PORTION
OF THIS
DOCUMEN
ARE
ILLEGIBL

CONF-810421--2

LA-UR -81-870

TITLE: IONOSPHERIC MODIFICATION BY HIGH-POWER RADIO WAVES

MASTER

AUTHOR(S): Lewis M. Duncan, Los Alamos National Laboratory, SSO

SUBMITTED TO: Ionospheric Effects Symposium, April, 1981
Alexandia, VA. Paper to be presented

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the Department of Energy.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

Form No. 836 R2
St. No. 2629
1/78

DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

IONOSPHERIC MODIFICATION BY HIGH-POWER RADIO WAVES

Lewis M. Duncan
University of California, Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Powerful, high-frequency radio waves have been used to temporarily modify the ionosphere. Thermal and parametric interactions have led to a diverse range of observed phenomena, including generation of density striations and artificial spread-F, enhancements of electron plasma waves, production of extrathermal electron fluxes and enhanced airglow, modification of the D-region temperature and densities, wideband signal attenuation, and self-focusing and scattering of the electromagnetic waves. The physics of ionospheric modification by high-power radio waves is reviewed in the context of our current theoretical understanding; disturbance generation mechanisms are qualitatively described. In addition, results of recent experiments are summarized in which ionospheric irregularities are generated and their evolution and decay processes investigated in detail. The effects and potential controlled applications of these HF ionospheric modifications for various RF systems studies are discussed. The C^3I scientific community provides an important motivation for these ionospheric modification studies; their increased interaction and active participation in experimental design and interpretation is encouraged.

INTRODUCTION

The ionosphere is commonly defined as that part of the earth's upper atmosphere where free electrons exist in sufficient numbers so as to affect radio wave propagation. Numerous telecommunications systems rely on this partially ionized plasma through ionospheric reflections or transionospheric propagation as part of their communications signal path. The majority of studies of the effects of the ionosphere on communications systems address specifically the influence of ionospheric disturbances on radio wave propagation. However, the propagation of electromagnetic radiation through a plasma is inherently a nonlinear process. Not only does the plasma through its index of refraction and collisional damping affect the propagating radio wave, but also the radio wave through ohmic heating and the ponderomotive force may influence the behavior of the plasma. This study discusses ionospheric modifications and accompanying RF systems effects which may be generated by high-power radio wave propagation through the upper atmosphere.

Within the past decade it has become technologically feasible to construct ground-based high-frequency (HF) transmitting systems capable of delivering RF energy to the ionospheric plasma with power densities sufficient to alter the ionospheric electron thermal budget and local plasma characteristics, driving a wide variety of plasma instabilities and nonlinear wave propagation effects. Some of the primary and secondary manifestations of such energy deposition in the ionosphere and upper atmosphere are noted schematically in Figure 1 (from Carlson and Duncan, 1977). Results of experiments performed using such high-power HF facilities have by now had important applications to a number of areas of plasma physics, telecommunications science, and basic ionospheric research. Such "ionospheric modification" or "heating" facilities have been operated in the United States (at Arecibo, Puerto Rico and Platteville, Colorado), the USSR (at Gor'kii and Moscow) and most recently in Europe (at Tromsø, Norway).

HF ionospheric modification research has many potential applications to studies of ionospheric effects on radio wave systems. High-power radio waves can be used to produce controlled ionospheric plasma envirorments to investigate the temporal and spatial evolution of induced ionospheric disturbances. Recent work in this area has concentrated on the dynamics and dissipation properties of ionospheric field-aligned density irregularities and artificial spread-F plasma striations. In addition, induced ionospheric irregularities or changes in the ionospheric thermal and IR backgrounds may perhaps be used to provide countermeasures to radars and satellite-based surveillance systems, to create new propagation paths not naturally present for over-the-horizon (OTH) radars or

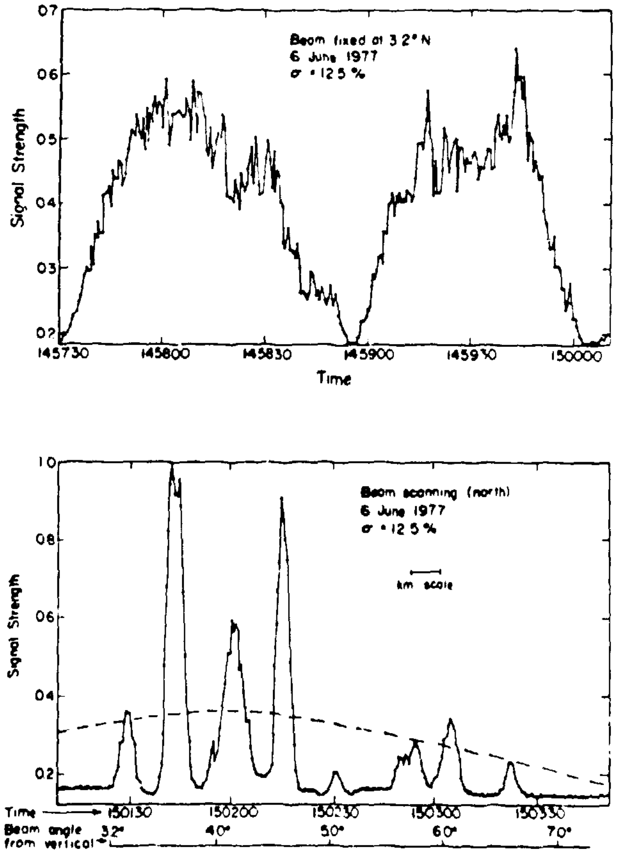

Figure 8. Experimental observations of wave self-focusing. The top figure shows the back-scattered enhanced plasma line signal modulation induced by the natural drift of self-focusing striations through the fixed radar beam. The lower figure presents a series of striations observed from rapid scanning of the radar beam across the interaction region immediately after the drift measurements. The dashed curve estimates the unstriated beam.

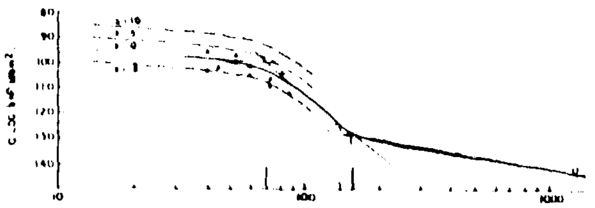

Figure 10. Observed coherent backscatter coefficient for scatter from small-scale field-aligned plasma striations, as a function of frequency.

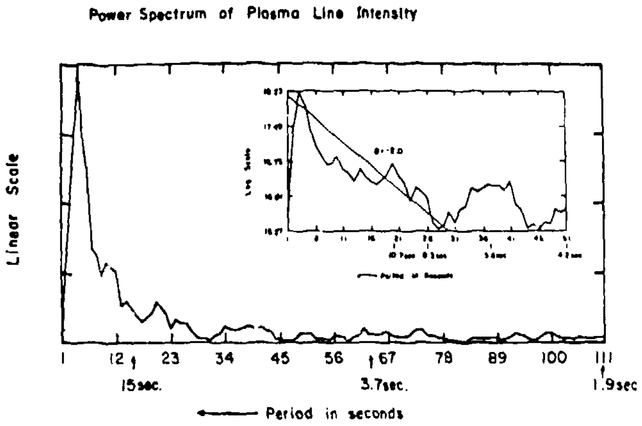

Figure 9. The power spectrum of fluctuations in the enhanced plasma line intensity, indicative of the associated electron density fluctuations.

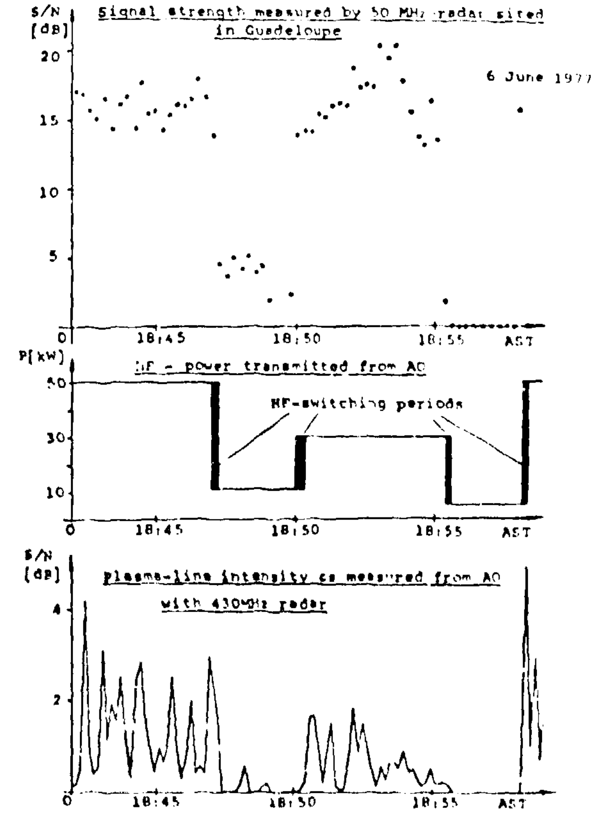

Figure 11. Comparison of 50-MHz radar coherent scatter signal strength with HF transmitted power and enhanced plasma line intensity.

plasma. Heating-induced changes in the local ionospheric conductivities can be used to generate LF and VLF radio waves emitted from the heated ionospheric regions. As a result of the nonlinear dependence of wave absorption on the incident field amplitude, strong amplitude-modulated radio waves may suffer appreciable self-distortion of their modulation as they propagate through the ionosphere. Analogous nonlinear distortions can affect the waveform of the envelope of strong radio wave pulses.

Change of Wave Refraction and Self-Focusing. Natural density fluctuations in the ionosphere cause small variations in the index of refraction of the plasma, resulting in a slight focusing and defocusing of an electromagnetic wave propagating through the medium. The electric field intensity increases as the incident wave refracts into regions of comparatively underdense plasma. Ohmic heating and the electric-field ponderomotive force (a radiation pressure) then drive plasma from these focused regions, further amplifying the initial perturbation. This self-focusing process continues until hydrodynamic equilibrium is reached, creating field-aligned striations within the plasma. This process is illustrated schematically in Figure 2.

As a result of the change of the refractive index of the wave in the plasma, the beam trajectory is distorted and the wave's direction and propagation path are shifted. For radio waves reflecting in the ionosphere, if thermally-induced imbalances of ionization are not significant, the wave's reflection height shifts upwards. Sufficiently powerful and narrow beams may then penetrate through critical density layers in the ionosphere.

Even a weak plasma nonlinearity causes radio wave propagation trajectories to bend noticeably. This leads to focusing and filamentation of the incident radio wave beam, to the onset of wave field intensity oscillations, and to stratification of the ionospheric plasma density. The resulting large-scale field-aligned ionospheric irregularities can impose severe scattering, scintillation, and distortion effects on other radio waves over a wide frequency range which may propagate through this modified region.

Wave Interaction. The nonlinearity of radio wave propagation through the ionosphere also manifests itself as a violation of the principle of superposition of waves. When a high-power radio wave propagates through a plasma, it changes the absorption and refraction properties of the medium not only for itself, but also for all other radio waves passing through the same region. The radio waves thus interact in the plasma. In particular, if the high-power radio wave is amplitude-modulated, then the resulting changes of absorption can cause this modulation to be transferred to other waves passing through the same region of the ionosphere. This phenomenon of cross modulation is of practical importance for radio wave systems operating at medium wavelengths and for short pulse wave interaction studies of the ionosphere. Absorption changes induced by strong radio waves can be made extremely large, and in practice can enable a strong radio wave to totally suppress or distort beyond informational use other RF signals propagating through the perturbed region.

Nonlinear interaction between several high-power radio waves can also be used to generate new radio waves at combination and difference frequencies, to drive resonant plasma oscillations unstable, or to produce new LF and VLF radio waves by low-frequency modulation of a single high-power wave. In addition, various normal components of the radio wave polarization nonlinearly interact with one another in a magnetoactive plasma. This can lead to a nonlinear rotation of the polarization ellipse and to self-modulation effects. The nonlinear interaction of radio waves in the ionosphere can also generate through nonlinear wave transformation processes other types of electromagnetic and electrostatic waves, such as plasma waves, whistlers, ion-sound waves, magnetohydrodynamic waves, or acoustic waves.

Breakdown Ionization. In the fields of very powerful radio waves, free electrons may become accelerated to energies sufficient to impact ionize molecules and atoms in the ionosphere during collisions. This electric breakdown of the neutral gas results in a rapid and large increase in the plasma electron number density. The nonlinearity associated with this process also leads to a very fast increase in the wave absorption, and to a rapid saturation of the wave field. The effect is thus self-quenching. An equally strong increase occurs in the absorption of other waves passing through the ionization region; the high-power radio wave effectively attenuates other RF signals propagating through this medium. In addition, the artificial ionization regions can be used to scatter or reflect VHF and UHF radio waves which normally pass through the ionosphere unimpeded, potentially impacting numerous telecommunications systems relying on transionospheric propagation.

Instability Excitation. High-power radio waves increase the electron temperature and change the electron and ion densities in the modified ionosphere. Artificial inhomogeneities can easily become unstable, such as with respect to flute, drift and ion-cyclotron waves. Ionospheric modification in the field of high-power radio waves can excite new plasma oscillations and enhance existing oscillations, forming an electrostatically turbulent plasma environment. This strongly influences the conditions of radio wave propagation in the modified region of the ionosphere, causing additional anomalous signal absorption and scattering.

Resonant instabilities can be excited in regions where the radio wave frequency is close to some natural oscillation frequency of the plasma. In these regions, the electromagnetic wave may excite natural plasma oscillations through linear wave transformation. This process leads to the development of small-scale field-aligned plasma striations and the effective absorption of radio waves by the plasma. The resulting small-scale plasma irregularities also effectively scatter VHF and UHF radio waves over a wide frequency band.

Another important nonlinear phenomenon that occurs in the plasma resonance region is the excitation of parametric instabilities. Parametric wave-plasma interactions can generate enhanced plasma and ion-acoustic waves in the field of a powerful radio wave. In addition, parametric instabilities can lead to effective nonlinear generation of noise and to absorption of the incident radiation by the plasma. Parametric interactions are usually accompanied by pulsations of the wave reflected from the ionosphere and by the generation of energetic electrons (1-20 eV) accelerated as a result of Landau damping of the enhanced plasma waves. Interactions between parametrically-enhanced electron plasma waves may also lead to the formation of short-scale plasma striations capable of coherently scattering VHF and UHF radio waves.

In addition to their local ionospheric effects, nonlinear wave-plasma interactions may be responsible for a number of new phenomena outside of the modified region. Electrons accelerated in the perturbed F-region ionosphere and high-power low-frequency radiation produced by wave modulation or wave-wave interaction processes both may have a strong influence on the behavior of the magnetospheric plasma. Wave energy absorbed by the ionospheric free electrons ultimately may be transferred through collisions to the neutral molecules and atoms of the upper atmosphere. This process can result in noticeable heating of the neutral atmosphere, airglow both in the visible and infrared, composition changes, and possibly the launching of acoustic-gravity waves and their associated travelling ionospheric disturbances. Each of these perturbations, through their interactions with other radio waves, ionospheric fields and currents, fast electrons, and magnetospheric whistlers, may themselves give rise to additional nonlinear phenomena.

EXPERIMENTAL HISTORY

The initial high-power high-frequency ionospheric modification facilities were constructed in anticipation of rather gentle enhancements of the ionospheric free electron temperature, with associated plasma redistribution. However, in addition to the expected increases of the electron gas temperature, a rich spectrum of plasma instabilities and nonlinear wave propagation effects were also excited. The most prominent nonlinear phenomenon detected in these early experiments was associated with HF-induced parametric instabilities, producing enhanced plasma waves, anomalous RF absorption, accelerated energetic electrons, and airglow excitation (Carlson and Duncan, 1977). These studies benefited greatly from the active interest of many leading plasma physicists (e.g., Perkins and Kaw, 1971; Valeo et al., 1972; Fejer and Leer, 1972; Harker, 1972; DuBois and Goldman, 1972; Rosenbluth, 1972). Reviews of results obtained in these early experiments can be found in special issues of Radio Science (9, 11, 1974) and Izv. Vyssh. Uchebn. Zaved. Radiofiz. (18, 9, 1975; 20, 11, 1977).

The parametric instability mechanism entails a pump or driving field whose energy cascades into plasma oscillations at two lower natural resonant frequencies in the plasma. In this case, the high-power HF electromagnetic radiation provides the initial driving field, and the longitudinal electrostatic electron plasma wave and the ion-acoustic wave (parametric decay instability) or zero-frequency ion mode (two-stream or purely growing instability) represent the parametrically enhanced oscillations. Radar measurements of the spectra of these enhanced plasma waves (Kantor, 1974; Showen, 1975; Duncan, 1977) investigated the enhanced plasma wave structure, including additional features apparently associated with the saturation of the parametrically enhanced oscillations. These structures were satisfactorily explained in terms of a saturation mechanism based on secondary parametric decay interactions, with the enhanced electrostatic plasma oscillations acting as new pump waves (Perkins et al., 1974; Fejer and Kuo, 1973). The instability threshold and saturation spectrum is affected by the local plasma collision frequency, density gradient, geomagnetic orientation, and amplification of the incident radio wave through focusing (self-action or pre-existing ducts) and Airy-structure swelling near the reflection altitude. Figure 3 presents an ambient ionospheric electron density profile as measured with the Arecibo incoherent backscatter radar, and a corresponding profile measured with the added influence of high-power HF radiation, showing a narrow region of parametrically-excited electrostatic turbulence near the HF reflection height.

Pulsed radar studies of the ionosphere often detect multiple or spread return echoes. Such echoes from the natural ionosphere have been used historically to identify and characterize an F-region phenomenon called spread-F, and have been attributed to electron density irregularities. The physics behind the generation and maintenance of the irregularities is still uncertain. Morphologically, naturally occurring irregularities are seen in the F-region ionosphere with fractional density changes as large as 10[illegible] to 10[illegible] in only a few kilometers. Satellite-borne probes on Atmospheric Explorer have measured scale sizes from several kilometers to as small as 60 m, limited by the telemetry rate on that information channel; coherent radar studies, particularly involving the 50-MHz radar at Jicamarca, Peru, have measured spread-F echoes from structure with 3-meter scale size. A condition indistinguishable on an ionogram from naturally-occurring spread-F can be generated reproducibly bv illuminating the ionosphere with intense HF radio waves (Figure 4; Utlaut and Violette, 1972). Experimental HF radar studies (Figure 5; Thome and Perkins, 1974), radio scintillation measurements (Figure 6; Getmantsev et al., 1976; Rufenasch, 1973), AE satellite measurements (Figure 7, J. P. McClure, 1977; Carlson and Duncan, 1977), and interaction region striation mapping (Figure 8; Duncan and Behnke, 1978) have presented observational data to support interpretation of these large-scale spread-F effects as due to a thermal self-focusing instability (Perkins and Valeo, 1974; Perkins and Goldman, 1980). Additional studies have confirmed that these HF irregularities apparently form with power spectral densities similar to natural spread-F, barium cloud striations, and irregularity structure found in the high-altitude nuclear environment (Figure 9, Ganguly, 1980) Ray tracing simulations of observations have suggested scale sizes perpendicular to B of a few kilometers, growth times of a few minutes, and saturation fractional plasma concentration changes of the order of 10^{-1} (Allen et al., 1974), in general agreement with the experimental observations. A different approach considering stimulated Brillouin forward scattering (decay of the electromagnetic wave into another electromagnetic wave and an ion sound wave) has also been developed (Cragin and Fejer, 1974), with collisional heating dominating the ponderomotive force and generating field-aligned irregularities with perpendicular scale sizes on the order of 500 meters. Although the initial approach differs, the physics of these mechanisms is quite similar.

VHF and UHF coherent radar observations of aspect-sensitive echoes from field-aligned irregularities have demonstrated the generation and decay of short-scale plasma striations on time scales on the order of 10 ms. The short-scale structures are believed to be excited by secondary thermal processes associated with the parametrically-enhanced electron plasma waves (Perkins, 1974; Vaskov and Gurevich, 1975; Cragin et al., 1977; Lee and Fejer, 1978). Experimental observations of this coherent scatter have been detected for radar frequencies from 50 to 400 MHz (Figure 10; Minkoff, 1974). The observed short-scale irregularities exhibit strong temporal and spatial variabilities (Figure 11; Frey, 1980). The role of short-scale field-aligned plasma striations in scattering of the incident HF radiation, producing an overshooting of the HF-induced parametric effects, and as a source of anomalous signal absorption in the HF interaction region, is a current subject of study.

As we can see from the preceding descriptions, nonlinear phenomena accompanying ionospheric modification by high-power radio waves constitute a rather diverse and extensive class of effects. This is due both to the inherent variety of nonlinear effects in plasmas and to the great differences in physical conditions found in the ionosphere as a function of time and altitude. Generally, the predominant effects in the lower ionosphere are associated with nonlinear changes in wave absorption, while upper ionospheric phenomena are more usually associated with changes in wave refraction and wave-plasma instabilities.

IONOSPHERIC IRREGULARITIES

The study of plasma striation dynamics using ionospheric modification by high-power radio waves is just in its infancy. Previous observations have demonstrated that ionospheric irregularities can be formed over a wide range of ionospheric conditions in a controlled experimental environment. A comprehensive array of ionospheric diagnostics have been fielded to investigate the associated plasma behavior. The principal experimental results are:

(1) Large-scale ionospheric irregularities form preferentially with 500 m to 1 km dominant scale sizes.
(2) The irregularities consist of density fluctuations of $\delta n/n \approx 2$-5 %.
(3) These large-scale structures decay on time-scales of several tens of minutes to hours, but also show significant early dissipation effects on a time scale of less than a few minutes.
(4) Small-scale field-aligned striations form with scale sizes of approximately one-third meter to several meters under specific ionospheric modification conditions and within a narrow altitude region.
(5) The small-scale structure decays on time-scales of less than 1 s.
(6) Both large- and small-scale irregularities drift together with apparently the background wind velocities.

Our investigation of HF-induced ionospheric irregularities suffers most from a lack of interaction with the theoretical scientific community studying irregularity stability and evolution. We solicit your advice and assistance in pursuing this relatively underdeveloped experimental capability. The observations to date address a number of unresolved phenomenological issues. These outstanding questions include:

(1) Why do large-scale irregularities form preferentially with 500 m to 1 km scale sizes?
(2) Why do these large-scale structures decay with such long time constants, and what is the dissipation mechanism?

(3) What determines the geometry and spatial extent of the large-scale ionospheric irregularities?
(4) By what processes do small-scale field-aligned striations form and decay?
(5) What secondary instabilities are likely to develop during the evolution of the irregularities?
(6) How do ionospheric disturbances drift?

In addition to the above physics questions, we can begin to address the problems of designing definitive experimental programs to determine the size and duration of ionospheric disturbance impacts on generic C^{3}I systems. The potential applications of HF ionospheric modification research to controlled experimental investigations of RF system performance in disturbed ionospheric conditions could be vigorously pursued if encouraged by the C^{3}I scientific community.

REFERENCES

Allen, E. M., G. D. Thome, and P. B. Rao, HF Phased Array Observations of Heater-Induced Spread-F, Radio Sci., 9, 905, 1974.

Carlson, H. C. and L. M. Duncan, HF Excited Instabilities in Space Plasmas, Radio Sci. 12, 1001, 1977.

Cragin, B. L. and J. A. Fejer, Generation of Large-Scale Field-Aligned Irregularities in Ionospheric Modification Experiments, Radio Sci, 9, 1071, 1974.

Cragin, B. L., J. A. Fejer, E. Leer, Generation of Artificial Spread-F by a Collisionally Coupled Purely Growing Parametric Instability, Radio Sci., 12, 273, 1977.

DuBois, D. F. and M. V. Goldman, Spectrum and Anomalous Resistivity for the Saturated Parametric Instability, Phys. Res. Lett., 28, 215, 1972.

Duncan, L. M., Experimental Saturation Spectrum of Parametric Instabilities, Ph.D. dissertation, Rice University, Houston, TX, 1977.

Duncan, L. M. and R. A. Behnke, Observations of Self-Focusing Electromagnetic Waves in the Ionosphere, Phys. Rev. Lett., 41, 998, 1978.

Duncan, L. M. and J. Zinn, Ionosphere-Microwave Interactions for Solar Power Satellites, Los Alamos National Laboratory report LA-UR-78-768, March 1978.

Fejer, J. A. and E. Leer, Excitation of Parametric Instabilities by Radio Waves in the Ionosphere, Radio Sci., 7, 481, 1972.

Fejer, J. A. and Y. Y. Kuo, Structure in the Nonlinear Saturation Spectrum of Parametric Instabilities, Phys. Fluids, 16, 1490, 1973.

Fejer, J. A., Ionospheric Modifications and Parametric Instabilities, Rev. Geophys. and Space Physics, 17, 135, 1979.

Frey, A., Artificially Produced Field-Aligned Short-Scale Striations, M.S. thesis, Rice University, Houston, TX, 1979.

Ganguly, S., Short-Term Variability in the HF-Enhanced Plasma Line, J. Geophys. Res., 85, [illegible], 1980.

Gurevich, A. V., Nonlinear Phenomena in the Ionosphere, Physics and Chemistry in Space, Vol. 10, Springer, Berlin-New York, 1978.

Getmantsev, G. G., L. M. Erukhimov, E. E. Mityakova, N. A. Mityakov, N. M. Prytkov, V. O. Rapoport, and V. A. Cherepovitskii, Certain Results of Investigating Ionospheric Irregularities Induced by Powerful Radio Emission Using Background Reception of Satellite Signals, Izv. Vussh. Ucheb. Zaved. Radiofiz., 19, 505, 1976.

Harker, K. J., Induced Enhancement of the Plasma Line in the Backscatter Spectrum by Ionospheric Heating, J. Geophys. Res., 77, 6038, 1972.

Holway, L. H. and G. Meltz, Heating of the Lower Ionosphere by Powerful Radio Waves, J. Geophys. Res., 78, 8402, 1973.

Kantor, I. J., High Frequency Induced Enhancements of the Incoherent Scatter Spectrum at Arecibo, 2, J. Geophys. Res., 79, 199, 1974.

Lee, M.-C. and J. A. Fejer, Theory of Short-Scale Field-Aligned Density Striations Due to Ionospheric Heating, Radio Sci., 13, 893, 1978.

McClure, J. P., private communications, 1977.

Minkoff, J., Radio Frequency Scattering from a Heated Ionospheric Volume, 3, Cross-Section Calculations, Radio Sci., 9, 997, 1974.

Perkins, F. W. and P. K. Kaw, On the Role of Plasma Instabilities in Ionospheric Heating by Radio Waves, J. Geophys. Res., 76, 282, 1971.

Perkins, F. W. and E. J. Valeo, Thermal Self-Focusing of Electromagnetic Waves in Plasmas, Phys. Rev. Lett., 32, 1234, 1974.

Perkins, F. W., C. Oberman, E. J. Valeo, Parametric Instabilities and Ionospheric Modification, J. Geophys Res., 79, 1065, 1974.

Perkins, F. W. and R. G. Roble, Ionospheric Heating by Radiowaves: Predictions for Arecibo and the Satellite Power Station, J. Geophys. Res., 83, 1611, 1978.

Perkins, F. W. and M. V. Goldman, Self-Focusing of Radio Waves in an Underdense Ionosphere, J. Geophys. Res., 86, 600, 1981.

Rosenbluth, M. N., Parametric Instabilities in Inhomogeneous Media, Phys. Rev. Lett., 29, 56[illegible], [illegible].

Rufenach, C. L., Radio Scintillation of Stellar Signals During Artificial Ionospheric Modification, J. Geophys. Res., 78, [illegible], [illegible].

Showen, R. L., Time Variations of HF Induced Plasma Waves, Ph.D. Dissertation, Rice University, Houston, TX, 197[illegible].

Thome, G. D. and F. W. Perkins, Production of Ionospheric Striations by Self-Focusing of Intense Radio Waves, Phys. Rev. Lett., [illegible], [illegible], 1974.

Utlaut, W. F. and R. J. Violette, Further Observations of Ionospheric Modification by a Higher Power HF Transmitter, J. Geophys. Res., 77, 6804, [illegible].

Valeo, E., C. Oberman, and F. W. Perkins, Saturation of the Decay Instability for Comparable Electron and Ion Temperatures, Phys. Rev. Lett., [illegible], [illegible], [illegible].

Vaskov, V. V. and A. V. Gurevich, Nonlinear Resonant Instability of a Plasma in the Field of an Ordinary Electromagnetic Wave, Sov. Phys. JETP, [illegible], [illegible], [illegible].

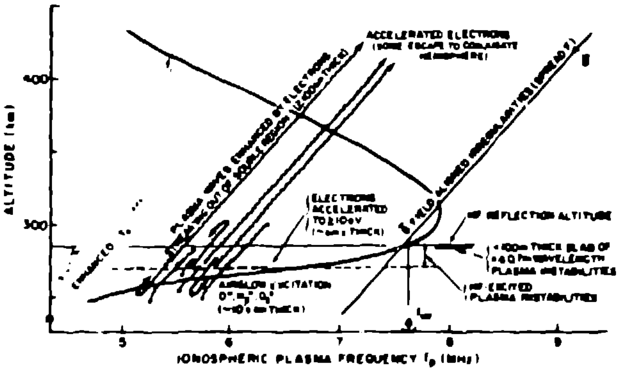

Figure 1. Effects produced by high-power HF ionospheric modification.

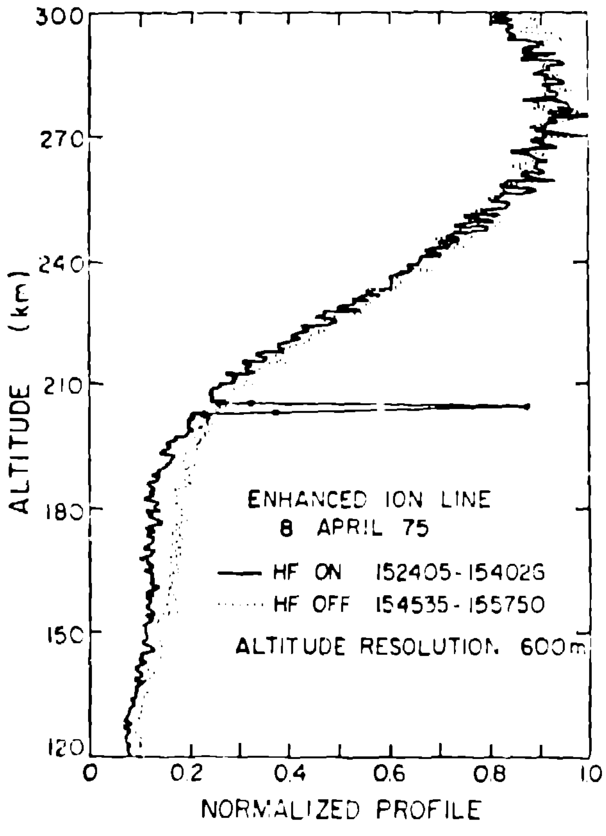

Figure 3. Arecibo ionospheric profiles measured by incoherent scatter radar, with and without HF ionospheric modification effects.

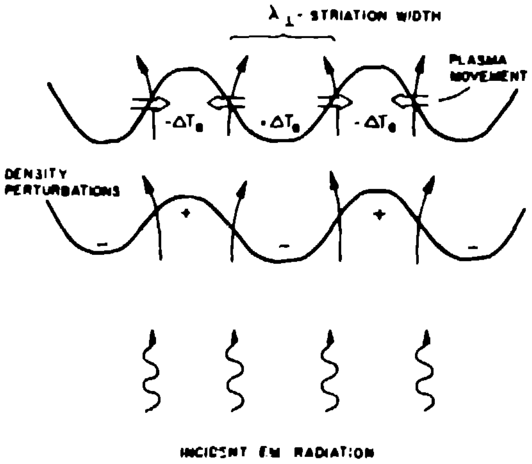

Figure 2. Schematic description of the thermal self-focusing process. Increased electron heating in the focused regions produces a temperature gradient that drives plasma out of the region, further focusing the beam.

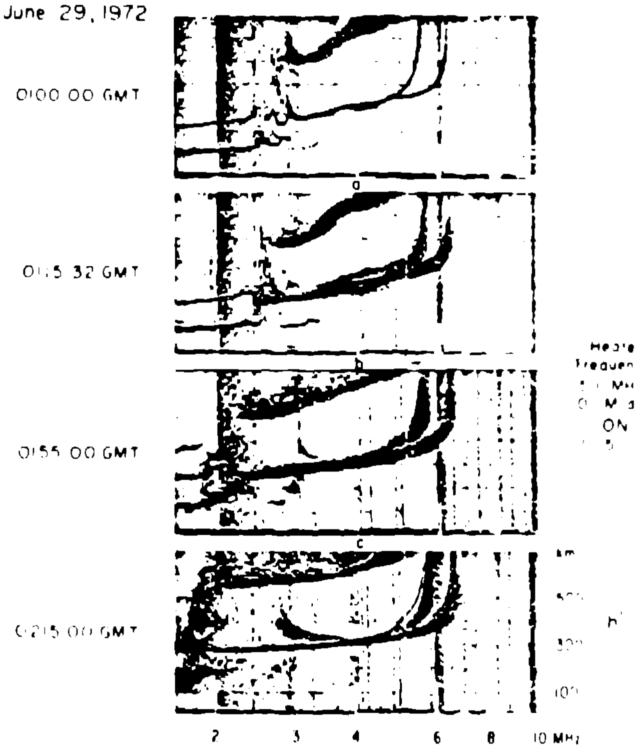

Figure 4. Ionograms illustrating artificial spread-F.

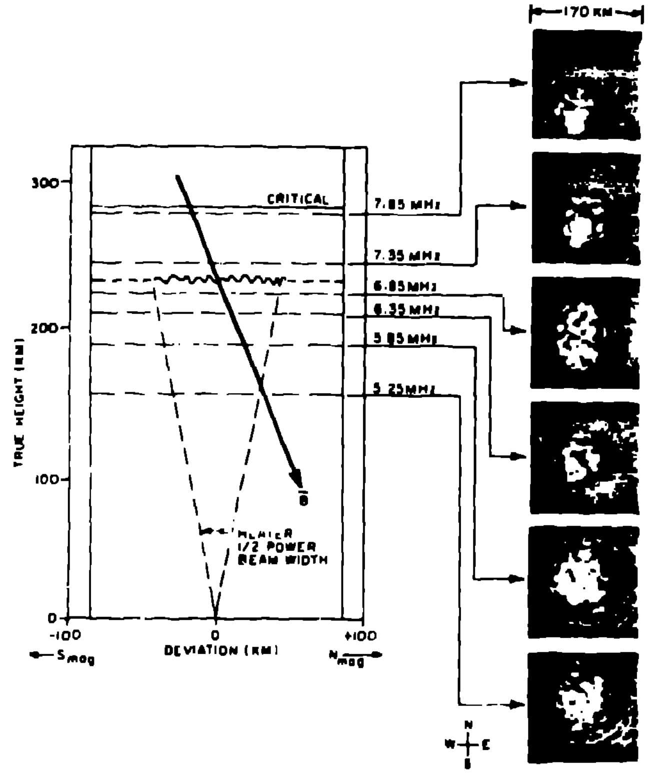

Figure 5. HF phased array frequency scan sky maps taken at six diagnostic frequencies.

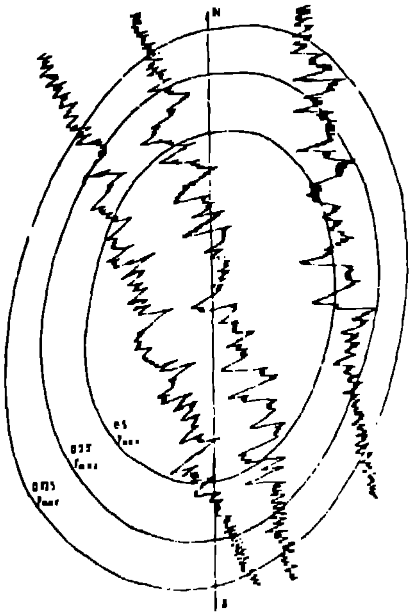

Figure 5. Satellite-to-ground signal fluctuations at 136-137 MHz for three flight paths through the modified ionosphere. The ovals estimate the heated region at 300 km.

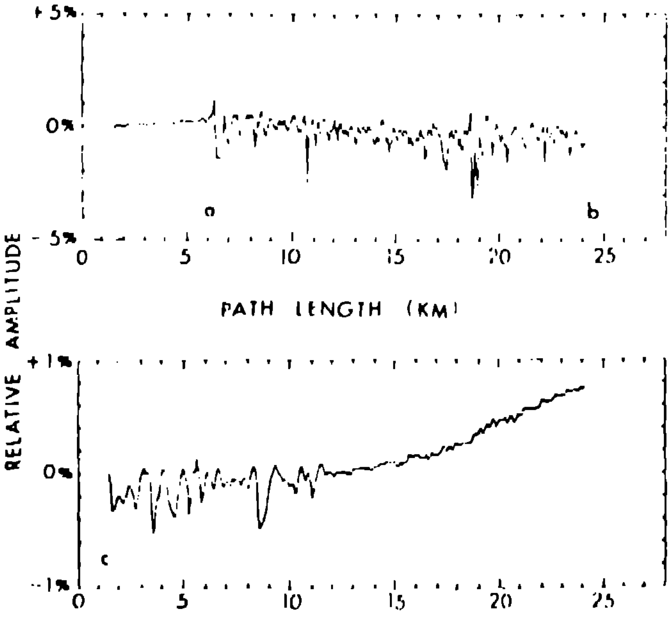

Figure 7. Atmospheric Explorer ion density fluctuation data for flight path through the modified region, (a) onset of instabilities (b) no data for next 23 km (c) data resumes.

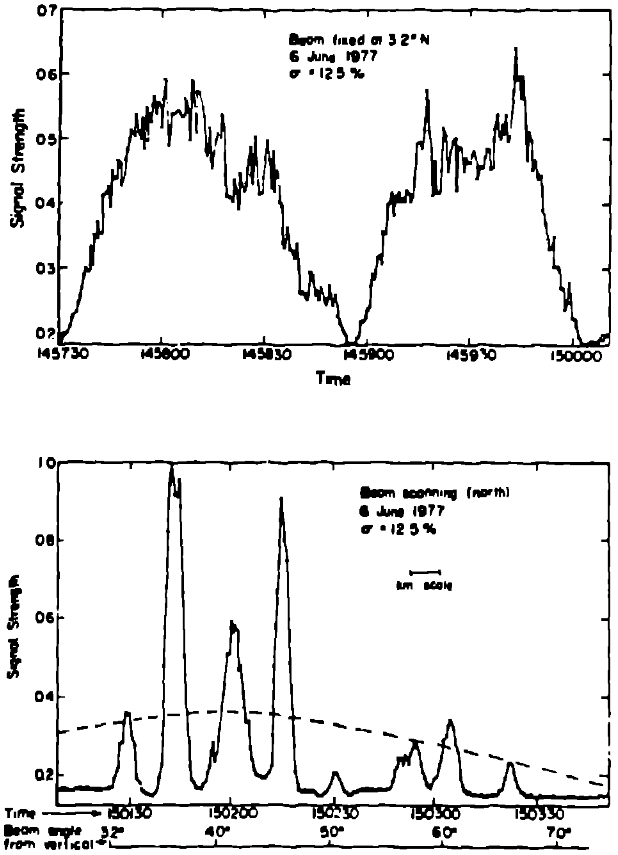

Figure 8. Experimental observations of wave self-focusing. The top figure shows the backscattered enhanced plasma line signal modulation induced by the natural drift of self-focusing striations through the fixed radar beam. The lower figure presents a series of striations observed from rapid scanning of the radar beam across the interaction region immediately after the drift measurements. The dashed curve estimates the unstriated beam.

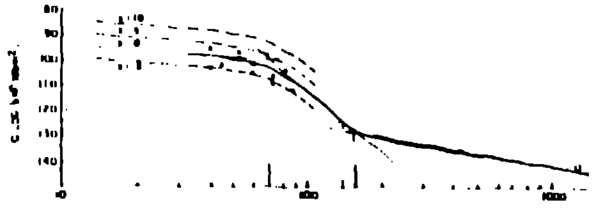

Figure 10. Observed coherent backscatter coefficient for scatter from small-scale field-aligned plasma striations, as a function of frequency.

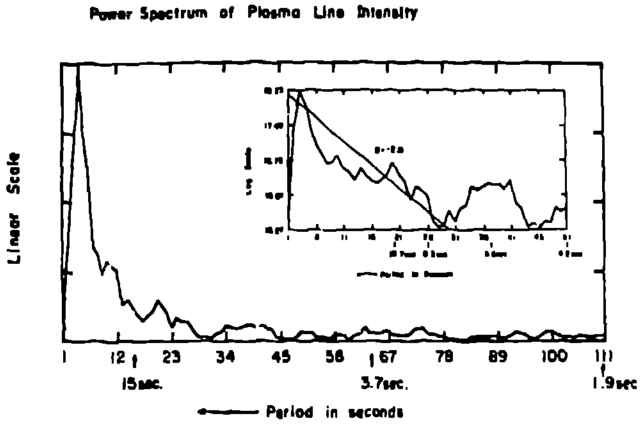

Figure 9. The power spectrum of fluctuations in the enhanced plasma line intensity, indicative of the associated electron density fluctuations.

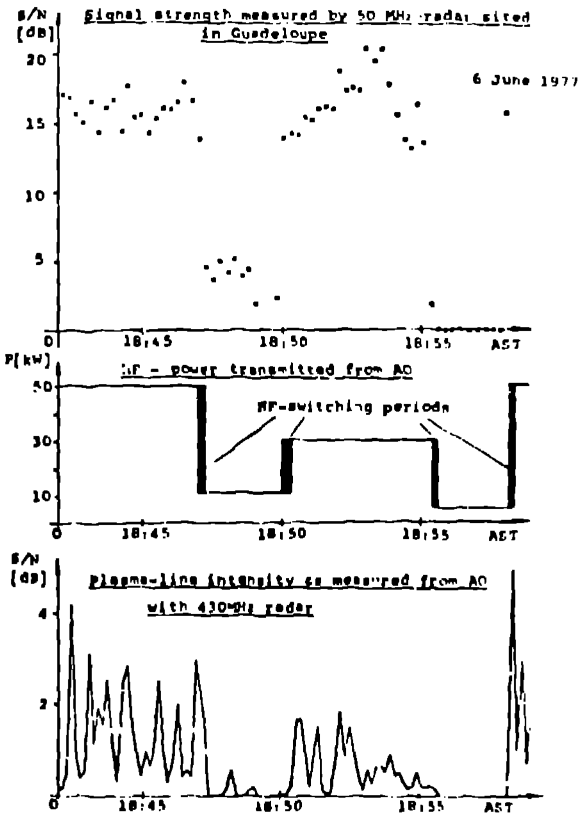

Figure 11. Comparison of 50-MHz radar coherent scatter signal strength with HF transmitted power and enhanced plasma line intensity.