RECOMMENDATION ITU-R P.532-1*

IONOSPHERIC EFFECTS AND OPERATIONAL CONSIDERATIONS ASSOCIATED WITH ARTIFICIAL MODIFICATION OF THE IONOSPHERE AND THE RADIO-WAVE CHANNEL

(1978-1992)

The ITU Radiocommunication Assembly,

considering

a) that artificial modification of the ionosphere and the radio-wave channel can be introduced by the application of RF power using terrestrial (or spaceborne) transmitters;

b) that ionospheric modification, particularly in the F-region, can occur as the result of high power flux-density in the ionosphere in the approximate frequency range 2 to 12 MHz, particularly for high radiation angles and for frequencies just below the layer basic MUFs at near vertical incidence; and that such ionospheric modification may allow propagation at frequencies up to about 400 MHz and over distances of up to 4 000 km;

c) that it has long been recognized that cross-modulation can occur at LF and MF when the power flux-density of signals in the ionosphere is large;

d) that if administrations continue to allow transmitter powers to increase, the ionosphere can be significantly altered with the result that both the services using the ionosphere as a propagation medium and VHF ground-wave services may experience deterioration of reception;

e) that the ionosphere can be modified by injection of chemical reagents, photo-ionizable constituents, energetic particles, and other species which will modify the natural distribution and character of the medium;

f) that inadvertent or unplanned modification can be introduced by reagent processes associated with rocket launches;

g) that artificial modification of the medium can introduce new transient modes of propagation, creating the potential for increased (or decreased) coverage beyond that established by standard radio-wave propagation prediction methods,

recommends

that in the planning and operation of radio systems utilizing the ionosphere, the following aspects should be taken into account:

1. that for determining the modifications to the ionosphere by ionospherically propagated high-power radio-wave transmissions, use should be made of the information contained in Annex 1;

2. that for determining the effects of ionospheric modification on radio-wave transmissions (cross-modulation), use should be made of the formulations given in Annex 2;

3. that for determining the modifications to the ionosphere by trans-ionospheric radio-wave transmissions, use should be made of the information contained in Annex 3;

4. that for determining the modifications to the ionosphere resulting from injection of chemical reagents, use should be made of the information contained in Annex 4,

recommends further

5. that attention be paid, and measures be taken, to minimize excessive power flux-densities at ionospheric heights for frequencies up to approximately 12 MHz;

6. that for operational communication systems, intentional modification of the ionosphere should be discouraged due to the deleterious effects on the services of other users.

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* Radiocommunication Study Group 3 made editorial amendments to this Recommendation in 2000 in accordance with Resolution ITU-R 44.

ANNEX 1

Ionospheric modification by ground-based, high-power radio transmission

1. Introduction

The modification of the ionospheric plasma by high-power radio transmissions divides into ohmic ionospheric heating, a non-linear but classical process, and into the generation of parametric instabilities by non-linear wave interaction processes.

Most ionospheric modification activities at HF are concerned with producing changes in the upper ionosphere (150-400 km) using purpose-built transmitters operating at frequencies close to the F-region critical frequencies. If the modifying frequency is less than the critical frequency, the modification is termed overdense; if however, the modifying frequency is greater than the critical frequency, the modification is said to be underdense. The ionosphere can be appreciably modified by an oblique high-power radio emission at frequencies considerably in excess of the critical frequency of the F-region of the ionosphere.

Transmitters operating over the range of VLF to UHF give rise to modifications in all regions of the ionosphere. The resulting modified region can have a significant effect on radio signals, used for communications purposes, which pass through it.

2. Ohmic heating theory

Theoretical work has suggested that ionospheric heating by ohmic dissipation should produce large-scale changes in the electron temperature and as a result in the electron density and other parameters. Many non-linear phenomena arise from the fact that the collision frequency depends on the electron temperature.

Simplified theory illustrates how ohmic heating can occur. A wave with electric field E, and angular frequency ω, is considered to pass through a slab of ionospheric plasma with effective collision frequency ν between electrons and ions or neutrals. This field acts upon the electrons, of mass m, and charge e and accelerates them. Collisions, however, retard them and energy is extracted from the wave, resulting in an increase in electron temperature. Although the electrons become hotter, they transfer only a small part of their excess energy to the ions or neutrals during collisions because the electron mass is so much smaller than the ion or neutral mass. In the F-region, the electron-ion collision frequency is $\leq 10^3$/s, the fractional energy loss per collision is $\leq 10^{-4}$, and the time constant for energy loss is therefore, ~10 s. This low loss rate makes appreciable heating of the electrons possible. Heating of the E-region is less easy. Here the electron-neutral collision frequency is $\sim 2 \times 10^5$/s, the fractional energy loss per collision is 5×10^{-3} and consequently the time constant for energy loss is only ~1 ms. Strong absorption of the incident radio wave occurs in the region where the electron plasma frequency is near the radio frequency. This is because the wave is slowed near this natural resonance, and the electrons have a greater opportunity to collide with the heavy particles.

The electric field needed to cause large thermal perturbation of the ionospheric plasma temperature and for $\omega >> \nu$, varies from about $3 \times 10^{-4} f$ (mV/m) in the D and E-regions to about $10^{-4} f$ (mV/m) in the F-region; f is the frequency of the perturbing wave (Hz). Such fields imply equivalent isotropically radiated powers of approximately 100 MW.

3. Parametric instability theory

The parametric wave-plasma instability generally involves a three-wave interaction. In the context of ionospheric modification, a high power HF electromagnetic wave provides the initial driving or pump field whose energy cascades into a lower frequency electrostatic electron plasma wave and a lower frequency ion-acoustic wave.

The non-linear mechanism responsible for most parametric instabilities in the ionosphere is the thermal pressure force. The electron temperature perturbations caused by wave heating give rise to an additional thermal pressure term in the electron equation of motion and lead to the generation of field-aligned ionospheric irregularities.

4. Modification effects

Some of the copious modification effects caused by HF (and other frequencies) heating radio waves are described below.

At altitudes of less than 200 km, electrons collide primarily with neutrals, the collision frequency increases with temperature and strong radio waves are absorbed more than weak radio waves. Above 200 km, where electrons collide primarily with ions, the collision frequency decreases with temperature and strong radio waves are absorbed less than weak radio waves.

Perturbations in electron density occur if heating is maintained for a sufficiently long time. At altitudes below about 200 km an increase in electron density occurs. At higher altitudes, in the F-region, high electron temperatures correspond to an increase in pressure causing plasma to stream out of the heated region along the geomagnetic field line. Electromagnetic energy is then focused into the region of reduced electron density leading to further heating and expansion. This results in large-scale irregularities in the F-region electron density, aligned along the geomagnetic field and with transverse dimensions of approximately 1 km. One result of this thermal self-focusing process is the production of artificial spread F.

One of the unexpected effects of the early HF ionospheric modification experiments was the generation of small scale (approximately 1 m) field-aligned irregularities which cause back-scatter to VHF and UHF waves. These irregularities are probably generated about 200 m below the reflection height of the HF heating wave where its heating effect is greatest.

For transmitted powers greater than a threshold value, received signals have been observed to decrease with an increase in e.r.p. It was also found that in the field of an obliquely incident high power wave with a frequency near to the MUF of the F2 layer a modification occurs in the regular ionosphere which can have a considerable effect on the characteristics of radio signals passing through this perturbation.

In addition to modification of the upper ionosphere by high power HF waves, it is possible to generate ELF and VLF waves as a result of modification of the lower ionosphere by use of pulsed high power HF waves.

Evidence of ELF/VLF generation apparently due to LF and MF broadcast emissions has been observed at high latitudes. These signals can heat the auroral D or E region, modulating the auroral electrojet which then emits ELF/VLF signals. Integral harmonics of the ELF modulating frequencies can be produced non-linearly in the auroral D and E regions. Controlled injection of VLF signals from ground-based transmitters causes electron precipitation from the radiation belts which increases ionization at ionospheric heights. Naturally occurring electron precipitation varies greatly from much lower to much higher than observed artificially produced precipitation.

5. Scattering of radio signals from artificially induced irregularities

With an e.i.r.p. of 0.5 MW or greater, large scale and small scale irregularities of electron density aligned with the Earth's magnetic field develop within seconds of the transmitter turn-on, as a result of ohmic heating and development of parametric instabilities and plasma waves. The consequence to radio signals passing through the disturbed region for paths with both terminals on the ground as well as Earth-space paths is that both the depth and rate of fading increase. In addition, because of the field-aligned irregularities, an effective reflector of large radar cross section ($\approx 10^5$ to 10^9 m^2) at altitudes of 250 to 300 km in the ionosphere is produced. These effects are produced when the heating transmitter frequency is below the critical frequency of the F-region ($\leq$ 12 MHz) but on a frequency which matches the plasma frequency at some height in the ionosphere.

The scattering properties of the field-aligned irregularities have been used to transmit voice, teletype, facsimile and pulsed transmissions between ground terminals separated by thousands of kilometres and using frequencies, ranging from HF to UHF, which would not otherwise have been useful for these paths. A fairly high degree of aspect sensitivity is associated with the F-region scattering. Thus, the locations on the Earth at which signals are received by this scattering mechanism depend in part upon the geomagnetic position and the altitude of the modified ionospheric region. In general, the signals can be received in an area on the equatorial side of the modified region which has a large East-West extent, ranging up to about 4 000 km, but only 200 to 500 km in North-South extent.

A strong scattering region near 110 km altitude in the E-region can also be produced when the heating transmitter is operating on frequencies below the E-region critical frequency. Fewer observations have been made of the E-region scattering during modification, but the limited evidence suggests that the scattering is less aspect sensitive than that from the F-region and, thus, signals may be received on the ground in areas having a greater North-South extent than that found for the F-region.

From the evidence thus far obtained it appears that there is a potential for increased interference due to signals scattered from intended or unintended modified regions, at frequencies ranging from HF to UHF. It may also be expected that under proper conditions, interference between earth terminals and satellites could exist, since scattering occurs in all directions defined by the scattering cone and thus an earth transmitter will have energy scattered into space, and *vice versa*, by the irregularities in the modified region.

ANNEX 2

Ionospheric cross-modulation

1. Introduction

The propagation of strong modulated waves through a plasma produces perturbations in the plasma which cause changes to take place in the electron temperatures which in turn affect the collision frequency, ion chemistry and electron density; and therefore the conductivity and permittivity of the medium. The result of these changes in the medium produced by one modulated intense radio wave is the superimposition of its modulation on the carrier of another wave propagating through the same region. Because of the large number of transmissions using the HF, MF and LF bands which propagate through the D and E regions, this wave interaction or ionospheric cross-modulation is difficult to distinguish from co-channel interference and even more difficult to measure.

Measurements made in the MF/LF bands at middle latitudes show cross-modulation depths less than 7%. The measurements are shown in Recommendation ITU-R BS.498.

2. The simple theory of cross-modulation

For the communications engineer concerned with estimating the interference caused by cross-modulation, the main features of the phenomenon are presented below.

2.1 The electron collisional process

The free electrons which are mainly responsible for the reaction of the ionosphere on radio waves are located in D and lower E regions and may be regarded as a gaseous constituent statistically in thermal equilibrium with the far more numerous molecules in the atmosphere. Each electron may be considered to have a thermal energy Q_0 and a velocity V_0 related to the temperature θ_0 of the atmosphere by the gas equation:

$$Q_0 = \frac{1}{2} m V_0^2 = \frac{3}{2} k \theta_0 \qquad (1)$$

where m is the mass of the electron (9.1×10^{-31} kg), k is the Boltzmann's constant (1.37×10^{-23} joules per Kelvin) and θ_0 is in Kelvin, Q_0 and V_0 being in MKS units.

If at the point under consideration the equilibrium is disturbed by increasing the velocity of the electrons to V, Q_0 and θ_0 change to Q and θ in accordance with (1), the temperature of the surrounding atmosphere being unchanged. There is no conclusive evidence as to how the electron collision frequency depends upon V in the lower ionosphere, but it will be assumed here that the mean free path of electrons is independent of electron velocity, so that the collisional frequency ν is increased from its equilibrium value ν_0 proportionately with V. Thus:

$$\frac{Q}{Q_0} = \frac{\nu^2}{\nu_0^2} = \frac{\theta}{\theta_0} \tag{2}$$

At each collision some energy is transferred to the surrounding atmosphere, the amount being proportional to the energy excess and equal to $G\,(Q - Q_0)$ where G is a constant that from laboratory experiments on nitrogen is found to have a value of about 10^{-3}. The equilibrium is disturbed by the passage of a radio wave, and if the energy extracted from the wave by an electron in a collision at the time t is Q_e, the energy equation for the electron is:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \nu\,Q_e - \nu\,G(Q - Q_0)$$

which from (2) may be written:

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} = \frac{Q_e\,\nu_0^2}{2\,Q_0} - \frac{G}{2}\left(\nu^2 - \nu_0^2\right) \tag{3}$$

If Q_e were constant ν would ultimately take up a value $\overline{\nu}$ given by:

$$\overline{\nu} = \nu_0\left(1 + \frac{Q_e}{G\,Q_0}\right)^{1/2} \tag{4}$$

except possibly for very strong fields, $Q_e \ll G\,Q_0$ and therefore $\nu - \nu_0 \ll \nu_0$.

Thus with the removal of Q_e, $\nu - \nu_0$ decays exponentially to zero with a time-constant of $1/G\nu_0$. In the region of the ionosphere under consideration ν_0 is of the order of 10^6 collisions per second, so that this time constant is about 10^{-3} s corresponding to a frequency of 1 000 Hz. It therefore follows that the collisional frequency is unable to respond to the changes at radio frequency in the wave.

As, however, Q_e is proportional to the power density in the wave and hence to the square of the electric field E, the collisional frequency can respond to the r.m.s. value of the field. If this r.m.s. value is amplitude-modulated at audio frequency, the collisional frequency will in some measure be able to follow the modulation for frequencies not greatly in excess of 500 Hz.

2.2 The modulation process

In general the modulation on the radio wave will contain many audio frequencies, but to estimate the level of cross-modulation it is sufficient to consider a single frequency $\omega/2\pi$ and only the component of this frequency in the square of the field. Thus writing the r.m.s. radio field as:

$$E = E_0\,(1 + M\cos\omega t) \tag{5}$$

the square will be taken as:

$$E^2 = E_0^2\left(1 + \frac{M^2}{2}\right) + E_0^2\;2M\cos\omega t \tag{6}$$

where $M = 1$ for 100% modulation.

The mean value of E^2 is thus significantly above E_0^2, and it is this increased value that determines the mean value of ν in (4) while ν takes the form:

$$\nu = \bar{\nu}\,(1 + M_\nu) \tag{7}$$

where M_ν is the modulation derived from the modulation term in (6).

Writing Q_e as

$$Q_e = C E^2 \tag{8}$$

where the constant of proportionality C will be found by considering the attenuation of the radio wave by the electron collisions as it passes through the ionosphere, and taking the modulation component of ν in (7) as $\nu_0\, M_\nu$, the modulation equation derived from (3), (6) and (8) becomes:

$$\nu_0 \frac{\mathrm{d}M_\nu}{\mathrm{d}t} = \frac{\nu_0^2 \; C E_0^2 \, 2M \cos \omega t}{2\, Q_0} - \frac{G}{2}\, 2\nu_0 \,(\nu_0\, M_\nu)$$

or

$$\frac{\mathrm{d}M_\nu}{\mathrm{d}t} + G \nu_0\, M_\nu = \frac{\nu_0\, C E_0^2 \, M \cos\ \omega t}{Q_0}$$

whence

$$| M_\nu | = \frac{C E_0^2 \, M}{Q_0 \, G \left[1 + \left(\dfrac{\omega}{G \nu_0} \right)^2 \right]^{½}} \tag{9}$$

The denominator shows how the response drops off at higher audio frequencies.

2.3 The absorption process

As the radio wave passes through the ionosphere, the loss of the energy extracted by the electrons in the collisional process causes the wave to be exponentially attenuated according to an amplitude reduction factor exp $(-\int \alpha \mathrm{d}s)$ where the integral is taken over the transmission path and α is an absorption coefficient. By considering the absorption of the wave passing through a thin slab of unit cross-section, it can be shown that the energy Q_e extracted by each electron in a collision is:

$$Q_e = \frac{2 \alpha \mu \, E^2}{N \nu \, Z_0} \tag{10}$$

where μ is the real part of the refractive index of the ionosphere given by the Appleton-Hartree equation, N is the electron density (number of electrons per m^3) and Z_0 is the impedance of free space, the field E being in V/m.

As the radio frequency may be in the neighbourhood of the gyromagnetic frequency f_H, it is important to include the effect of the Earth's magnetic field by considering the case for which it is greatest, when the propagation is along the direction of the Earth's field. The value of α is then known to be:

$$\alpha = \frac{N e^2 \, Z_0 \, \nu}{2 \mu \, m \left[4\pi^2 \,(f \pm f_H)^2 + \nu^2 \right]} \tag{11}$$

where e is the electron charge (1.60×10^{-19} coulomb), f is the radio frequency in Hz, and the + and – signs refer to the ordinary and extraordinary waves respectively.

Thus from (8), (10) and (11):

$$C = \frac{e^2}{m \left[4\pi^2 \,(f \pm f_H)^2 + \nu^2 \right]} \tag{12}$$

The ν^2 term in the denominator can be neglected in the present estimate of cross-modulation if, say $4\pi^2 (f \pm f_H)^2 > 10\nu^2$ or $(f \pm f_H) > \nu/2$. This criterion is well enough obeyed at high and medium frequencies, except for the extraordinary wave near to the gyrofrequency, which is of the order of 1 MHz, where a resonance occurs increasing the value of C. Under these resonance conditions, especially for high power transmissions, the value of $\nu - \nu_0$ may be comparable with ν_0, and (4) from (8) and (12) should be regarded as a quadratic equation in $(\overline{\nu})^2$. At lower frequencies where f is of the order of or less than ν, a much more sophisticated full-wave treatment of the whole problem is really needed.

The value of C in (12) used in (9) gives

$$| M_\nu | = \frac{2e^2 E_0^2 M}{3\, m\, k\theta_0 \left[4\pi^2 (f \pm f_H)^2 + \nu_0^2\right] G \left[1 + \left(\frac{\omega}{G\nu_0}\right)^2\right]^{1/2}} \tag{13}$$

where Q_0 has been given its value in (1) and in the denominator ν^2 has been approximated by ν_0^2, in keeping with the assumption made in deriving (9) that C is a constant for a given carrier frequency.

2.4 Demodulation and cross-modulation

As the attenuation of the wave has the form of an amplitude reduction factor, the direct dependence of α in (11) upon ν implies that the modulation transferred from the wave to the collisional frequency reacts back on the amplitude of the wave. Actually this produces some demodulation of the wave, which is a phenomenon of considerable interest when using modulation experiments to investigate the physical structure of the lower regions of the ionosphere. For this purpose it is really necessary to make a much more detailed statistical analysis of the electron motion than has been adopted here which includes a close study of the gyromagnetic resonance.

More importantly here, however, the modulation imposed on α can similarly be transferred to the amplitude reduction factor of another wave of different frequency passing through the modulation region, giving rise to cross-modulation. Apart from its physical significance, this phenomenon is a source of interference which it is here the purpose to assess. In principle the effect is mutual, each wave to some extent being demodulated and modulating the other, but it is now desirable to distinguish between the frequencies and to regard one transmission as wanted, with its own modulation on to which some modulation is imposed from an unwanted or disturbing transmission. Calling the frequencies f_W and f_D respectively, the frequency f in (13) must now be interpreted as f_D.

If the amplitude reduction factor for the wanted wave is ρ, from (7) and (11) it is then given by

$$\rho = \exp\left(- \int \frac{Ne^2\, Z_0\, \overline{\nu}\, (1 + M_\nu)\, \mathrm{d}s}{2\mu\, m\, [4\pi^2 (f_W \pm f_H)^2 + \nu^2]} \right) \tag{14}$$

The integration is extended over the region of cross-modulation, which is of limited size because of the attenuation suffered by the disturbing wave in passing through the ionosphere, whereby the modulation in (13) imposed on the collisional frequency decreases with the decrease in E_0. The region may, however, be sufficiently extended for the increase of N and the decrease of ν with height in the ionosphere to be significant in estimating ρ in (14). Eventually the product $N\nu$ decreases, but initially it can increase with height.

The time of passage of a wave-front through the region is so short that (14) may be regarded as an integration across the region at a moment of time on the audio-frequency time scale. Thus M_ν is held constant with respect to time during the integration, and the consideration of the time variation of M_ν at the audio frequency shows that ρ becomes modulated and may be written in terms of a mean value and modulation M_ρ by:

$$\rho = \bar{\rho}\,(1 + M_\rho) \tag{15}$$

Thus:

$$\log_e \rho = \log_e \bar{\rho} + \log_e (1 + M_\rho)$$

or since it may be anticipated that $M_\rho << 1$

$$\log_e \rho = \log_e \bar{\rho} + M_\rho \tag{16}$$

As $M_\rho = 0$ when $M = 0$, it follows from (14) and (16) that

$$\log_e \bar{\rho} = - \int \frac{N e^2 \, Z_0 \, \bar{\nu} \, \mathrm{d}s}{2\mu \, m \, [4\pi^2 (f_W \pm f_H)^2 + \bar{\nu}^2]} \tag{17}$$

$$M_\rho = - \int \frac{N e^2 \, Z_0 \, \bar{\nu} \, \mathrm{d}s}{2\mu \, m \, [4\pi^2 (f_W \pm f_H)^2 + \bar{\nu}^2]} \tag{18}$$

where in the denominators the modulation on ν^2 has been neglected by using the mean value.

The integral for M_ρ in (18) may now be estimated by taking M_ν outside as a mean value while formally retaining the dependence of N and ν on position inside the integral, so that from (17) in terms of amplitudes

$$| M_\rho | = - | M_\nu | \log_e \bar{\rho} \tag{19}$$

and hence from (13):

$$| M_\rho | = - \frac{2e^2 \, E_0^2 \, M \log_e \bar{\rho}}{3 \, m \, k \theta_0 \left[4\pi^2 \, (f_D \pm f_H)^2 + \nu_0^2 \right] G \left[1 + \left(\frac{\omega}{G \nu_0} \right)^2 \right]^{1/2}} \tag{20}$$

with an estimated mean value of E_0^2 within the modulation region.

The determination of $\log_e \bar{\rho}$ from (17) implies a knowledge of the distribution of N and ν in the modulation region for an assumed model of the ionosphere. The reduction factor $\bar{\rho}$ may be derived from measurements of the reflection coefficient of the ionosphere for the frequency of the wanted wave, on the assumption that there is no deviative absorption near to the reflection point in the ionosphere, that all the absorption occurs at the level of cross-modulation, and remembering that the modulation may not occur on both the upgoing and downcoming paths. If $\bar{\rho}$ is expressed in terms of a positive decibel loss D, then:

$$D = - 20 \log_{10} \bar{\rho} = - 8.7 \log_e \bar{\rho} \tag{21}$$

If also the cross-modulation region is at a distance d km from the disturbing transmitter which has an e.i.r.p. of P kW in the direction of the region, then:

$$E_0 = \frac{0.1732}{d} \sqrt{P} \qquad \text{V/m} \tag{22}$$

It will then be found from (20), (21) and (22) that with the numerical values of e, m and k already given, and for $G = 1.3 \times 10^{-3}$ and $\theta_0 = 300$ K at the modulation level:

$$|M_\rho| = \frac{0.31\, P\, D\, M}{d^2 \left[(f_D \pm f_H)^2 + 0.025\, \nu_0^2 \right] \left[1 + \frac{2.34 \times 10^{-5}}{\nu_0^2} f_M^2 \right]^{½}} \tag{23}$$

where f_D, f_H and ν_0 are in MHz and the modulation frequency $f_M = \omega/2\pi$ is in Hz.

3. Improved theory

Although a useful guide, the simple theory discussed above may not always be adequate to assess the probable levels of cross-modulation to be expected. By classifying a given situation into one of five basic categories, Table 1 shows under what conditions the simple theory may be expected to fail and how it may be amended easily to achieve more reliable predictions. For example, calculations borne out by experimental results show how the transferred modulation is greater than expected when the wanted wave reflection level is located within the disturbed region. If the disturbed region is very low down in the ionosphere, however, an increase in the average power of the disturbing wave does not necessarily imply an increase in the modulation transferred to the wanted wave. These are examples of cases III and I respectively, of Table 1.

4. Discussion

A simple derivation of an approximate cross-modulation equation is given in symbolic form in (20) and in numerical form in (23). It is based on the concept of the change in absorption caused by the change in collision frequency as the link between the modulation on the disturbing wave and that transferred to the wanted wave. Section 3 of Recommendation ITU-R BS.498 lists some of the factors on which the depth of the cross-modulation depends.

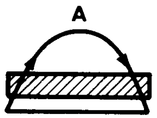
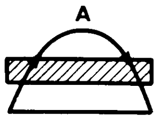
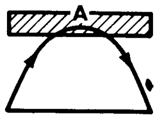
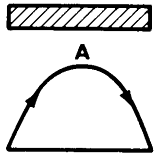
As is to be expected, the cross-modulation is directly proportional to the depth of modulation on the disturbing wave and on the radiated power in the direction of the modulation region in the ionosphere from the disturbing transmitter. The dependence upon the decibel loss suffered by the wanted wave in the modulation region stresses the fact that not only must the wave pass through the modulation region on its passage to the receiving point on the Earth, but that it must also suffer absorption in the process. Thus although the cross-modulation does not depend intrinsically on the power of the wanted transmission, this power must be sufficient for the received signal to survive the loss by absorption in the region. A typical value of D would be 10 dB if the loss is not to be excessive, while it is clear that the phenomenon will not be observed on sufficiently high frequencies where the absorption is very small because of the large value of f_W in (14).

The direct effect of the Earth's magnetic field on the wanted wave is implicit in determining the value of D from $\bar{\rho}$. It is greatest for the extraordinary wave for which, under some conditions, the absorption may be effectively complete, leaving only the cross-modulation on the ordinary wave. The reception of cross-modulated signals therefore depends on the polarization characteristics of the transmitting and receiving antennas and on the time of day.

TABLE 1

Categories for cross-modulation estimation

The path of the wanted wave is shown in relation to the disturbed region

Case	I	II	III	IV	V
Configuration					disturbing wave frequency close to gyrofrequency
Location of disturbed region	far below A	below A	near to or at A	above A	anywhere
M_ρ (relative)	small	medium	large	small	large (if geometry suitable)
Simple theory	not adequate	adequate	not adequate	not adequate	not adequate
Examples	$f_W \approx 10 f_D$ or $f_W > 10 f_D$	$C_D f_D < C_W f_W$	$f_W > f_D$ $(C_D f_D \approx C_W f_W)$	$10 f_W < f_D$ or $f_D \approx f_W$ $(C_D f_D > C_W f_W)$	disturbing transmitter close to wanted wave trajectory

where C_D C_W are the cosines of the angles of incidence on the ionosphere of the disturbing and wanted waves respectively.

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As shown in (23) the part played by the Earth's field is more significant for the disturbing wave. The transmission may be intended for medium or low frequency ground wave propagation on the basis that the wave entering the ionosphere is heavily absorbed. It is evident that the extraordinary wave is particularly effective in modulating the collisional frequency when the disturbing frequency is near to the gyrofrequency. On the other hand the absorption of the wave restricts the volume of the cross-modulation region and hence the decibel loss of the wanted wave in traversing the region. In a more rigorous investigation of the power absorbed by the medium from the disturbing wave, the combined effect of the ordinary and extraordinary waves must be used.

The relation between M_ρ and M_ν in (19) is based on a mean value of M_ν and this implies a mean value of ν_0 in (23) and a power P somewhat less than the actual e.i.r.p. of the disturbing transmitter. The collisional frequency has a controlling influence at the gyromagnetic resonance for the extraordinary wave, but otherwise the rapid decrease of ν_0 with increasing height mainly restricts the audio-frequency range over which cross-modulation is obtained. Values for ν_0 decrease exponentially with height and typically at night there are 10^6 collisions per second at 81 km and 10^5 at 94 km.

As the frequency of the disturbing wave is increased above the gyrofrequency, the cross-modulation eventually varies as f_D^{-2}.

Then (23) can be put in the simple approximate form:

$$P = \frac{3.2 \, | M_\rho | \, d^2 f_D^2}{M D} \qquad \text{kW} \tag{24}$$

In order to assess the nuisance value of interference on the wanted wave, it is assumed that $| M_\rho | = 0.03$, that the disturbing wave is 40% modulated so that $M = 0.4$, and that $D = 10$ dB. Then at 1.6 MHz for $d = 150$ km, corresponding to a wave incident on the ionosphere at about 45°, the power of the disturbing wave should not exceed 1.4 MW if cross-modulation is to be acceptable. With the e.i.r.p. values now obtainable at MF, it seems likely that cross-modulation interference troubles may arise, especially as the simplified form in equation (24) excludes possible gyromagnetic resonance effects. However, a study for the same conditions for frequencies above 5 MHz shows that even the very high values of e.i.r.p. currently associated with HF broadcasting are unlikely to cause sufficient modulation to be a nuisance.

5. Experimental measurements of cross-modulation imposed upon signals with frequencies as low as 20 kHz have been made using transmissions from WWVL at Fort Collins, Colorado (United States of America) as the wanted signal and transmissions from Platteville, Colorado (United States of America) as the modifying signal. The Platteville transmitter operated on 7.4 MHz and had an e.i.r.p. of 50 MW. The 60 kHz transmission from WWVB from Fort Collins, Colorado (United States of America) received at Bennet, Colorado, was the wanted signal. Both ordinary and extraordinary polarizations of the Platteville signals were used. The cross-modulation effects were, as expected, much stronger for the extraordinary than the ordinary polarization.

6. Interpretation of cross-modulation effects has been largely confined to the changes in conductivity (i.e., modulation transfer as a result of changes in wanted signal attenuation) and has not considered changes in permittivity. The changes in permittivity that can result from the presence of signals from high power transmitters suggests that wanted signals involving modulation other than amplitude modulation may also be affected by a cross-modulation phenomenon.

ANNEX 3

Solar power satellites and the ionosphere

In the late 1970s and early 1980s, solar power satellites (SPS) were viewed as possibly providing a significant contribution to the Earth's future energy requirements. A typical concept of such a system involved collecting solar energy by a large array of solar cells in geostationary orbit, converting to RF power at microwave frequencies and beaming the microwave energy to earth collectors for conversion into a d.c. power grid. Because the power levels involved with SPS systems far exceed those normally encountered in radio transmission, it is possible that the interaction of the microwave beam with the ionosphere and troposphere could produce serious effects on existing radio services.

The impact of the operation of solar power satellites on the ionosphere may be separated into two broad categories: those in which the ionospheric plasma influences the propagation characteristics of the microwave power beam and those whereby the ionospheric plasma itself is modified. In the former case, electron density gradients and irregularities may affect the propagation of the power beam. Refraction effects may cause the apparent position of the power beam to change. Ionospheric irregularities could cause scintillation and scattering of the power beam possibly giving rise to co-channel interference to other radio systems.

The modification of the ionospheric plasma by the passage of a high power microwave beam through it results from the ohmic heating of the electrons by the power beam. This ohmic heating can cause increased absorption of radio waves transversing the same region as the microwave power beam. Also the ohmic heating could produce thermal self-focusing leading to the formation of electron density irregularities that could scatter radio waves at much lower frequencies if they encountered the scattering volume. Fortunately the region of the ionosphere in which these effects are likely to occur is generally confined to the vicinity where the power beam passes through the ionosphere.

ANNEX 4

Artificial modification of the ionosphere by chemical injections

Typical rocket exhaust products such as H_2, H_2O and CO_2 can cause large-scale depletions of the electron density in the ionospheric F-region. This results from these products transforming the F-region plasma which is usually dominated by atomic ion processes to a plasma that is dominated by molecular ion processes. Once the molecular ions associated with these products are formed, they dissociatively recombine with the ambient electron density at a rate that is 100 to 1 000 times faster than the recombination of electrons with the naturally occurring molecules of nitrogen (N_2) and oxygen (O_2). The result of this is the creation of an "ionospheric hole" in the F-region. The lack of large-scale effects due to chemical injections in the lower ionosphere is due to the high neutral densities and molecular ion chemistry that dominates at D- and E-region heights.

The ionospheric depletion that results from chemical injections has been observed using measurements of total electron content and HF radio signals. The theory explaining the physical mechanisms involved in the creation of ionospheric depletions by chemical injections is well developed.