

RECOMMENDATION 532-1

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

(Question 39/6)

(1978-1992)

The CCIR,

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.



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 $\leq 10^3/\text{s}$, 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 $\sim 2 \times 10^5/\text{s}$, 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 $\omega \gg \nu$, 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 m²) 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 (≤ 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 4000 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 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:

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

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.