Modifying the Ionosphere with Intense Radio Waves

Powerful ground-based radio transmissions are now being used to induce observable ionospheric changes.

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Appreciable local perturbations of the ionosphere are now being produced by the action of powerful radio waves directed vertically upward. These modifications are transitory and self-reversible, having lifetimes of the order of seconds, minutes, or hours, but not days. The modified region is about 100 kilometers in diameter, centered at a height between 250 and 350 kilometers, and shaped in the form of a spheroid, prolate along the lines of the geomagnetic field.

The ionosphere is that region of the earth's upper atmosphere where the constituent gases are slightly (up to 1 percent) ionized, mainly by solar radiation. It is an electrically neutral region, with equal numbers of positive and negative particles. Negatively charged electrons, being less massive than the positively charged ions, are the ionospheric particles that interact most strongly with radio waves. Ionization in amounts large enough to have significant effects on radio waves begins in the D region at an altitude of about 60 kilometers, and the density of ionized particles tends to increase with height through the D and E regions (see Fig. 1). Above these regions is the F region, having peak electron and ion densities in the neighborhood of 10^6 particles per cubic centimeter at a height of about 300 kilometers. The shape of the ionization profile varies diurnally, seasonally, with sunspot activity, and with latitude and longitude. The ionization between 200 and 400 kilometers consists primarily of O^+ ions and an equal number of electrons. These charged particles are immersed in about 10^8 particles per cubic centimeter of neutral gases, consisting largely of O_2, O, N_2, and He. The various constituents are characterized by temperatures derived from the kinetic theory of gases known as the ion temperature T_i, the electron temperature T_e, and the temperature of the neutral particles, T_n. Typical daytime values expected near 300 kilometers at Boulder, Colorado, are $T_i = 1000°K$, $T_e = 2000°K$, and $T_n = 950°K$, whereas evening values are $T_i = 900°K$, $T_e = 1200°K$, and $T_n = 900°K$.

The ionosphere interacts with radio waves, thus permitting relatively inexpensive long-distance communications by virtue of the bending of radio waves of appropriate frequencies back toward the earth, through refraction. The ionosphere can also have an effect on radio waves used in space communications. In addition to their utility in long-range communications, radio waves constitute a convenient means for the remote study of the local ionosphere. The ionosphere has been studied for many years by means of radio, photometric, and in situ probe techniques.

Since the advent of rockets and satellites, man has employed artificial modification of the ionosphere as a method for studying it. Modification has been accomplished by such means as the release of chemicals, the detonation of atomic bombs, and the use of small electron-beam accelerators. The possibility of active experimentation, in which the ionosphere is temporarily modified by means of high-power, ground-based radio transmissions, has long been a desire of researchers. By contrast with the other techniques, ionospheric modification with the use of radio transmissions at frequencies that interact with the ionosphere represents an attractive and hygienic alternative, in view of its relative controllability, repeatability, and rapid reversibility. Such modification is useful for the determination of parameters of interest in aeronomy, for application to ionospheric telecommunications, and for the production and study of instability phenomena related to plasma physics.

The development of radio methods for modifying the ionosphere, in combination with radio and optical techniques for monitoring the resulting perturbations, represents a means for carrying out experiments on the ionospheric plasma, rather than merely a means for observing it. Thus, the "outdoor plasma" can now, for the first time, be treated somewhat as if it were a laboratory plasma. Moreover, this "plasma laboratory in the sky" represents an arena that has certain advantages over a laboratory plasma. One of these advantages is the absence of boundaries and their associated complications. On the other hand, the ionospheric plasma is permeated, for better or worse, by the geomagnetic field, which is difficult to vary artificially. At least one plasma instability has been excited in the ionosphere during modification. We anticipate that the study of artificial instabilities will provide information to aid in understanding naturally occurring ionospheric instabilities. Indeed, the artificial instability that can now be excited, giving rise to ionospheric "spread F" irregularities (discussed in the section on "Experimental Results"), may be identical to the natural instability associated with at least some classes of these irregularities.

The ionospheric modification studies discussed here involve mainly that portion of the ionosphere known as the F layer, in particular, the altitude range from 150 to 400 kilometers. Much of the impetus for studies of F-layer modification stems from the work of Ginzburg and Gurevich (*1*) and of Farley (*2*). Farley was concerned initially with the possible F-layer modification (through heating of the ionospheric electrons) that might be inadvertently produced by the powerful incoherent scatter radars while they were being used for ionospheric studies. He found that the electron temperature elevation resulting from the incoherent scatter radiation was negligible, even at the lowest radio frequency (42 megahertz) used by such radars. Thus, in the course of measurements of the electron tem-

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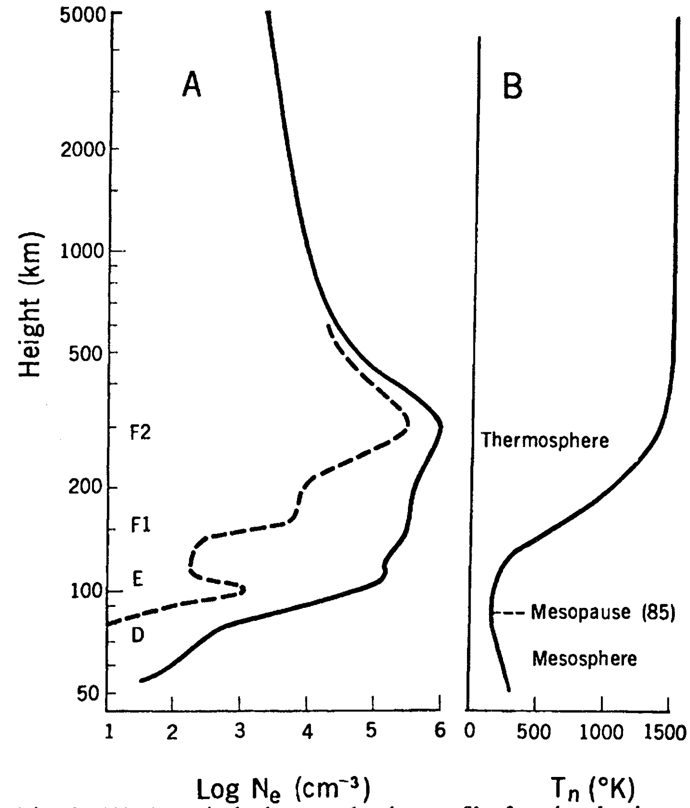


Fig. 1. (A) A typical electron density profile for the daytime (solid line) and nighttime (dashed line) ionosphere at mid-latitudes, showing the strata known as the D, E, F1, and F2 layers. (B) A height profile of neutral temperature in the daytime. [This figure was adapted from (*21*); courtesy of John Wiley & Sons, New York]

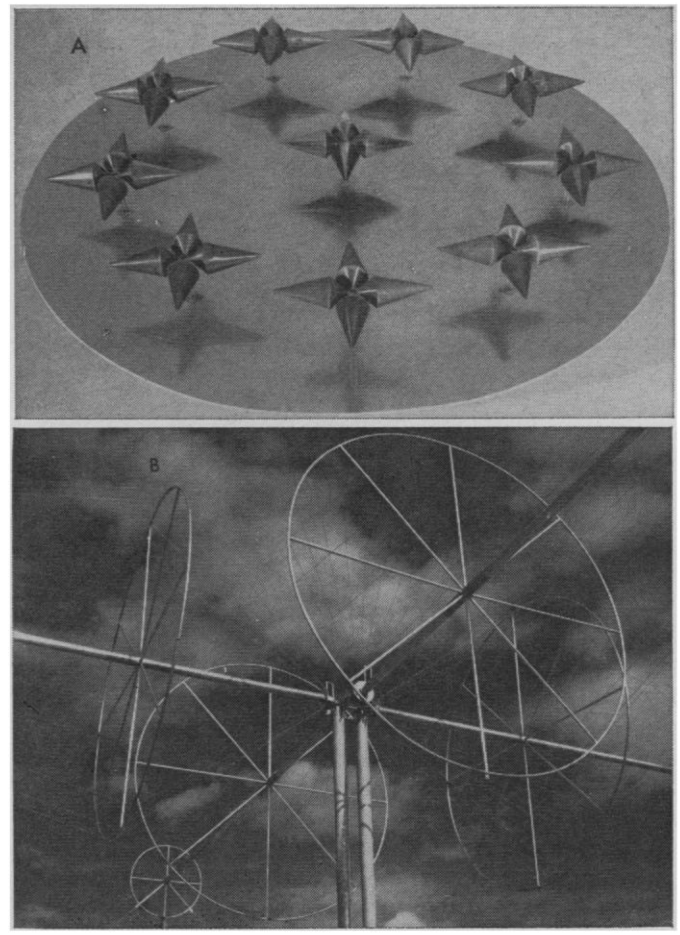
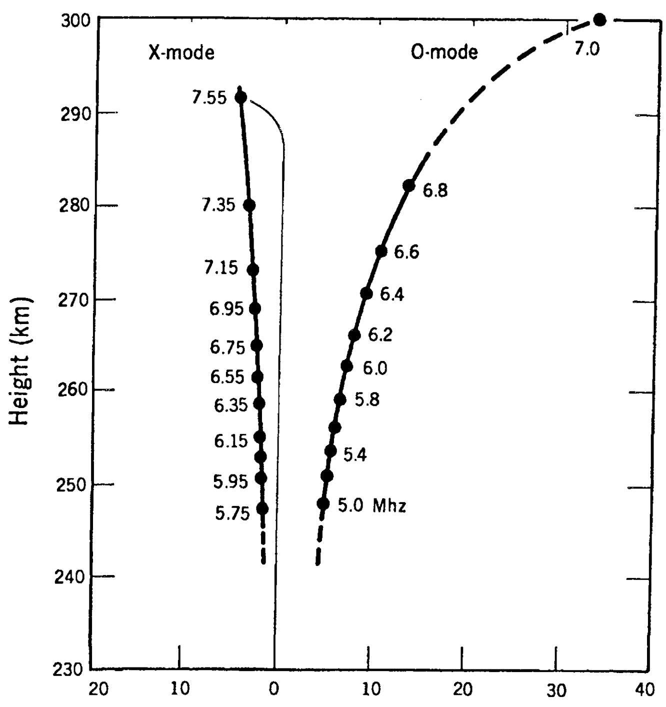


Fig. 2. (A) A model of the 5- to 10-megahertz crossed-dipole antenna array at Platteville, constructed to a scale of 1 : 100. The nine-element ring has a diameter of 110 meters in the full-scale array. The central element aids in suppressing side lobes. (B) A portion of one element of the actual antenna array at Platteville.



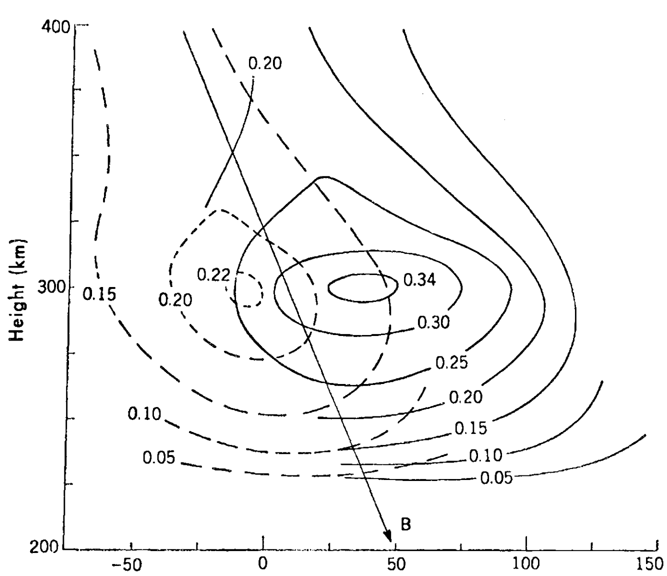


Fig. 3 (left). Typical apogee positions in the magnetic north-south vertical plane (referred to the location of the heating transmitter) attained by the O-mode and X-mode, as a function of frequency. Penetration frequencies for the O-mode and X-mode are 7.00 and 7.75 megahertz, respectively. Fig. 4 (right). Predicted relative change in the steady-state electron temperature, expressed as a fractional increase of the ambient value, in the plane of the magnetic meridian for O-mode (solid line) and X-mode (dashed line) heating. The direction of the geomagnetic field is shown by the vector, **B**. These results are based on the theory outlined in (*4*) and have been computed for a radiated power of 1 megawatt and an effective antenna gain of 17 decibels with a half-power beam width of about 20 degrees. Estimates of the O-mode and X-mode heating are for frequencies 0.3 and 1.4 percent higher than the respective penetration frequencies. The ionospheric model is taken to be a Chapman layer with a scale height of 40 kilometers, a peak height of 300 kilometers, and a maximum plasma frequency of 7.0 megahertz.

perature with the incoherent scatter technique, there is no associated perturbation of the parameter being measured.

However, Farley sensibly went on to calculate how an appreciable perturbation of the ionospheric F layer could be effected by the utilization of radio transmission at a more strongly interacting frequency, resonant with the highest natural oscillatory frequency of the F layer. (The electrons in plasmas naturally oscillate back and forth weakly at a frequency proportional to the square root of the local electron concentration and reflect radio waves at that frequency. This frequency is known as the "electron plasma frequency." The maximum ionospheric plasma frequency at a given time is called the "critical" or "penetration" frequency, f_0, of the F layer. The F-layer penetration frequency is the lowest radio-wave frequency that would pass through the ionosphere, and typically it ranges between about 5 and 10 megahertz.) On the basis of their calculations, both Farley (*2*) and Gurevich (*3*) predicted that a doubling of the ionospheric F-layer electron temperature could be achieved, with sufficiently powerful combinations of transmitter and antenna, during evening hours. In this conclusion both Farley and Gurevich assumed the absence of the highly absorbing daytime D layer, which presumably would cause insufficient radiation to reach the F layer. (Nevertheless, as we shall see, an appreciable daytime modification has been produced.)

According to Farley (*2*), the diffusion of the hot electrons up and down along the geomagnetic field lines would simultaneously result in a depletion of the electron concentration in a region; that is, a hole in the ionosphere would be created. Electrons are constrained to spiral along magnetic field lines and thus can diffuse (and heat can be conducted) more readily along these lines than across them.

A more refined, time-dependent calculation of ionospheric heating was made by Meltz and LeLevier (*4*). This treatment includes the ionospheric refraction of radio waves in the presence of the earth's magnetic field, and it is based on the assumption that the incident radiation is deposited in the ionosphere at a frequency just above the (time-varying) F-layer penetration frequency. In practice, large transmitters are difficult to tune and operate continuously at variable frequencies. Accordingly, the modus operandi for the actual modification experiments presently involves the utilization of a relatively fixed transmitter frequency, usually located somewhat below the penetration frequency. (Frequencies as low as 50 percent of the penetration frequency and up to 20 percent above it have actually been employed.) A complete theoretical analysis for frequencies departing appreciably from the penetration frequency has not yet been carried out. However, Thomson (*5*) has treated this case, including a consideration of ionospheric refraction but omitting a

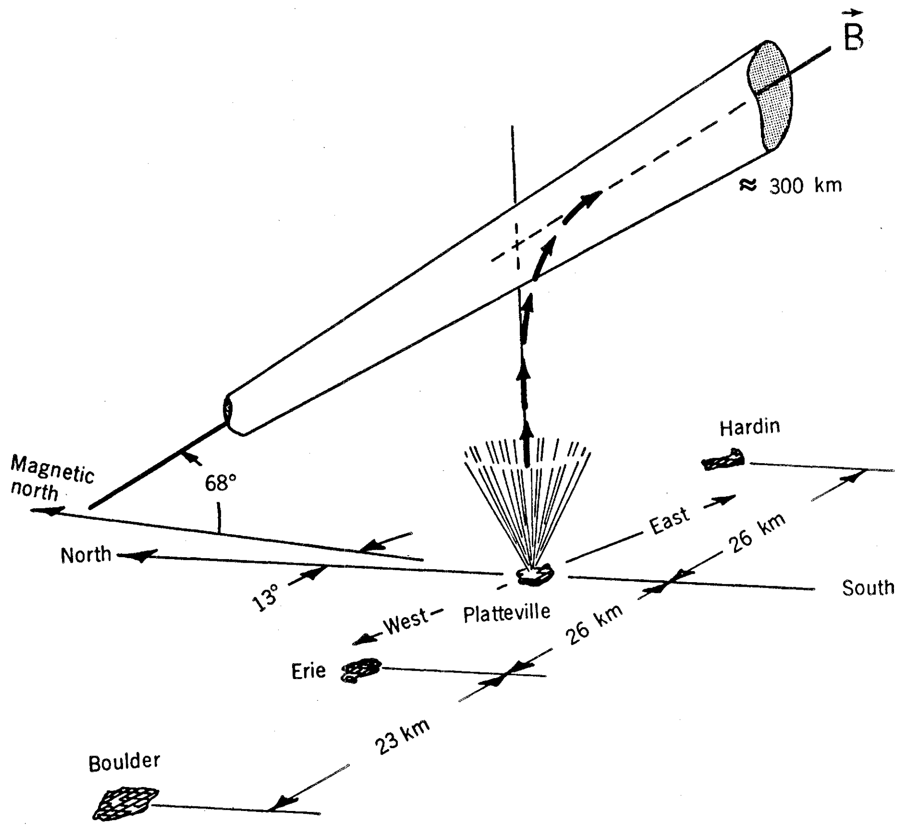


Fig. 5. Schematic view of the ionospheric modification experiment. The Platteville transmitter facility (40.18°N, 104.73°W) with a power-aperture product of 10^4 megawatt–square meters is the source of the excitation. Ionosondes were located at Erie and Boulder, and oblique path radio-wave measurements were made between Erie and Hardin. Optical and infrared observations at 6300 angstroms and 1.27 microns were also made at Erie. A typical X-mode ray path is illustrated by a series of arrows.

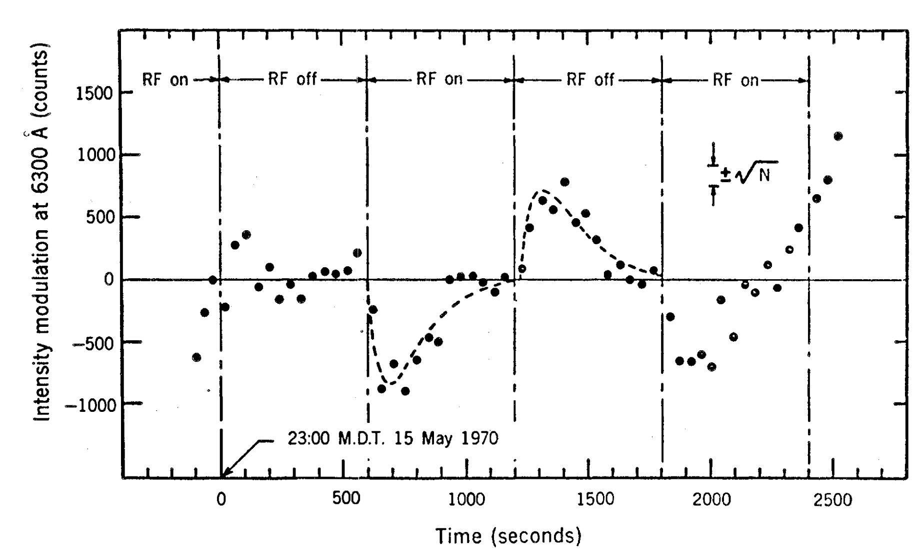


Fig. 6. Airglow intensity modulation at 6300 angstroms induced by cycling the X-mode excitation on and off at 10-minute intervals. RF, radio frequency. The dashed curve is a theoretical fit to the data based on appropriate parameters. [Adapted from figure 2 in (*9*); courtesy of the American Geophysical Union, Washington, D.C.]

consideration of the influence of the geomagnetic field. His treatment should be an aid in understanding the experimental results.

Soon after Farley suggested the experiment, Potemra (*6*) attempted to produce ionospheric heating, utilizing a 40-kilowatt transmitter at 7.7 megahertz and an antenna beam width of 12 degrees. However, the sensitivity of his system was inadequate to detect any modification effects. Two experimental facilities with greater capability now exist and have produced significant ionospheric modifications. One of these is operated by the U.S. Department of Commerce near Boulder, Colorado (*7*); the other is the Arecibo Observatory in Puerto Rico, operated by Cornell University (*8*).

Experimental Installations and Theoretical Expectations

We describe here briefly our Boulder facility, which consists of a transmitter capable of delivering about 2.0 megawatts to a large ring-array antenna, which provides a power-aperture product of about 10^4 megawatt-square meters. The antenna (Fig. 2) has been designed to operate between frequency limits of 5 to 10 megahertz, approximately the diurnal range of ionospheric penetration frequencies usually encountered over Boulder. The antenna beam width is about 16 degrees (between half-power points) at mid-band. This antenna can be excited so as to radiate electromagnetic energy having either right-circular or left-circular polarization (that is, with electric vectors rotating clockwise or counterclockwise). These polarizations nearly coincide, respectively, with the "ordinary" and "extraordinary" modes of propagation characterizing a doubly refracting magnetoionic medium such as the ionosphere. These modes, usually described as the O-mode and the X-mode, respectively, have different propagation velocities and traverse different paths in the ionosphere.

An example of the difference in propagation of the two modes is shown in Fig. 3. Here, in the vertical, north-south magnetic plane, both ordinary and extraordinary modes of various frequencies are considered to be launched at vertical incidence to the ionosphere. Ray-tracing analysis is then used to determine the paths of the rays at each frequency for each mode. Such rays attain a highest altitude, or "apogee height," at which they are reflected. Figure 3 is a plot of the loci of such apogee heights. Thus, the X-mode experiences a deviation toward the south, since it has a tendency to travel parallel to the geomagnetic field, whereas the O-mode experiences a deviation toward the north since its direction of propagation tends to perpendicularity with the field. At a given frequency, the O-mode attains a greater height than the X-mode. The consequence of this magnetoionic refraction is that the modified volume is displaced magnetically either north or south of the vertical, depending upon what polarization is radiated.

The expected absorption process by which ionospheric heating of the F layer is produced by an intense radio wave is as follows. Electrons located near a height at which the plasma frequency is close to the radio-wave frequency are driven into oscillation. They would merely reradiate the additional energy at the radio-wave frequency but for the fact that individual electrons undergo collisions (about 10^3 per second and mainly with ions) prior to the reflection or transmission of the incident wave. Those electrons experiencing collisions thus extract a small amount of energy from the wave, in the form of random (that is, thermal) motion. Because of this absorption, the ambient electron temperature is increased in the neighborhood of the height of energy deposition. Heat is conducted away from the height of deposition up and down along geomagnetic flux tubes, with the result

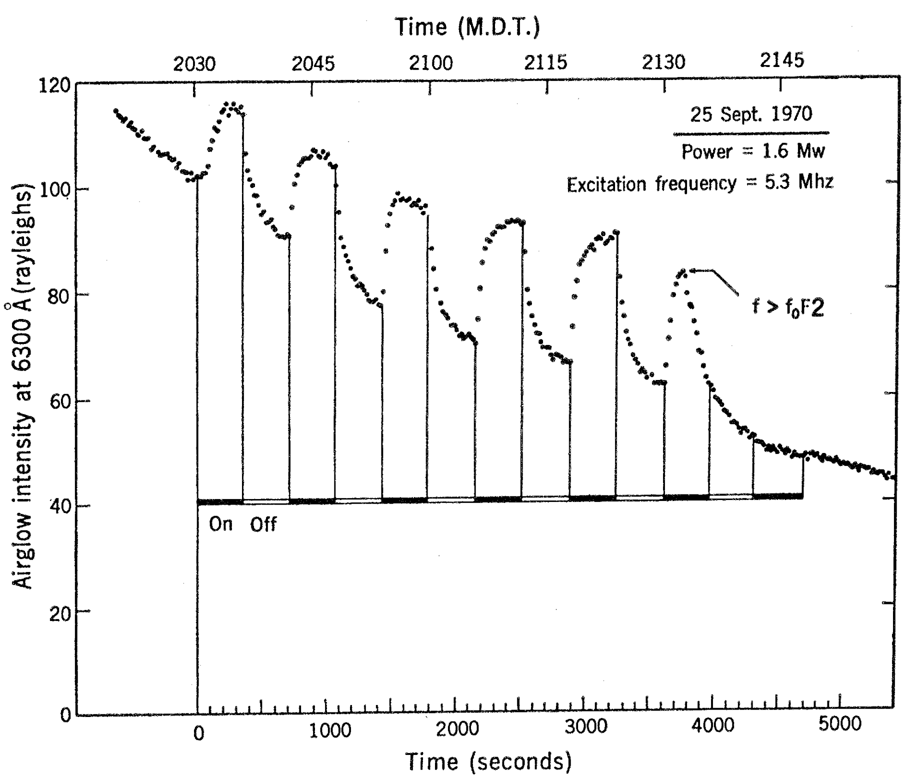


Fig. 7. Intensity modulation at 6300 angstroms induced by cycling the O-mode excitation on and off at 6-minute intervals. [Provided by Sipler *et al.* (*10*).]

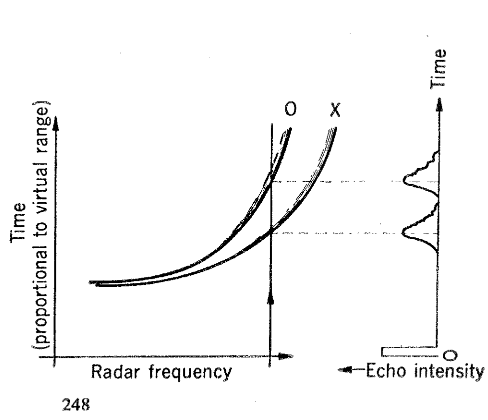


Fig. 8. A demonstration of ionogram synthesis. At the right is a plot of echo intensity versus time delay for a single frequency, and the ionogram at the left is produced by the superposition of such information as a function of frequency, with the echo-intensity information used to modulate the intensity of the oscilloscope trace. The traces on the ionogram are spread, to illustrate the phenomenon of spread F.

that there is produced a heated region of considerable extent above and below that height.

Thomson (*5*) studied how the efficiency of absorption varies with the frequency of the radio wave and demonstrated that the ionosphere acts like a blackbody in the vicinity of the penetration frequency. Near that frequency, less energy is reflected and more energy is absorbed from the incident radio wave. As the incident frequency approaches the penetration frequency from below, the wave is increasingly absorbed at heights near its level of reflection. This is so because, for a typical profile of F-layer ionospheric electron density (Fig. 1), the wave is continuously slowed down by the medium. This effect has a height dependence roughly the inverse of the rate of change of ionization with height. More slowly moving waves spend a longer time in the medium and are able to deposit heat more effectively; hence reflectivity gives way to absorptivity as lower gradients are approached, and absorption is maximized at the penetration frequency, where the gradient is zero. Above the penetration frequency, reflectivity decreases to zero, absorptivity decreases with increasing frequency, and the ionospheric transmissivity soon increases to nearly unity.

Thus, at a selected radio frequency of excitation, heat is deposited into the ionosphere at a height of comparable electron plasma frequency and conducted along geomagnetic field lines, resulting in the development of spheroidal contours of incremental electron temperature. Calculations by Meltz and LeLevier (*4*), based upon the parameters of the Boulder installation, gave these contours for the case of optimum heat transfer, where the modifier transmitter is tuned to a frequency just above the F-layer penetration frequency. An example of their predicted contours in the magnetic north-south vertical plane is shown in Fig. 4. Because of the difference in wave paths for the two magnetoionic modes, as shown in Fig. 3, two sets of results are obtained, according to which mode is launched by the antenna. These sets of contours are superimposed in Fig. 4 and are the predicted percentage increments in electron temperature expected after several minutes of irradiation at frequencies about 1 percent greater than the respective penetration frequencies of the ordinary and extraordinary modes.

Enhancements in electron temperature, as shown in Fig. 4, taking place within tens of seconds, would then be expected to lead to ambipolar diffusion (diffusion in which the Coulomb attraction between oppositely charged particles is important) of the heated plasma along geomagnetic field lines, in directions away from the positions of most intense heating. Such diffusion would produce a region of reduced electron density embedded in the ambient ionospheric plasma, and this volume would be described by contours similar to those of Fig. 4, with the difference that these contours would represent depletions in the electron density. The rate at which electron density would be reduced, however, would be much slower than that at which temperature enhancements would be produced, contrary to the original prediction of Farley (*2*). Time constants of about 20 minutes rather than 20 seconds would be required, and such times are comparable to times during which appreciable natural changes of the ambient ionosphere occur. (This sluggishness occurs because the plasma must maintain local electrical neutrality; hence the more slowly moving ions that must accompany the electrons retard them through Coulomb attraction. The ions are less mobile than the electrons because of their greater mass and also because of collisions with neutral particles.)

The expected modifications of electron temperature and density, motions of the ionospheric plasma, and changes in other properties of the plasma should be amenable to experimental detection. Various techniques are available for this purpose. Techniques employed to date include the observation of atmospheric airglow emissions and the reflection and incoherent scattering of radio waves. Changes induced in airglow emissions (at 6300 angstroms) can be interpreted in terms of changes in the electron temperature, since the dissociative recombination rate of electrons and O_2^+ ions (which produces the normal airglow) has an inverse temperature dependence (*9*).

The incoherent scatter technique (employed at Arecibo) is capable of monitoring electron density and temperature changes, along with plasma motions. Ionosonde (swept-frequency radar) measurements provide informa-

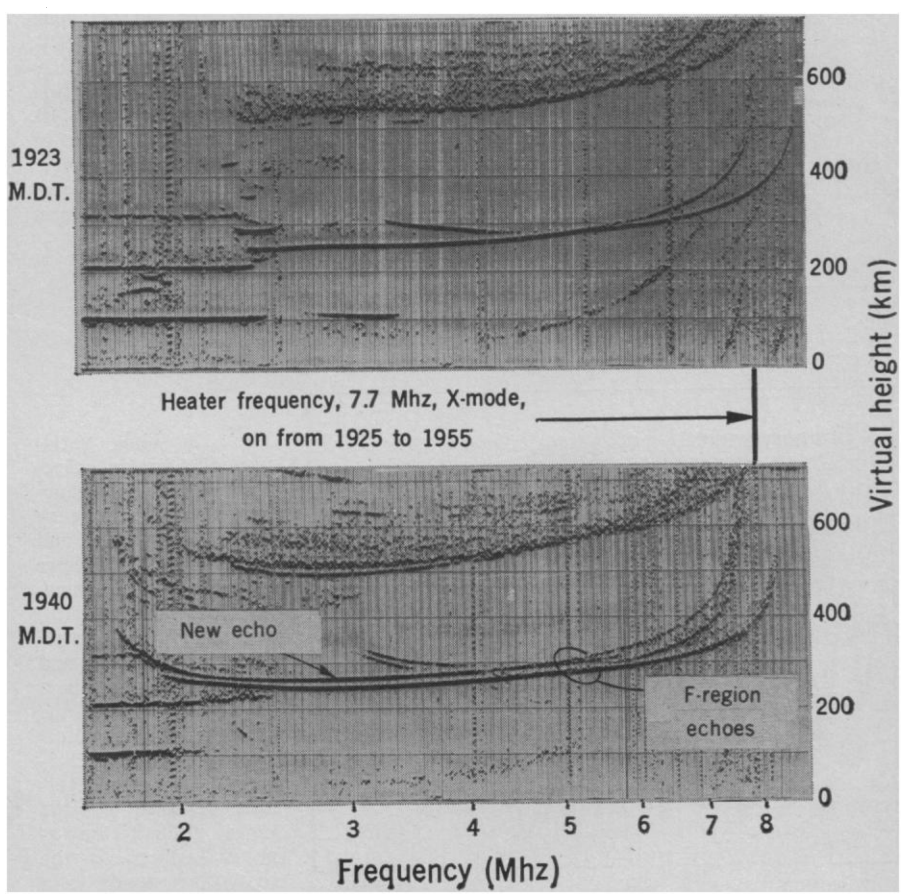


Fig. 9. Erie ionograms (30 April 1970) showing the development of a delayed, broadband trace during the ionospheric modification.

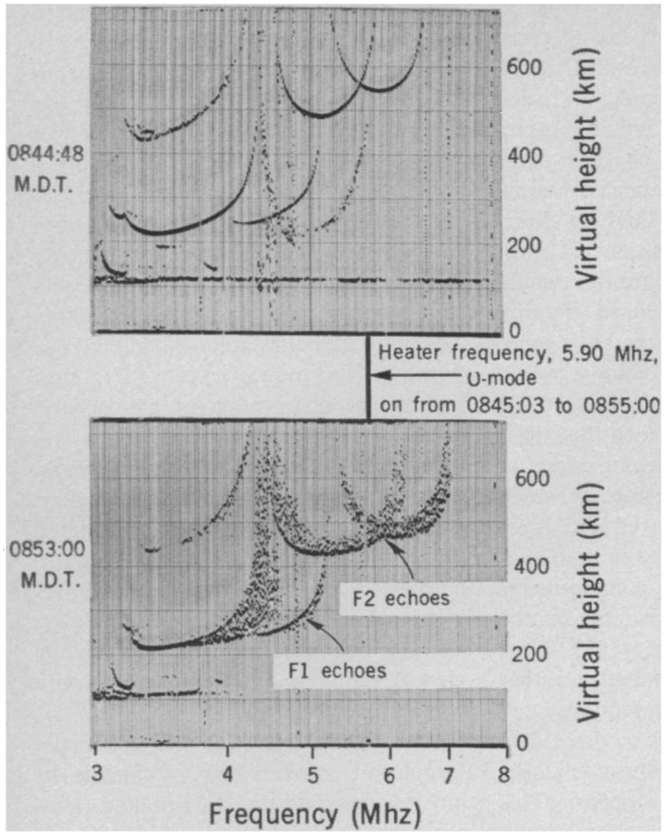


Fig. 10. Erie ionograms (24 July 1970) showing the development of daytime spread F during excitation by the high-power ground-based transmitter.

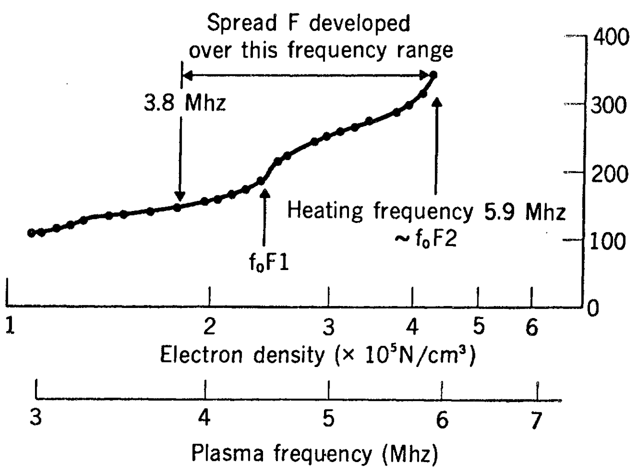


Fig. 11. True-height profile (24 July 1970, 0844:48 M.D.T.) derived from the first ionogram of Fig. 10, showing the range of heights at which irregularities resulting from modification were presumably located.

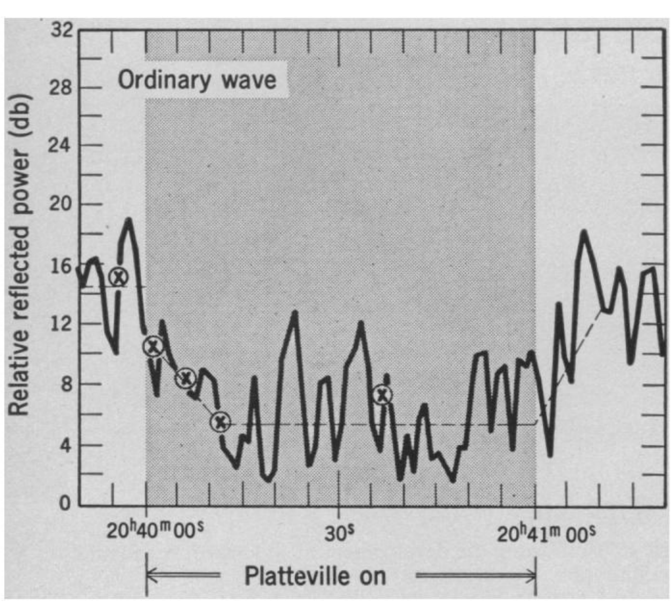


Fig. 12. Time variation of O-mode reflectivity, based on a diagnostic wave frequency of 6.342 megahertz and an O-mode modifier frequency of 6.25 megahertz (3 August 1970). Points plotted are 1-minute averages, and the dashed curve is a smoothing through the fading. The points marked "X" refer to 5-second signal-level averages centered on the times plotted; the X-point farthest to the right corresponds to a 45-second average.

tion on variations in electron density. Measurement of relative radio-reflectivity was regarded as a technique that would provide information on changes in the electron temperature, since the reflectivity was expected to increase with electron temperature. All of these techniques, as it turned out, yielded some unexpected results, although some of the observations were in accord with expectations.

A schematic diagram of the experimental configuration employed near Boulder is shown in Fig. 5. The high-power transmitter is located at Platteville, ionosondes are at Boulder and Erie, airglow photometers are at Erie, and radio receivers are located at Hardin. A geomagnetic field line, **B**, is shown oriented at a dip angle of 68 degrees from the horizontal and at a declination of 13 degrees east of north. Part of a typical flux tube surrounding **B** is indicated as receiving energy deposited by radiation of the X-mode. The series of arrows represents the propagation path of the X-mode.

Experimental Results

Using X-mode excitation, Biondi *et al.* (*9*) observed airglow from excited oxygen atoms at 6300 angstroms; these observations showed the predicted suppression of ambient intensity, as illustrated in Fig. 6 for a transmission cycle of 10 minutes on and 10 minutes off. These results indicated an increase in the electron temperature of about 35 percent. However, subsequent measurements in which O-mode excitation was used resulted (*10*) in an appreciable enhancement of the ambient airglow emissions, as shown in Fig. 7. The enhancement of the normal airglow implies that collisional excitation of atomic oxygen by electrons is occurring. This process requires significant numbers of electrons with energies greater than 2 electron volts, but, for a thermal (Maxwellian) distribution of electron velocities, this would require electron tempertures of about 2000°K to be attained (*11*). On the other hand, a nonthermal distribution of electrons could be present, having high-velocity electrons contributed by the excitation of a plasma instability or by photoelectrons that are guided by the geomagnetic field as they travel from the F layer at the magnetically conjugate location in the Southern Hemisphere (*11*).

During observations limited to X-mode transmissions, airglow emission from excited oxygen molecules at 1.27 microns (infrared) was enhanced (*12*). The mechanism for exciting such emissions is unclear, as is the case for aurorally associated emissions at 1.27 microns that occur naturally; hence the interpretation of the results is not yet possible. The photometer could measure this emission when viewing a region located at an altitude of 200 kilometers situated along the geomagnetic tubes of force connected to the heated volume, centered at about 300 kilometers. However, no radiation was observed when the heated volume was viewed directly. These observations are still unexplained.

Radio-wave techniques were employed to obtain the remainder of the experimental observations summarized here. The ionosonde technique was used at Boulder to probe any electron-density modifications that were produced. This technique yields "ionograms," which display echo time-delay as a function of the radio frequency employed. Thus, if the radio wave were moving at the speed of light, an ionogram would show the range from the radar at which a plasma frequency equal to the exploring radio frequency is encountered. Since the ambient ionospheric plasma is usually characterized by approximately horizontal stratification, echoes would be obtained—in the absence of a geomagnetic field—from directly overhead, and the observed ranges would correspond to heights.

In actuality, there are several factors complicating this idealization. For one thing, in an ionized medium permeated by the geomagnetic field there are two magnetoionic modes that propagate at different velocities, both of which are less than the velocity of light. Also, these modes do not travel vertically in the ionosphere, even when it is horizontally stratified, but are deviated northward and southward, as shown in Fig. 3. Consequently, ionograms are really plots of apparent or "virtual" range versus the exploring radio frequency. Virtual range is determined from the time delay of the echo, on the assumption that the propagation is at the velocity of light.

The virtual range is thus somewhat greater than the actual range to the reflection point, with the actual value dependent upon the amount of retardation experienced by the waves in traversing the intervening ionosphere. For an ionospheric F-layer profile such as that shown in Fig. 1, the resulting ionogram resembles that of Fig. 8, with separate traces for the O- and X-modes.

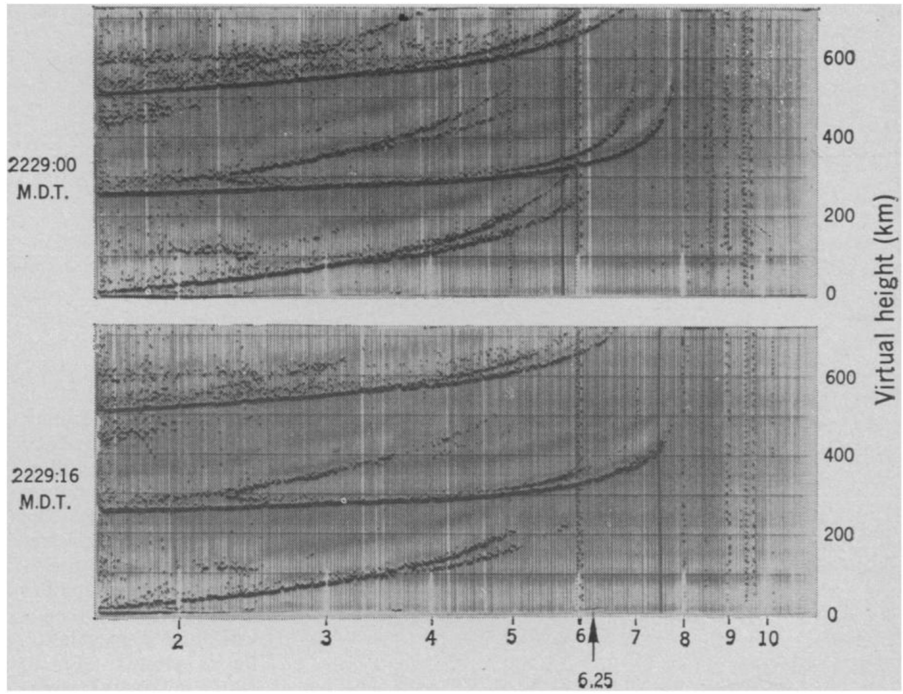


Fig. 13. Ionograms (30 July 1970) illustrating prompt attenuation of reflected signals over the frequency range of about 6.0 to 7.0 megahertz when modification is carried out with the O-mode at 6.25 megahertz.

During certain naturally occurring conditions, F-layer echoes can become diffuse or spread in the virtual range. The resulting configurations on ionograms are then described as spread F. The spread in echo delay is attributable to echoes that arrive over paths characterized by differing virtual ranges. A simple case to visualize is that of a horizontal sinusoidal ripple in the medium, which perturbs an otherwise horizontal stratification of electron density isopleths. Then, instead of only a single echo from the vertical direction, an even number of additional echoes would be obtained from points at which rays were orthogonally incident on the ripple. Actual ionospheric situations are more complicated than this simple case, inasmuch as naturally occurring F-layer irregularities tend to be aligned with the geomagnetic field. The spread-F phenomenon is still relatively unexplained theoretically, but it is generally regarded as the manifestation of a plasma instability.

One of the unexpected outcomes of the ionospheric modification experiments at Boulder was the generation of artificial spread F (*13*), as illustrated in the ionograms of Fig. 9. The upper ionogram was made just prior to modification. The echoes near 100, 200, and 300 kilometers, in the vicinity of 2 megahertz, are returns from the E region, with the upper two echoes resulting from multiple bounces, between the ionosphere and the ground, of energy returned from the first direct echo from the E region. The echoes starting near 250 kilometers, extending upward in frequency and forking into O- and X-mode branches, are direct returns from the F region, and the penetration frequencies are determined where the traces become vertical. The first multiple of these echoes is visible above 500 kilometers, and the splotchiness there is due to the fact that energy is scattered back from different portions of the ground. The lower ionogram, made after 15 minutes of modification, shows spreading of the F region O- and X-mode echoes, especially near the penetration frequencies. A second salient manifestation of the modification was the appearance of a new broadband echo visible in the lower ionogram at a slightly greater range than the original echo from the F region and extending from the very lowest frequencies upward. This additional echo trace, which emerged from the original trace, gradually increased in range and simultaneously slowly eroded away, beginning at high frequencies. The time history of the

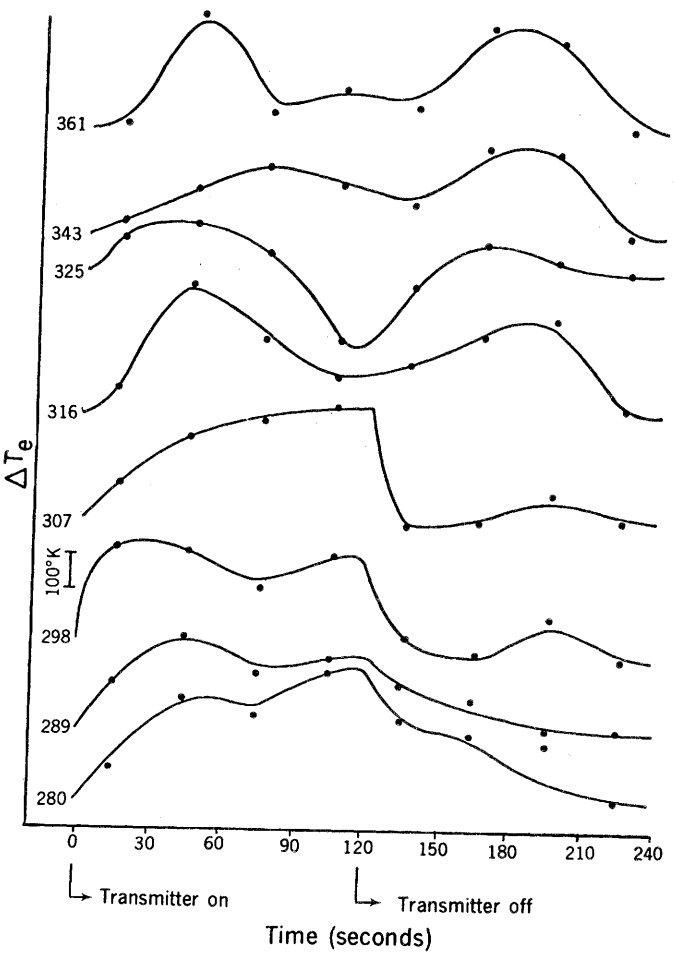


Fig. 14. Relative variation of the electron temperature at fixed heights stated in kilometers at the left of each curve (26 October 1970, 0030 to 0110 A.S.T.). Note the 100°K reference temperature at the lower left. The F-layer penetration frequency was 5.7 megahertz, and the modifier transmitter frequency was 5.6 megahertz. Points plotted refer to 30-second averages centered on the times indicated; solid curves are an attempt to interpolate between the measurements.

additional echoes suggests that a major redistribution of electrons was occurring, and specifically that a depleted ionospheric volume was displaced upward along the geomagnetic field lines.

When spread F occurs naturally at Boulder, it is almost always a nighttime phenomenon, usually occurring after midnight. However, the Boulder experiments have generated artificial spread F irregularities at any time of day when either the O- or X-mode of excitation is used. Figure 10 is an example of the daytime production of spread F, with the upper and lower ionograms showing, respectively, conditions prior to and during modification. In the daytime, the ambient ionization of the F region is often divided into two strata known as the F1 and F2 layers. In the top ionogram of Fig. 10 the two uppermost U-shaped traces, between about 5 and 7 megahertz, are echoes from the F2 layer. The two lower traces in the top ionogram of Fig. 10, which if extended upward nearly vertically would meet the left side of the U-shaped traces, are echoes from the F1 layer. In both cases the highest frequencies at which the traces approach vertical, because of large wave retardation, identify the O and X penetration frequencies for the F1 and F2 layers. The echo near 100 kilometers is from the E region, and other visible traces are various multiple echoes from the F region. The spread caused by modification is visible in the lower ionogram on the F2 O and X traces, but, for the F1 layer, spread shows principally only on the O trace. The F1-layer X-mode echoes would have been reflected from true heights below about 150 kilometers, and it thus appears that modification-induced irregularities in the ionosphere, resulting in spread F, were created mainly above that height. For higher F1 layers, spread F is produced on both the O and X traces.

A true-height (as contrasted to virtual-height) electron density profile for the ambient ionosphere was calculated from the upper ionogram in Fig. 10. That profile is plotted in Fig. 11, and the gradient changes in it indicate the stratification. If the irregularities generated by the modification, as depicted by the spreading in the lower ionogram of Fig. 10, are assumed to be located at the true heights at which the spread echoes appear, then these results suggest that the first irregularities are formed at the height of energy deposition, which is near the height at which the modifier frequency is reflected. In this case, the energy is initially deposited near 330 kilometers, the height of maximum ionization, at which height irregularities develop, and this is followed by the appearance of additional irregularities at both higher and lower levels. This development of spread F is completed in about 90 seconds, as determined from an intermediate sequence of ionograms which is not included in Fig. 10.

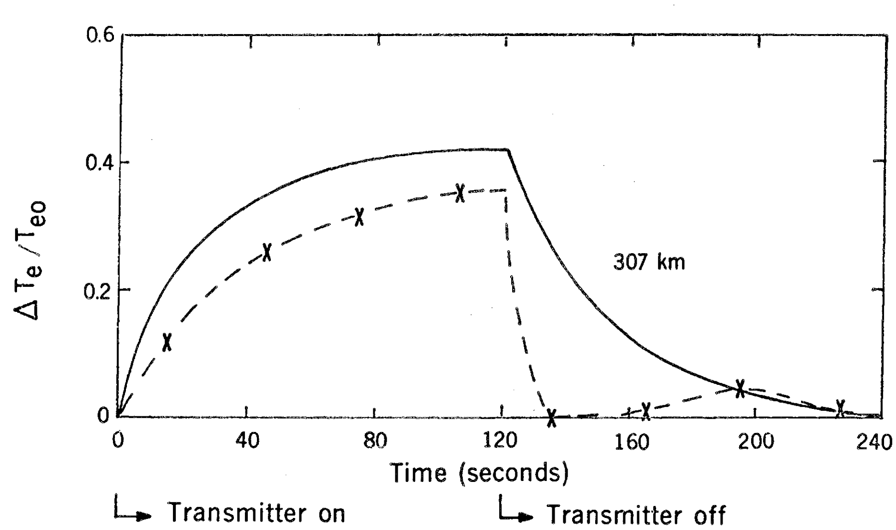


Fig. 15. Comparison of predicted time constants (*15*) and observed time constants (taken from Fig. 14) for heating and cooling. Changes in the electron temperature, ΔT_e, are referred to the measured ambient value, ΔT_{eo}, at 307 kilometers. (Dashed line) Measurements made at Arecibo; (solid line) theoretical curve.

Spread F produced in daylight has shorter persistence, after removal of the excitation, than the nighttime variety. It tends to disappear on the F1 echoes within a few minutes but may remain up to 5 or 10 minutes on the F2 echoes. Artificial nighttime spread F may persist for tens of minutes or longer, sometimes lasting until nearly sunrise, especially when created after midnight.

In an effort to determine the variations in electron temperature associated with the ionospheric modification, we monitored the radio reflectivity of the ionosphere by transmitting signals at frequencies near the modifier frequency over a nearly vertical path between Erie and Hardin (see Fig. 5). It was anticipated (because electrons would be heated) that a slight increase in reflectivity would be observed when the relative intensity of reflected signals was measured during a time extending over the transition between several states of the ionosphere, that is, when reflecting signals from ambient electrons and from heated electrons. However, contrary to this theoretical expectation, large "anomalous" decreases in reflectivity of the O-mode were experienced (*14*) during evening hours, as shown in Fig. 12, within 5 to 10 seconds after excitation with the O-mode. Decreases in O-mode reflectivity were also experienced on a shorter time scale when the transmitter was modulated on and off at 100-millisecond intervals. Ionograms obtained at Erie reveal the reflectivity changes qualitatively, as a function of frequency. Figure 13 illustrates O-mode attenuation, appearing on ionograms taken within a few seconds after the transmitter was turned on, on all frequencies above and slightly below the 6.25-megahertz modifier frequency. The lower ionogram was completed 6 seconds after excitation, and the upper one was made just prior to the time when the transmitter was turned on. In the lower ionogram of Fig. 13 a lower band of frequencies (5 to about 5.6 megahertz) is attenuated on the first multiple echo, for reasons that are unclear.

Measurements of incoherent scatter were obtained at Arecibo (*8*) during a modification of the ionosphere with a 100-kilowatt transmitter signal fed into the 300-meter Arecibo antenna. This antenna-transmitter combination has a power-aperture product about 3 decibels less than that of the Boulder system. The measurements show that the electron temperature of the ionosphere is increased by as much as 30 percent at and just below the height of energy deposition, when either O- or X-mode excitation is used. The time-dependence of heating was investigated by means of a 2-minute-on, 2-minute-off transmitter cycle. Temperature variations (in degrees Kelvin) at eight heights are plotted in Fig. 14. At 307 kilometers, heating and cooling time constants of 40 seconds and less than 10 seconds, respectively, were obtained. At lower heights (with the exception of 298 kilometers), shorter heating time constants and longer cooling time constants were observed. At heights above penetration height (313 kilometers), substantial fluctuations were observed, thus suggesting that the heat was transported upward from the height of deposition. The results are in essential agreement (Fig. *15*) with theoretical predictions (*15*) based upon (*4*), for electron temperature increases at Arecibo.

Table 1. Summary of experimental observations; +, positive results; —, negligible effect; *, inapplicable; 0, results to date not completely conclusive, but qualitatively small or negligible effect; U, information not yet available.

	O-excitation		X-excitation	
	Day	Evening	Day	Evening
Spread O echo	+	+	+	+
Spread X echo	+	+	+	+
Attenuation of O echo	0	+	0	—
Attenuation of X echo	0	—	0	—
Delayed broadband echo	0	+	0	+
Airglow (6300 angstroms enhancement)	*	+	*	—
Airglow (6300 angstroms) suppression	*	—	*	+
Airglow (1.27 microns) enhancement	*	U	*	+
Electron temperature increase observed with incoherent scatter	+	+	+	+
Plasma-line enhancement	+	U	—	U
Micromodulation of O echo	U	+	U	U
Micromodulation of X echo	U	—	U	U

Enhancement of the incoherent scatter "plasma line" has also been produced (*16*) at Arecibo by the action of the modifier. The plasma line is a feature in the incoherent scatter power spectrum (a plot of the scattered power received versus the frequency of its reception) separated by the local plasma frequency from the frequency of the exploring wave. Normally, photoelectrons produce an enhancement about an order of magnitude above the thermal level of power scattered at this frequency, but the enhancement created artificially at Arecibo is up to four orders of magnitude greater than the thermal level. This remarkable effect is probably the result of a plasma instability (v.i.) On the other hand, the observation at Boulder of enhanced airglow emission at 6300 angstroms discussed earlier is presumably an indication that extrathermal electrons (with an energy of the order of several electron volts) are being excited.

The experimental results obtained thus far are summarized in Table 1. Gaps still exist in our knowledge of some of the observed phenomena. However, certain consistent patterns are discernible in the summary, based upon results available from about a year of studies.

Interpretation

Some of the unexpected results reported above gave rise to further theoretical examination. More seemed to be happening than was indicated by the original predictions, based solely upon the elevation of the electron temperature. For example, the rapid production of spread F both during the day and at night was surprising, since the predicted changes in electron density would occur too slowly. The generation of spread F, the strong attenuation of reflected radio waves, and subsequently the enhancement of airglow and of the incoherent scatter plasma line all point to the occurrence of a plasma instability excited by a strong alternating electric field incident upon the ionosphere at its own plasma frequency.

Such considerations led Perkins and Kaw (*17*) to suggest the process—involving plasma waves—known as parametric instability to explain all or some of the unanticipated observations.

"Parametric" refers to periodic modulation of some parameter of an oscillating system at such a frequency and with sufficient amplitude so that the oscillations become unstable. Presumably the spread F irregularities could be accounted for by an instability, for example, a drift instability (*18*), triggered by anomalously large temperature gradients (*15*) or self-focusing (*19*).

Summary

The ionospheric modification experiments provide an opportunity to better understand the aeronomy of the natural ionosphere and also afford the control of a naturally occurring plasma, which will make possible further progress in plasma physics. The ionospheric modification by powerful radio waves is analogous to studies of laser and microwave heating of laboratory plasmas (*20*). "Anomalous" reflectivity effects similar to the observed ionospheric attenuation have already been noted in plasmas modulated by microwaves, and anomalous heating may have been observed in plasmas irradiated by lasers. Contacts have now been established between the workers in these diverse areas, which span a wide range of the electromagnetic spectrum. Perhaps ionospheric modification will also be a valuable technique in radio communications.

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WWNSS: Seismology's Global Network of Observing Stations

Standardized collection and efficient distribution of earthquake data yield social and scientific rewards.

Jack Oliver and Leonard Murphy

During the early 1960's the World-Wide Network of Standard Seismograph Stations (known as WWNSS) was created. This network consists of some 120 continuously recording stations distributed over much of the land area of the world. Its successful operation depends upon widespread voluntary cooperation by individuals, institutions, and nations. It is by far the finest, general-purpose, global system of seismic monitoring stations ever operated. It has become the essential core of observational seismology; without it, this branch of science would be severely crippled. The WWNSS includes a microfilming service, which makes data from any of the stations of the network readily available to anyone at nominal cost and which is a remarkable improvement over older methods of communicating seismic data. The data from the WWNSS are widely used for applied purposes and for research. The network is very important in the construction of modern maps of global and regional seismicity that are essential in dealing with the earthquake hazard.

Fortuitously, the WWNSS became productive just prior to what has been called the "revolution" in geology based upon the concepts of sea-floor spreading, continental drift, and plate tectonics; thus, data from the WWNSS played a key role in seismology's contribution to the testing and development of those concepts. Curiously, for a system that is so necessary in modern society and that seems to provide social benefit and scientific knowledge of value far greater than the cost of the network itself, the WWNSS has had a perilous history and has followed a rather roundabout course to achieve its present status, which even today is somewhat precarious and irregular. This article presents a brief history of the WWNSS, a short description of the network and of the instrumentation at a single station, a summary of the results of some studies based upon WWNSS data, and a prognosis of what the role of this network may be.

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