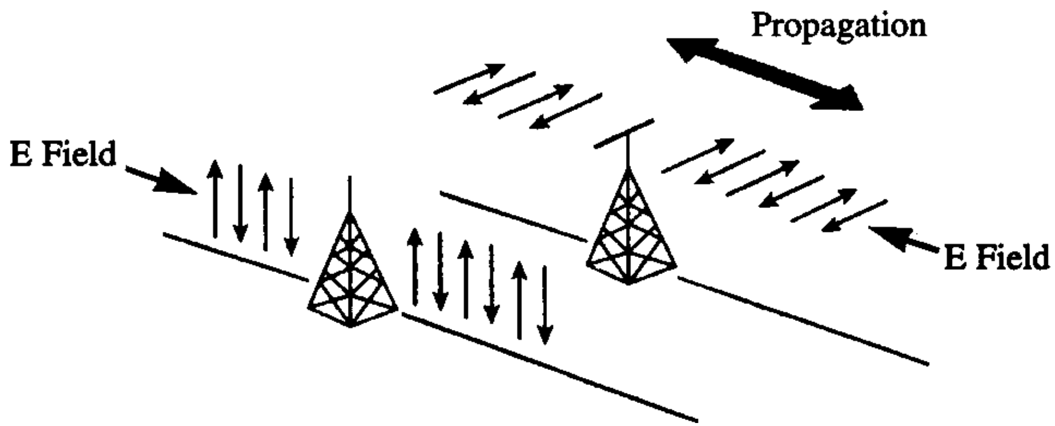
circular polarization

$$|E_{ox}| = |E_{oy}|, \angle E_{ox} = \angle E_{oy} \pm \frac{\pi}{2} \rightarrow$$

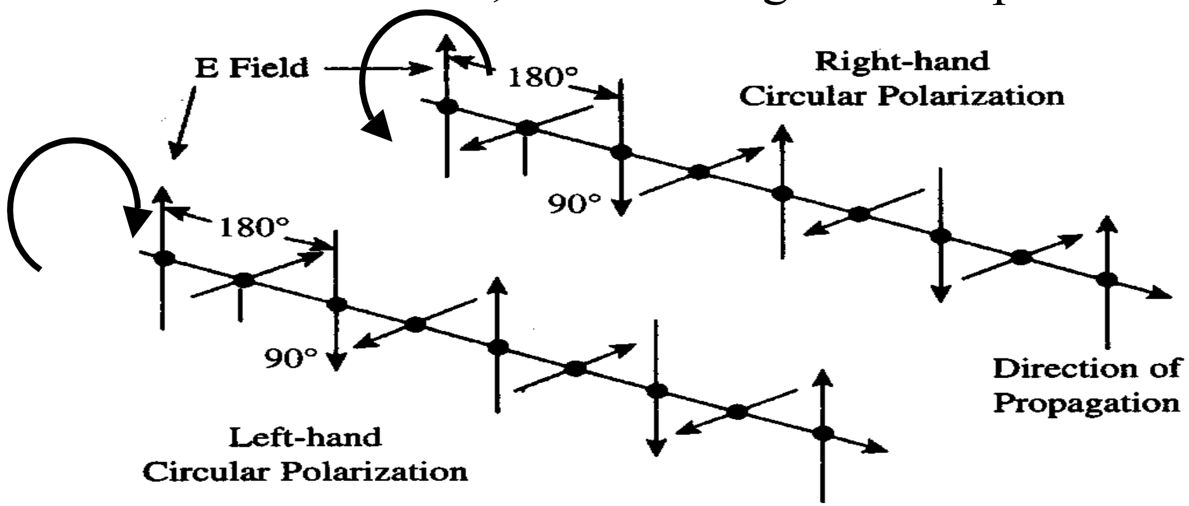
$$\vec{E}(0) = E_{ox}(\hat{x} \pm j\hat{y}) \text{ LHCP and RHCP}$$

LP = RHCP + LHCP

AM radio: vertical polarization
TV: horizontal polarization

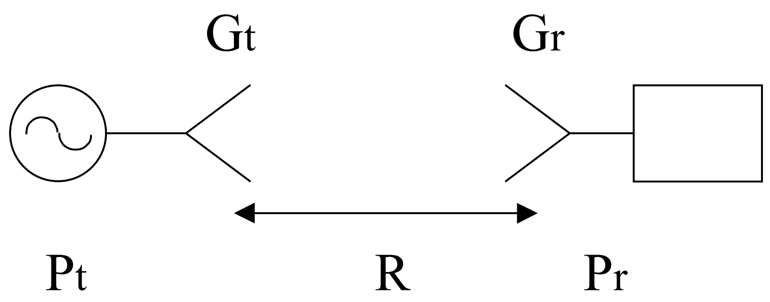


satellite communication, broadcasting: circular polarization



1.7 Propagation

1. Isotropic antenna (point source) $\rightarrow$ spherical TEM wave
   $\rightarrow$ planar wavefront in the far field
2. Inverse square law
   P_T: total radiated power from a point source
   R: distance
   power density at R: $P_D = \dfrac{P_T}{4\pi R^2} (W/m^2)$
3. Friis power transmission formula



$$P_r = \frac{P_t G_t A_e}{4\pi R^2} = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2}$$

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

4. Ex.1.6 P_T=1000W, R=1000km

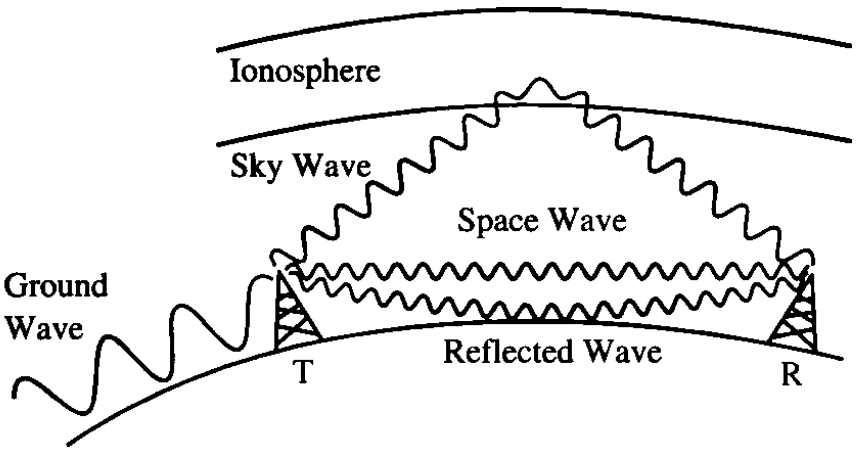
$$P_D = \frac{1000}{4\pi(1000)^2} = 80\times10^{-12}(W/m^2)$$

5. Ex. earth station @6GHz, P_t =120W,
   G_t =42dB → 2m dia. θ =1.7º
   geo-synchronous satellite G_r =31dB → 0.6m dia. θ =6.2º
   → P_r = -75.3dBm

6. Ex. A handset P_t =100mW, short dipole antenna G_t =1.76dB
   at 10cm away from head
   → $$P_D = \frac{100\times1.5}{4\pi(10)^2} = \frac{150}{400\pi} = 0.12(mW/cm^2)$$

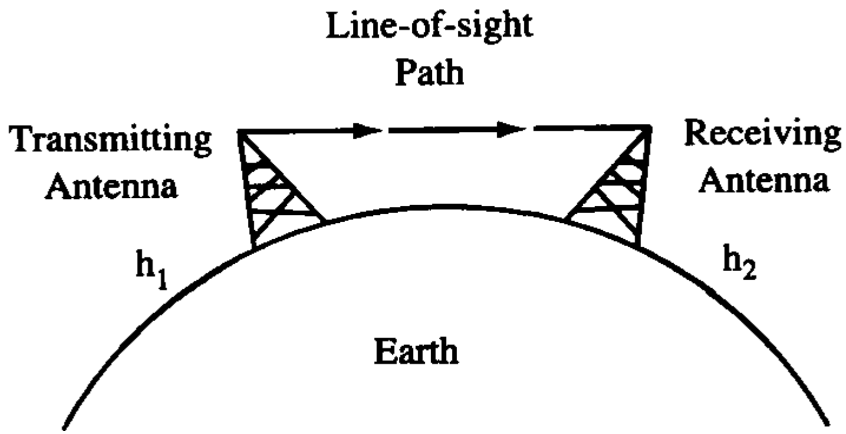
   at 1cm away from head
   → $$P_D = \frac{100\times1.5}{4\pi(1)^2} = \frac{150}{4\pi} = 12(mW/cm^2)$$

1.8 Propagation Paths



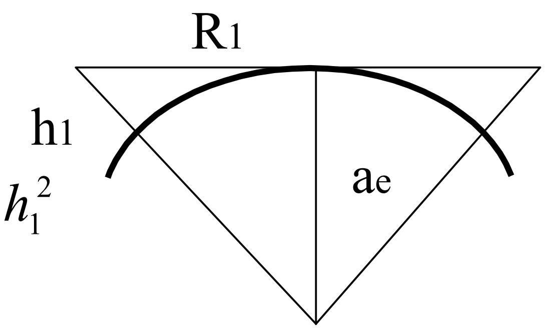
1. Ground wave (LF band) travels over and near the earth surface
   → ground absorption loss, especially for h-polarization
   → AM radio uses vertical polarization
2. Sky wave (HF band) performs refraction (signal bending) in ionosphere
   plasma frequency ~ 9MHz → short-wave radio
3. Space wave (VHF, UHF and microwave): direct wave (line-of sight, LOS) and reflected wave → interference or multipath phenomenon

4. Microwave suffers the small variation in the permittivity of atmosphere → fading (long term fluctuation) and scintillation (short term fluctuation) in signal strength
5. Optical range or LOS range for two antenna with height h_1 and h_2



$$R = 1.42(\sqrt{h_1} + \sqrt{h_2}) \quad R\text{:mile, } h\text{: ft}$$
$$= 4.12(\sqrt{h_1} + \sqrt{h_2}) \quad R\text{:km, } h\text{:m}$$

Diffraction effect → actual distance ~ 4R/3 : radio horizon



$$(h_1 + a_e)^2 = R_1^2 + a_e^2 \rightarrow R_1^2 = 2h_1 a_e + h_1^2$$

$$\rightarrow R_1 \approx \sqrt{2h_1 a_e}$$

$$a_e : \text{effective earth's radius} \approx \frac{4}{3}\text{earth's radius}$$

$$= \frac{4}{3} \times 6378\ Km \approx 8500\ Km \approx 5280\ mile$$

$$R_1(mile) = \sqrt{2h_1 5280} = \sqrt{2\frac{h_1(ft)}{5280} \times 5280} = \sqrt{2h_1(ft)}$$

$$1mile = 5280\ ft$$

6. Ex. 1.7 $h_1=h_2=25$ft $\rightarrow$ R=14.2 mile
   Ex. 1.8 transmitting antenna tower $h_1=15$m, receiving antenna $h_2=1.5$m $\rightarrow$ R=21km

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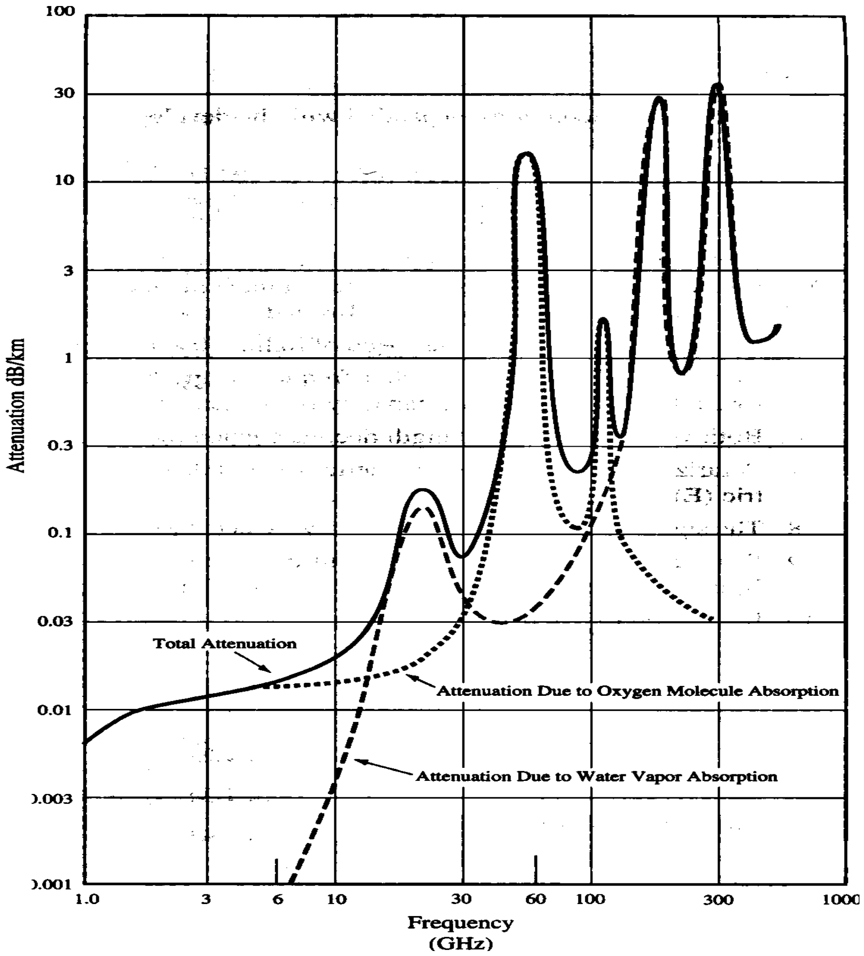
7. Atmospheric attenuation for microwave



water vapor resonance: 22.2, 183.3, 320GHz

molecular oxygen: 60, 120GHz

mmw window: 35, 94, 135GHz

spacecraft-to-spacecraft communication: 60GHz

8 Advantages of microwaves

1. Short wavelength monochromatic radiation

- Antenna gain ∝ the electric size of the antenna → λ ↓, gain ↑
- radar cross section (RCS) ∝ target electrical size → λ ↓, RCS ↑

$$\sigma = \frac{P_s}{S}$$

radar equation $$P_r = P_t \frac{G}{4\pi R^2}\sigma \frac{G}{4\pi R^2} A_e = P_t \frac{G^2\lambda^2\sigma}{(4\pi)^3 R^4}$$

- coherent wave → higher resolving power
- line of sight propagation → wireless or mobile communication, broadcasting
- low atmospheric attenuation and not effected by cloud, fog,… → wireless and satellite communication, radar, broadcasting
- molecular, atomic and nuclear resonance → remote sensing

2. Width of spectrum available for use

- frequency reuse in communications

<u>**Homework #1**</u> (due 2 weeks)
Chapter 1 problems