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I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

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COLLEGE ON THEORETICAL AND EXPERIMENTAL RADIOPROPAGATION SCIENCE

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ELECTROMAGNETIC WAVE AND HUMAN COMMUNITY

Feng Kongyu
Institute of Electronics, Academia Sinica, Beijing, P.R. China

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Feng Kongyu

Institute of Electronics, Academia Sinica
Beijing 100080
People's Republic of China

PREFACE

The great content of Electromagnetic wave theory and its applications makes it impossible to deal with subject in any detail within the scope of two one hour lectures. And it is not our purpose to systematically relate any concrete problems or to derive any formule. We confine ourselves only to the presentation, by a few examples, of how the radiopropagation physics is intimately relevant to the progress of human community. It might stimulate our enthusiasm for wave propagation researches.

PART I

INFORMATIVE PROPERTIES OF ELECTROMAGNETIC WAVES AND TWO ERAS OF HUMAN HISTORY

1.1 Electromagnetic Wave Is One of the Elements in the Nature

Although electromagnetic wave was understood by mankind only about one hundred years ago, it coexists with celestial bodies in the nature. So we say, electromagnetic wave is one of the elements of the nature. It is a form of energy and implies frequency. Frequency is one sort of special natural resources belonging to whole mankind as the air. The electromagnetic spectrum is devided into subdivisions used for various purposes. It is shown in Figure 1.1[1].

1.2 Wave Parameters and Their Availability

1.2.1 <u>Wave parameters.</u> The uniform plane wave in free space is given by

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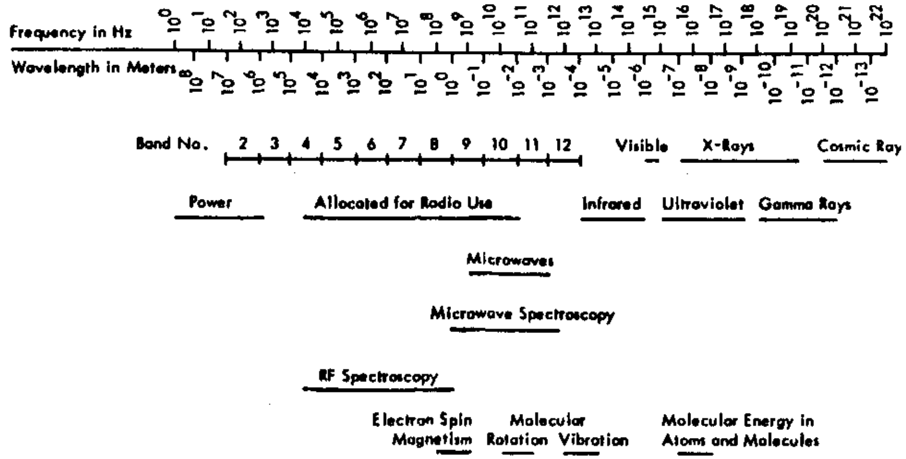

Figure 1.1 The electromagnetic spectrum. The horizontal lines indicate the approximate spectral ranges of various physical phenomena and practical applications.

$$\vec{E}(z,t)=\hat{x}E_0\cos[2\pi f(t-\frac{z}{c})+\phi] \tag{1.1}$$

$$\vec{H}(z,t)=\hat{y}\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2}E_0\cos[2\pi f(t-\frac{z}{c})+\phi] \tag{1.2}$$

Five parameters: frequency (f), amplitude (E_0), phase (ϕ), polarization direction ($\hat{x}$) and time (t).

All of these five parameters can be used to carry the information.

1.2.2 <u>Active carry.</u>

Amplitute modulation

$$U_A(t)=U_c(1+m_A\cos\Omega t)\cos(\omega_c t+\phi) \tag{1.3}$$

where $\Omega=2\pi F$; $\omega_c=2\pi f_c$; $U_A(t)$ is amplitude modulation signal; U_c is carrier amplitude; f_c is carrier frequency; F is modulation frequency; m_A is amplitude modulation coefficient and ϕ is initial phase of carrier.

Frequency modulation

$$U_F(t)=U_c\cos(\omega_c t+m_F\sin\Omega t+\phi) \tag{1.4}$$

where $U_F(t)$ is frequency modulation signal and m_F is frequency modulation coefficient.

Phase modulation

$$U_\phi(t)=U_c\cos(\omega_c t+\Delta\phi\cos\Omega t+\phi) \tag{1.5}$$

where $U_\phi(t)$ is phase modulation signal and $\Delta\phi$ is phase modulation coefficient. It is the maximum shift of the carrier phase varying with frequency modulated.

1.2.3 Passive carry. Example 1. Information detected from frequency variation. Principle of speed measuring Doppler radar: In Figure1.2, target B moves with velocity $\vec{v}$ with respected to radar A. θ is the angle between $\vec{v}$ and line AB. Then v is given by[2]

$$v=\frac{\lambda_c f_D}{2\cos\theta} \quad (1.6)$$

where λ_c is the operating wavelength. v is obtained by measuring the Doppler frequency f_D.

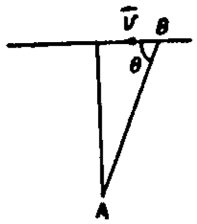

Figure 1.2

Example 2: Information detected from time delay. Principle of ranging radar: In Figure 1.3, t_D is the time delay of the object's response with respect to pulse transmitted, then the distance between radar and object is given by

$$D=\frac{ct_D}{2} \quad (1.7)$$

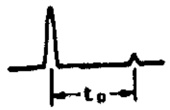

Figure 1.3

Example 3: Information detected by polarization variation. Principle: In Figure 1.4, $\vec{E}^s$ is the scattered electric field from target B illuminated by incident electric field $\vec{E}^i$. The relationship between $\vec{E}^s$ and $\vec{E}^i$ can be formulated by scattering matrix. If the polarizations of $\vec{E}^i$ and $\vec{E}^s$ are expressed in terms of circular polarization components, we obtain the scattering matrix for circular wave components as follows[3].

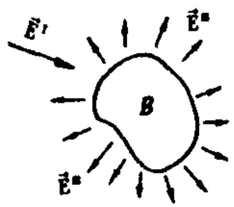

Figure 1.4

$$\begin{bmatrix} E_R^s \\ E_L^s \end{bmatrix} = \frac{1}{r\sqrt{4\pi}} \begin{bmatrix} A_{RR} & A_{RL} \\ A_{LR} & A_{LL} \end{bmatrix} \begin{bmatrix} E_R^i \\ E_L^i \end{bmatrix} \quad (1.8)$$

where the elements of [A] are functions of parameters and orientation of the target. The subscript R and L refers to right and left hand circular component respectively. We define the circular polarization ratio as:

$$q=E_L/E_R \quad (1.9)$$

The difference between q_s and q_i may be used to discriminate the targets. The principle is used in hail studies radar to distinguish between the rain and the hail in Alberta, Canada[4]. The results of experiments are shown in Figure 1.5. The ordinate is the circular depolarization ratio (CDR) and the abscissa is the reflectivity. The dashed curve in Figure 1.5 seperates most, but not all, hail (>0.5 cm diameter) reports from the rain and shot-sized hail (<0.5 cm diameter) reports. Below reflectivities of 30 dBZ only rain or shot-sized

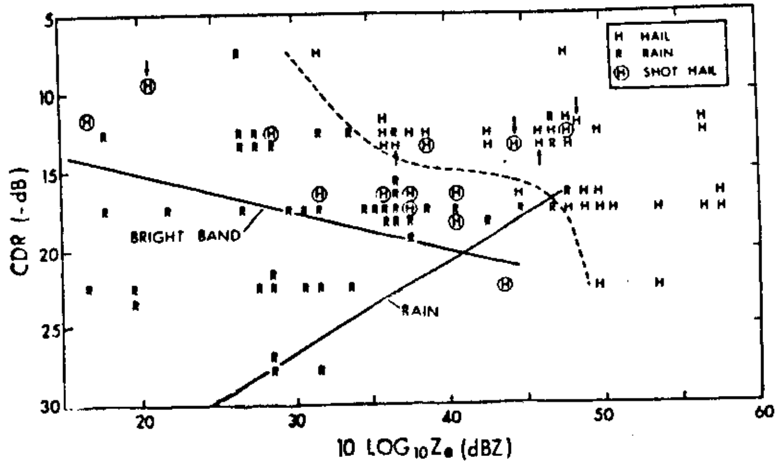

Figure 1.5

hail was received at the ground surface while reflectivities above 50 dBZ were always associated with hail. For any reflectivity in the transition region between 30 and 50 dBZ, hail likelihood increases with increasing CDR. Thus while reflectivity alone gives some indication of hail occurrence, the CDR evidently supplies additional information in the important range from 30 to 50 dBZ.

Electromagnetic wave possesses such properties that it is natural in connection with information. Really, any electromagnetic waves in the nature or produced by mankind always carry some information with them.

1.3 The Era of Unconscious Usage of EMW.

Electromagnetic Wave (EMW) is one of the elments of the nature, and its light parts are earliest experienced by mankind. At that time, people did not know the electromagnetic character of light, but they had used it to understand the nature and to create life. For examples:

People observed the celestial bodies by their lights and set calender for agriculture and life.

Beacon-fire was used to give border alarm in ancient China. That was the beginning of utilizing light relay to pass the information.

Convex lens was used to get fire. That was an outstanding example of utilizing the electromagnetic wave energy.

That is the era of unconscious usage of EMW in human history.

1.4 The Era of Conscious Usage of EMW

J.C.Maxwell announced his electromagnetic theory in 1864. H.R.Hertz demonstrated the existence of electromagnetic wave by his experiment in 1887. These two great events indicate that people had got the rational knownledge about EMW and began to master it actively. Since then, human history has advanced into the era of conscious usage of EMW. That was first used in the communication, then in the broadcasting, and made information transmission more rapid and distant.

Besides, the advances of radiopropagation physics promote the developments of radar and remote sensing technology. They are extensively used in the military, agriculture, forestry, mapping, prospecting and traffic regulation. Owing to immense quantities of radiation systems operated, people live in the electromagnetic environment nowadays. Radiation damage to organism especially to human body and electromagnetic compatibility are going to be the serious problems. On the other hand, EMW is extensively used in the biomedical field. Irradiation of microwave and laser become a powerful treatment in curing the cancer. The application of electromagnetic wave energy is growing rapidly as well. Microwave ovens have got into families. A programme for setting up space power station has been proposed by some country. The idea is that the solar energy is turned into microwave energy in the station, then it is transmitted to the earth by antenna and available power is about five million kilowatts. It is meaningful to overcoming the energy crisis, but serious electromagnetic environment is quite a problem not to be tolerable. All of the above aspects need absorb the nourishments from studying problems of EMW.

In sciences, electromagnetic wave theory is more and more interacted on plasma physics, space physics, solid physics and signal processing, and new branches of science are sprouted.

It is worth while to point out that the transient electromagnetic field is noticeably studied in recent years, and breakthrough might be expected.

In conclusion, radiopropagation physics is intimately relevant to science advances, information community, natural resources exploitation, energy engineering, ecological environment etc.

PART II

THE EFFECTS OF RADIOPROPAGATION PHYSICS ON THE DEVELOPMENT OF MODERN SCIENCE AND TECHNOLOGY

There are many kinds of communication, but we would confine ourselves only to showing a few of them. Of course, all of them are wireless. There are three basic demands in the communication, and they are: quality, capacity and secrecy. The progress of communication is really the progress of realizing these three demands.

2.1.1 Short wave communication. Short wave (usually, 4~21 MHz) communication is dependent upon the reflection of radio wave from the ionosphere. The typical distribution of ionization in the ionosphere is shown in Figure 2.1. It should be pointed out that Figure 2.1 represents a long-term average and that the actual electron-density distribution is a function of the time of day, season, latitude and year relating to the eleven-year sunspot cycle[5].

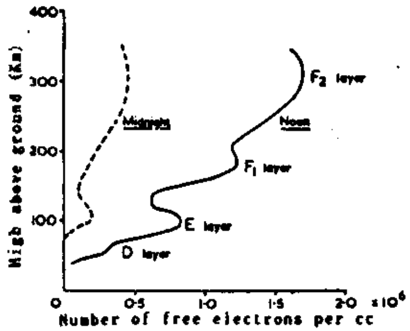

Figure 2.1

Determination of the working frequency, transmitted power, elevation of antenna and site for station of the short wave communication are dependent upon the laws of radiopropagation in the ionosphere.

Example: Determination of the working frequency.

The related knowledge: (1) The critical frequency (f_{CR}) for any given layer is

$$f_{CR}=\sqrt{81N_{MAX}} \qquad (2.1)$$

where N_{MAX} is the maximum ionization density (electrons per cubic meter). Because the ionosphere vary throughout the day, and vary regularly with season of year as well, the critical frequencies and virtual heights vary with these factors. Figure 2.2 shows the diurnal variation of critical frequency and virtual height of the regular ionospheric layers: (a) summer at period of sunspot minimum; (b) summer at sunspot maximum; (c) winter at sunspot minimum; (d) winter at sunspot maximum[6]. (2) The maximum usable frequency (MUF) is:

$$MUF=f_{CR}\sec\Phi_I \qquad (2.2)$$

where Φ_I is the angle of incidence. The largest angle of incidence Φ.

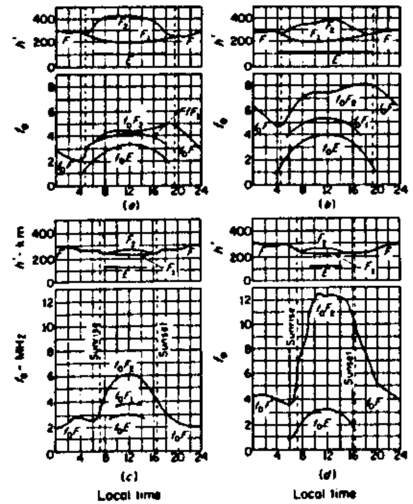

Figure 2.2

that can be obtained in F-layer reflection is of the order of 74 degrees. This occurs for a ray that leaves the earth at the grazing angle. Then

$$MUF(max) \approx 3.6\ f_{cR} \qquad (2.3)$$

(3) The lowest useful high frequency (LUHF) is defined as the lowest frequency (in the high-frequency band) that will give satisfactory reception for a given distance and given power. It depends upon the following factor: (a) The effective radiated power. (b) The absorption characteristics of the ionosphere for the paths concerned. (c) The required field strength, which depends upon radio noise at the receiving point and the type of service involved.

The working frequency (f_w) is determined by

$$LUHF < f_w < MUF \qquad (2.4)$$

Actually, the optimum working frequency (f_{op}) for transmitting between any two points is selected as:

$$f_{op} = 0.5 \sim 0.85\ MUF \qquad (2.5)$$

Owing to the f_{cR} varies with the time of day, season etc., the f_w of a given path should be varied accordingly. Suffering from serious fading caused by ionosphere disturbance and multipath propagation, short wave communication is not at good quality, besides its capacity is relatively small and its secrecy is bad. Therefore the short wave communication has been gradually replaced by other means, but in some special cases, especially mobile communication, short wave is still used nowadays.

2.1.2 <u>Microwave relay</u>

Based on the principle of space wave propagation, microwave relay was developed after World War II. Propagation researches relating to microwave relay are involved in the following two aspects:

(1) The effects of terrain on the space wave propagation

The effects of terrain on the space wave propagation are very complicated in the microwave band. Here, we would only show the calculation of space wave intensity under the ideal conditions.

$$E = \frac{\sqrt{30P}}{R}\ V \qquad (2.6)$$

where P is transmitted power (watt), R is the distance between transmitter and receiver (Km), V is interfering factor which depends upon R, terrain, antenna elevation, antenna directivity, electric parameters of the ground surface and the refractive index of the troposhere. In most actual cases, the module of reflection coefficient of the ground approximates to 1 and its phase approximates to 180° [7]. Then

$$V \approx \{2 + 2\cos[\pi + \frac{\pi R H_n^2}{\lambda R_1 (R - R_1)}]\}^{1/2} \qquad (2.7)$$

where H_n is the clearence of the path.

n=odd corresponding to reflected wave is inphase with the incident wave, i.e. the hig est point of the path is at the odd order Fresnel zone. Then V is maximum.

n=even corresponding to reflected wave is out of phase with the incident wave, i.e. the highest point of the path is at the even order Fresnel zone. Then V is minimum.

The profile of the path concerned is shown in Figure 2.3 .

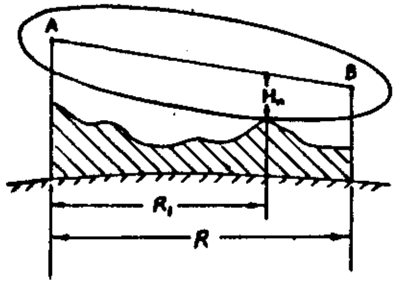

Figure 2.3

(2) The effects of climate and atmosphere on the space wave propagation.

The effects of climate and atmosphere on the space wave propagation may be summarized as follows: a. Attenuation caused by the resonance of gas molecule may be ignored, if wave length is longer than 2 centimeters. b. Additional attenuation caused by rain, fog and snow becomes considerable, if wavelength is shorter than 5 centimeters. c. Wave refraction caused by inhomogeneous structure of the troposphere seriously affects the signal received. This effects may be depicted approximately by equivalent radius (R_E) of the earth.

$$R_E = \frac{R}{1 + \frac{1}{2} R \frac{d\varepsilon}{dh}} \qquad (2.9)$$

where R is the radius of earth. If value of the permittivity (ε) of atmosphere decreases with increasing in height h, $R_E > R$ and wave will bend down to the ground. It is equivalent to enlarging the H_n. If ε increases with increasing in height h, $R_E < R$ and wave will bend upward away from the ground. It is equivalent to decreasing the H_n. The variation of permittivity of the atmosphere mainly causes the slow fading of the signal at the receiving point and at the worst cases, the communication will be interrupted.

2.2 Sound and Visual Broadcasting

There are many kinds of broadcasting such as long wave, medium wave, short wave and ultra-short wave sound broadcasting; conventional television and satellite direct broadcast TV. As for most courtries, usually the medium wave broadcasting and conventional television is most meaningful. Therefore we are interested in the radiopropagation

2.2.1 Medium wave broadcasting

In medium wave (usually, 0.5～1.6 MHz) broadcasting, the space wave is very weak and can be ignored. Hence wave propagates to the receiving point mainly by ground surface and sky. In the day time owing to the existance of D layer, the sky wave is greatly attenuated and only surface wave plays a role in the service. This service coverage is limited in the region with radius about 100 Km from the transmitter. At night time, the D layer disappears. The sky wave is reflected by E layer and interferes with the surface wave, thereby causing fading at distances between 100 and 200 Km. Beyond the fading region the sky wave is dominant, and there is a secondary service region of relative inferior reception which lies between about 250 Km and 750 Km from the transmitter.

If surface wave is used to cover a country with a vast territory, it is necessary to set a number of stations. For the purpose of freeing from interference between the adjacent frequencies and getting good quality reception, we must proceed to draw up a broadcasting coverage programme of the country by theoretical calculations and practical measurements. Here, we will roughly relate some formulae for calculating the field strength in the broadcasting coverage programme as follows[1],[5],[6].

$$E_{MV}=\frac{3\times10^5\sqrt{\eta P}}{R}F(h)A_1A_2 \qquad (2.10)$$

where E_{MV} is field strength in millivolts/meter; P is radiated power in kilowatts; η is antenna efficiency; R is distance from radiator in meters; F(h) is normalized horizontal field strength, with respect to the horizontal field strength of short vertical radiator, for antenna of height "h"; A_1 is surface wave attenuation factor and A_2 is spherical earth factor. At the surface of the earth, A_1 has been evaluated as follows.

$$A_1=|1-j\sqrt{\pi p_1}\ e^{-p_1}\mathrm{erfc}(j\sqrt{p_1})| \qquad (2.11)$$

$$\mathrm{erfc}(j\sqrt{p_1})=2\frac{1}{\sqrt{p_1}}\int_{j\sqrt{p_1}}^{\infty}e^{-v^2}dv \qquad (2.12)$$

$$p_1=pe^{jb} \qquad (2.13)$$

$$p=\text{numerical distance}\approx(\pi R\cos b)/(\lambda x) \qquad (2.14)$$

$$b=\text{phase constant}\approx\mathrm{arctg}[(\varepsilon_r+1)/x] \qquad (2.15)$$

$$x=18\times10^3\sigma/f_{MHz} \qquad (2.16)$$

where erfc( ) is the complementary error function, ε_r is the relative permittivity of the earth; λ is wavelength in meters and σ is the earth conductivity in mhos per meter. The A_2 for idealized earth constants is shown in Figure 2.4[5] [(1) vertical polarization if earth is perfect conductor (2) vertical polarization if earth is perfect dielectric constant]. Practically, in case of vertical polarization: curve(1) is fairly accurate for medium waves over sea-water, and is a rough approximation for medium waves over good conducting ground. For medium waves and poor ground conductivity the exact curve lies between (1) and (2). For short waves curve (2) is a fair approximation.

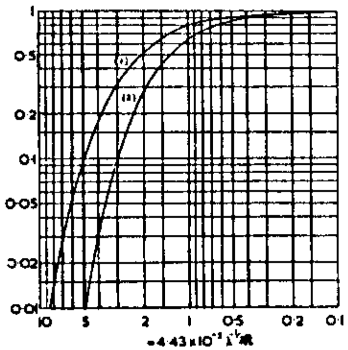

Figure 2.4

In China, the field strength of sky wave at night time is calculated by the curve shown in Figure 2.5 [6]. This curve is based on the curves offered by C.C.I.R.(International Radio Consultative Committee) Report, Proc. I.R.E. Oct. 1938. The field strengths in the former are the "medium values" which are defined as the field strengths exceeded instantaneously 50 per cent of the time, while in the latter are "quasi-maximum values" which are defined as the field strengths exceeded instantaneously about 5 per cent of the time. And

medium value≈0.35×quasi-maximum value

The curve in Figure 2.5 is based on 1 kilowatt effective power radiated by monopole. If we use it to calculate the field strength of any practical cases, the value obtained from the curve must be multiplied by the gain of power and gain of antenna at the elevation concerned.

2.2.2 Conventional Television

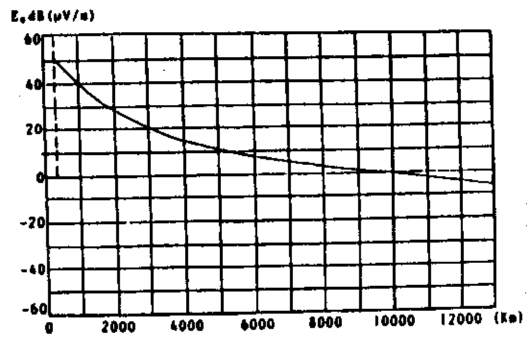

Figure 2.5 Sky propagation curve for medium wave (yearly midnight medium value)

The transmission of conventional television is dependent on the space wave including direct wave and reflected wave. The calculation of field strength at the receiving point is quite the same as that of the microwave. Generally, conventional television is operated on the VHF, therefore the fading caused by interference of direct wave with reflected wave is not serious. However, the ghost caused by the time delay of reflected wave seriously affects the reception quality. How to eliminlate the ghost is concerned universally. Some has intended to find the way of eliminating the ghost by utilizing the wave propagation mechanism and proposed to transmit the television by circularly polarized wave.

It is well known that in the case of a conductive plane reflector at normal incidence, the circularly polarized (CP) wave is totally reflected, but the sense of rotation is reversed. If the performance of receiving antenna responds to direct wave, the reflected wave will be rejected. However, the characteristics of the CP wave after reflection from a surface is quite dependent on the nature of the surface and grazing angle of the incident wave. Hence the profit of using CP wave in TV transmission is worthy to be studied. Figure 2.6 shows the dependence of axial ratio and rotation sense of the reflected wave on the grazing angle ψ, when a CP wave is incident on the surface with permittivity $\epsilon = 3-j0.009$ which is said to be typical of large city industrial areas[10]. In the Figure 2.6 the reflected wave is in opposite sense in the interval of grazing angle ψ from 30° to 90°. Evidently, the ghost can be weakened in the most part of TV coverage.

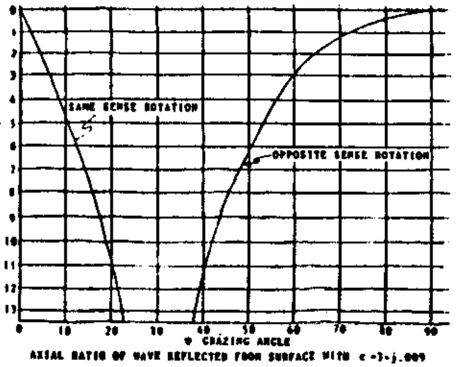

Figure 2.6

Experimental CP TV has been carried out in America and also in China by National Broadcasting Administration Bureau. CP-CP is compared with HP-HP at five outdoor receiving points in Beijing under the conditions of that the transmitter was alternately connected to the CP or HP transmitting antenna and that the gains of CP and HP antenna were identical in transmitting and receiving. Some results are shown in Figure 2.7 [11]. The ghosts are weakened by CP-CP evidently.

Figure 2.7 Experiment CP TV Compared with HP TV in China

2.3 Radar and Remote Sensing

2.3.1 The basic equations. Remote sensing may be classified into two kinds— passive and active. The active remote sensing is to detect the information from the received EM field scattered by the object. In this system, a transmitter is necessary. The passive remote sensing is to detect the information involved in the electromagnetic waves from the thermal radiation of substances. In this system, only receiving system is necessary. Radar is usually classified into bistatic radar which has the transmitting system and receiving system situated at different locations, and monostatic radar which has these systems located at the same place, usually sharing the same antenna. The performance of radar and active remote sensing are both governed by the radar equation as follows[2].

$$P_R = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R_T^2 R^2} A_T A_R \eta_T \eta_R L_P \quad (2.17)$$

where P_R is received power; P_T is transmitter power; G_T is gain of the transmitting antenna in the direction of the target; G_R is gain of the receiving antenna in the direction of the target; η_T is efficiency of the transmitting system; η_R is efficiency of the receiving system; R is range between the target and the receiving antenna; R_T is range between the transmitting antenna and the target; A_T is attenuation factor allowing for propagation loss in the medium of transmitting path; A_R is attenuation factor of receiving path; σ is radar cross section of the target; λ is operation wavelength of radar and L_P is numerical factor allowing for polarization loss.

For monostatic radar sharing the same antenna system,

$G_T = G_R = G, \quad R_T = R, \quad A_T = A_R = A$, then

$$P_R = \frac{1}{(4\pi)^3} \frac{P_T G^2 \sigma \lambda^2}{R^4} A^2 \eta_T \eta_R L_P \quad (2.18)$$

In the above equations, target is characterized by the quality σ which has the dimension of area and is dependent on the direction and polarization. It is defined as

$$\sigma = 4\pi \lim_{R\to\infty} R^2 \frac{\vec{E}^s \cdot \vec{E}^{s*}}{\vec{E}^i \cdot \vec{E}^{i*}} \quad (2.19)$$

where $\vec{E}^i$ and $\vec{E}^s$ are the incident and scattered electric fields, respectively.

For passive remote sensing, the basic equation is Planck's radiation law. According to Planck's radiation law, a blackbody radiates uniformly in all directions with a spectral brightness B_F given by.

$$B_F = \frac{2hF^3}{c^2} \left(e^{hF/KT} - 1\right)^{-1} \quad (2.20)$$

where B_F is Blackbody spectral brightness, $Wm^{-2}Sr^{-1}Hz^{-1}$; h is Planck's constant=6.63×10^{-34} joules; F is frequency, Hz; K is Boltzmann's constant=1.38×10^{-23}, joule K^{-1}; T is absolute temperature, K; and c is velocity of light=3×10^8 ms^{-1}.

A family of curves of B_ν as a function of frequency with T as parameter is shown in Figure 2.8[3].

2.3.2 The dependence of imaging on electromagnetic wave theory

There are three stages in the visual sense of mankind. They are discovering, discriminating and imaging. The advances of the functions of radar systems also follow these stages, and imaging is the highest stage that we want to attain. In EMW point of view, all of the discovering, discriminating and imaging is just the inverse-problems of the scattering. We will discuss the mechanism of imaging in the aspect of EMW theory to look for the possible way of realizing it.

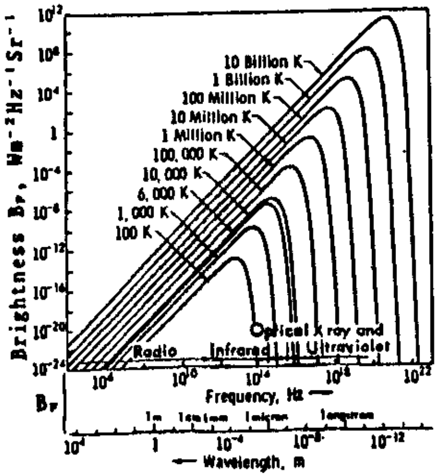

Figure 2.8 Planck radiation-law curves

The amount of information involved in the various imaging theories:

(1) Imaging based on geometrical optics theory

Geometrical optics theory of wave propagation is based on the high frequency approximation. Its main idea is that the wave propagation can be depicted by successive wavefronts and an associated family of rays as shown in Figure 2.9. The surface $S(x,y,z)=S_0$ and $S(x,y,z)=S_0+\delta S$ are the wavefronts at time t_0 and $t_0+\delta t$ respectively. Geometrical optics is then concerned not only with the form of these surfaces but also with a point-to-point transformation from one wavefront into the succeeding one. The point-to-point correlation of wavefronts is established by the "rays", a family of curves having at each point the direction of the energy flow in the field. By these conceptions, the magnitude of the scattered field amplitude $|E_p|$ at a distance p along the reflected ray from a given point p on the conductive reflector (as shown in Figure 2.10) is given by equation[4]:

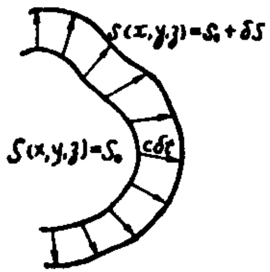

Figure 2.9

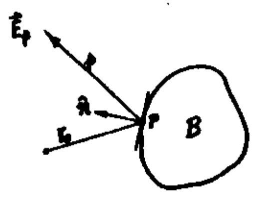

Figure 2.10

$$|E_p|=|E_R|\left[\frac{R_1R_2}{(R_1+p)(R_2+p)}\right]^{1/2} \qquad (2.21)$$

where $|E_R|$ is the magnitude of reflected field at the point of reflection, and R_1, R_2 are the principal radii of curvature of the reflected wavefront.

It should be noticed from the above discussion that in the far region $\vec{E}_p$ involves only the information of the reflection point of the object.

The typical example of imaging based on the geometrical optics theory is using the Radon transform in the tomography. The Radon transform of a function at a given hyperplane is defined as the integral of the function over that hyperplane[5]. The Radon problem is the determination of a function from its Radon transform. The Radon transform is defined in the n-dimensional space, but for simplicity, we will confine our remarks to the problem in the 3-dimensional space. A hyperplane in 3-dimensional Euclidean space is defined by

$$\vec{\xi}\cdot\vec{x}=p \qquad (2.22)$$

where $\vec{x}$ is the spatial position vector; $\vec{\xi}$ is a unit vector orthogonal to the hyperplane; and p is the Euclidean distance from the origin. The Radon transform $\check{f}(\xi,p)$ of a function $f(\vec{x})$ over the hyperplane is given by

$$\check{f}(\xi,p)=\int_{\vec{x}\cdot\vec{\xi}=p} f(\vec{x})\,ds \qquad (2.23)$$

where s is a surface element on the hyperplane and is of degree 2, and ds is its differential. In reconstructive tomography, the 3-dimensional structure of an object is recovered by reconstructing successive cross sections orthogonal to a common axis. Measurements of transmitted radiation such as X-rays provide the projections of the density of a cross section. The projection p is simply the line integral of the density in the direction of projection ψ as illustrated in Figure 2.11.

$$P(\psi,p)=\int_{L(\psi,p)} f(x_1,x_2)\,dL \qquad (2.24)$$

The equation (2.24) is the Radon transform in two dimensions, and hence the problem of recovering $f(x_1,x_2)$ is the Radon problem with n=2. This Radon problem is given by

$$f(\vec{x})=\frac{1}{4\pi}\int_{|\vec{\xi}|=1} H\check{f}_{\xi}(\vec{\xi},\vec{\xi}\cdot\vec{x})\,d\xi \qquad (2.25)$$

where H denotes "Hilbert transform of". Radon transform used in tomography is

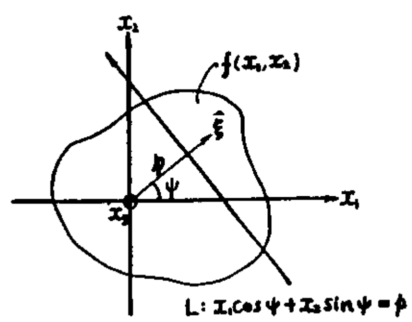

Figure 2.11 Geometry of 2-D projection problem

very successful, but it needs a great deal of measurements to get necessary information for inversion.

(2) Imaging based on physical optics theory

Figure 2.12 shows that the wavefront of impulse electromagnetic field is sweeping across the object (conductor) and its left part (without shadow) has been illuminated. The formula for scattered field of the object based on physical optics theory is as follows[6].

$$\vec{H}^s(\vec{r},t)=\frac{1}{4\pi r_0}\frac{\partial}{\partial t}\int_{illu.}[\vec{J}(\vec{r}',\tau)\times\hat{R}_s]ds', \quad (2.26)$$

$$\tau=t-R$$

$$\vec{J}(\vec{r},t)=2\hat{n}\times\vec{H}^i(\vec{r},t) \quad (2.27)$$

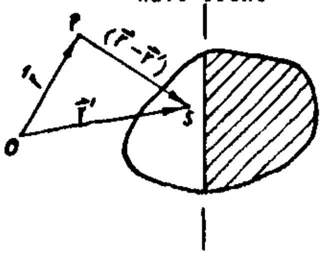

Figure 2.12

where $\vec{H}^s(r,t)$ is scattered magnetic field at the observation point; $\vec{H}^i(r,t)$ is incident magnetic field; $\hat{n}$ is outward unit vector normal to surface of the object; $\vec{r}$ is position vector to the observation point p; $\vec{r}'$ is position vector to the integration point s; $\hat{R}_s$ is unit vector from the integration point to the far-field observer; t is time in light metres; and r_0 is distance to the far field observer.

Evidently, the scattered field obtained under the physical optics approximation involves only the information of illuminated part of the object and never involves the information of the rear of the object, but it is more than that obtained under the geometrical optics approximation. Therefore, it is reasonable to expect that the aspects needed to take measurements in the imaging based on physical optics theory may be less than that needed based on geometrical optics theory.

(3) Imaging based on exact electromagnetic theory

In fact, the induced currents $\vec{J}(\vec{r},t)$ at any points on the object are not only determined by the local incident field $\vec{H}^i(\vec{r},t)$, but also causally correlated with any other points on the illuminated part of the object. Exact electromagnetic theory has pointed out that $\vec{J}(\vec{r},t)$, that is equation (2.27), in equation (2.26) must be corrected as follows.

$$\vec{J}(\vec{r},t)=2\hat{n}\times\vec{H}^i(\vec{r},t)+\vec{J}_c(\vec{r},t) \quad (2.28)$$

$$\vec{J}_c(\vec{r},t)=\frac{1}{2\pi}\int_s \hat{n}\times\{[\frac{1}{R^2}+\frac{1}{R}\frac{\partial}{\partial\tau}]\vec{J}(\vec{r}',\tau)\times\hat{R}\}ds', \tau=t-R \quad (2.29)$$

where $\hat{R}=(\vec{r}-\vec{r}')/R$, $R=|\vec{r}-\vec{r}'|$.

Substituting equation (2.28) into equation (2.26), the scattered magnetic field $\vec{H}^s(\vec{r},t)$ can be calculated strictly. When integration is performed causally all over the object, $\vec{H}^s(\vec{r},t)$ at the observation point consequently involves the information of the whole object.

From the above discussions we can conclude: For getting the information of the whole object, to take data in all aspects round the object is necessary, if imaging is performed on the basis of geometrical optics theory. In many practical cases, it is not allowable to do so, and we always expect to reconstruct the object by taking measurements in the finite number of aspects. From the above three theories for imaging, it is evident that only the exact electromagnetic theory might provide the possibility of decreasing the number of measuring aspects to the minimum. However, how to seperate the information of each point of the object from $\vec{H}^s$ received is quite a problem. This is just the work that we should do.

2.4 Environmental protection and biomedical engineering

Now people live in the electromagnetic environment, and the effects of EMW on the organism, particularly on the human body cannot be ignored. Really, an excess of electromagnetic wave has been regarded as the pollution of the environment. For the safety of the people living or working near the high power radiation source, the protection regulations are being set in many countries, and the related problems are being studied. There are two kinds of damages: One is the thermic damage—organism burned by the heating effect of the wave, and the other is the non-thermic damage such as the functions of nervous system disturbed by induction of the electromagnetism. On the other hand, electromagnetic wave may be used to cure diseases. For instance, the cancer is cured by the irradiation of microwave or laser. For the purpose of avoiding the blind operation and improving the treatments, it is necessary to study the wave propagation in the organism, so that we can fix the exact location to be irradiated and give the necessary dose of irradiation.

The related topics have been studied theoretically in our laboratory, and some interesting results have been obtained. They are shown in Figure 2.13 [7]. In Figure 2.13, (a) is a lossless dielectric cylinder with radially stratified relative permittivity. (b) and (c) are the electric field distribution inside the cylinder under the eccentric irradiation of electromagnetic beam. There are two points which should be noticed: 1. Internal field distribution is not symmetric to the axis of the beam. 2. The location of maximum field intensity does not align with the axis of the beam.

It is reasonable to imagine that if radially inhomogeneous conductivity is considered as well, the problem will become more out of foreknowledge. Evidently, if we have not mastered the mechanism of wave propagation in the human body to cure diseases by irradiation, the normal tissue would be damaged, but morbid tissue will be free due to the insufficient dose.

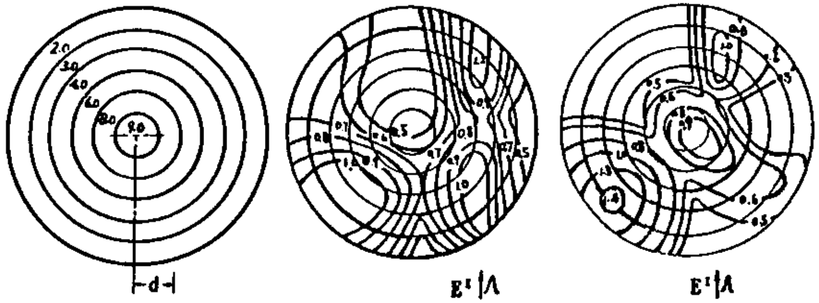

Figure 2.13

2.5 Energy source

EMW is one sort of energy. If we want to develop a new frequency band for scientific and technical purposes, the prerequisite is having the energy source. It means that first of all we must develop the device working at this frequency band. However, the operation mechanism of any device, vacuum or semiconductor, is based on the interactions of the charged particles with electromagnetic wave (field). Therefore electromagnetic wave theory is very useful to investigating the mechanism of the new device or equipment. The development of free-elctron laser (FEL) is one instance of successes.

FEL is a device in which a beam of relativistic electrons is injected into a wiggler magnet, a periodically alternating magnetic field (period l_0) as shown in Figure 2.14 [18][19][22], and the coherent radiation produced is at wavelength

$$\lambda = \frac{l_0}{2\nu^2} \qquad (2.30)$$

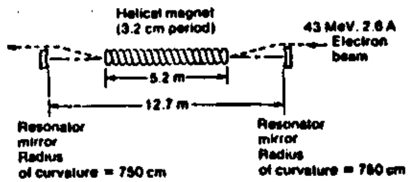

Figure 2.14 schematic of a free-electron laser [cited from reference 22]

where $\nu^2=(1-v^2/c^2)^{-1}$ is the relativistic factor, c and v are the velocities of light and electron respectively. FEL consists of electron beam source, wiggler and resonator three parts. It is anticipated that FELs may be as sources of tunable, coherent, high-power (both cw and pulsed) radiation in the far infrared (long-wavelength) and vacuum ultraviolet (short-wavelength) region.

The directed EM energy in space is an attractive problem to the scientists in recent years. Tai Tsun Wu has pointed out in 1985 that under transient excitation the energy transmitted by an antenna of finite size to a faraway receiver can decrease much more slowly than the usual R^{-2}. Instead, by a suitable choice of excitation, this quantity can decrease as slowly as one wishes, under the physical restriction that the total energy radiated by the antenna is finite. It encourages the scientists to study that problem. In our laboratory the radiation of a disc excited by impulse current has been studied theoretically, and following results are obtained:[20]

$$Z_{MAX}=\frac{(a-\rho)^2-(ct_0)^2}{2ct_0} \qquad (2.31)$$

where Z_{MAX} is the maximum distance of the existance of the unattenuated propagation; a is the radius of disc; ρ is the distance from centre of the disc to the projection of the observation point on the disc plane; and t_0 is the width of exciting impulse. It should be noticed that Z_{MAX} exists only in the cylindrical space confined by the disc, decreases as the ray going away from the central axis of the disc, becomes zero near the edge of the cylinder. For instance, if a=3m, $Z_{MAX}=10^3$m required, then $t_0 \approx 1.5\times10^{-11}$sec, and $Z_{MAX}=0$ would happen at ρ=2.937m. This phenomenon is just like a missile, so it is termed EMP missile. Although EMP missile is hard to be realized in the technology at present, it is very interesting theoretically and practically, and it will be useful for civil and military purposes.

Now we are going to see that EMW is available not only to the survey of the petroleum, but also to exploit it. MWD (measurement-while-drilling) system is very profitable to the drilling. When drilling a well, data from downhole is currently brought to the surface primarily by mud pulse or wireline systems. Unfortunately, wireline system is very hard to be manipulated and mud pulse system offers too low data transmission rate. People expect to realize MWD by means of EMW propagation, i.e. modulated ultimate-low frequency wave is radiated from downhole and transmitted to the ground surface via propagation. It is necessary to investigate the mechanism of ultimate-low frequency wave propagation in the stratum, before we answer the questions about the possibility of transmitting information, the maximum usable frequency, the effective radiated power required and the kind of receiving system. The related topics are studied in our laboratory, and the electric field strengths on the surface are calculated[21]. The configuration of EMW-MWD system is shown in Figure 2.15. In the Figure, region (I) is the free space, region (II) is the stratum, and region (III) is the mud. If L=3000m, D=2990m, a=8cm, b=63cm, σ_1=0.2mho/m, σ_2=8.0mho/m, and V=1volt, the electric field strengths at the surface calculated are shown in Figure 2.16. The abscissa ρ is the distance to the centre of the hole, and the ordinate is the field strength. Evidently, the attenuation of propagation is strongly dependent on the frequency, if well is deep. Therefore EMW-MWD system must operate on the ultimate-low frequency such as lower than 5 Hz, and the data transmission rate is relatively high. The correlation reception system is required for detecting the weak signal from the serious background.

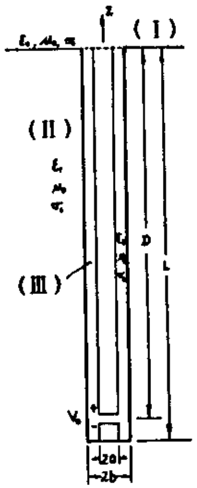

Figure 2.15

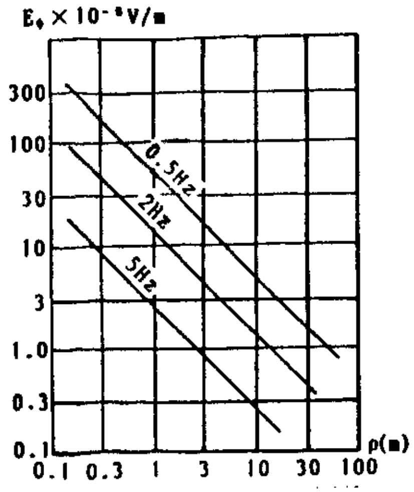

Figure 2.16

CONCLUSIONS

It has been briefly discussed above how radiopropagation is relevant to the human civilization, and from these discussions, we can conclude that there are three natures in the radiopropagation physics.

(1) International Nature

Frequencies as the natural resources are the common wealth of human beings. For the purpose of coordinating the usage of frequencies in various regions and countries, International Frequency Registration Board and International Radio Consultative Committee regularly propose the suggestions concerning efficient use of frequencies to his members. On the other hand, in order to get the complete feature of radiopropagation for communication and other purposes, international cooperations and exchanging experiences such as ionospheric forecasting are also necessary. These demonstrate that radiopropagation physics is a highly international science.

(2) Regional Nature

Because climate and geograph are quite different from country to country, we should not only absorb the advanced technology and experience from abroad but also master the domestic or regional properties of radiopropagation in developing our own broadcasting, communication etc. If we want to draw up a national medium wave broadcasting coverage programme, we must have the knowledge of ground conductivities over our country and some studies of medium wave propagation should be made. If we want to lay a microwave relay route, we must have the data of attenuations due to rain and snow etc. of respective regions. Of course, the typical data provided by other countries are valuable to reference, but practically they cannot be used to replace local data. Therefore, every country should study the problems of radiopropagation according to his own requirements.

(3) Precedent Nature

The precedent nature of radiopropagation physics means: radiopropagation study is usually prior to other work in developing any new radio system. For instance, in the history of developing optical fibre communication, the wave propagation studies such as that J.Tyndall experimented in light transmitted along a water column in 1870 and D.Hondros & P.Debye theoretically studied EMW transmitted along long dielectric cylinders in 1910, are the precedent work. These laid the foundation of developing the optical fibre communication system. Up to now, such precedent work is still necessary to be done. In the developing EMW-MWD system, first of all we must master the mechanism of ultimate-low frequency wave propagation in the stratum, or we will get into trouble, wasting our time and funds.

On the whole, the studies of radiopropagation are very necessary to every country and international cooperations are important.

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