LA-UR-80-3095

MASTER

TITLE: SPS IONOSPHERE/MICROWAVE BEAM INTERACTIONS:
ARECIBO EXPERIMENTAL STUDIES

AUTHOR(S): Lewis M. Duncan, P-4, LASL

SUBMITTED TO: Solar Power Satellite Project Division,
DoE, Office of Energy Research (for
eventual publication)

DISCLAIMER

By acceptance of this article, the publisher recognizes that the U.S. Government retains a non-exclusive, 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

EAB

SPS IONOSPHERE/MICROWAVE BEAM INTERACTIONS: ARECIBO EXPERIMENTAL STUDIES

October 1980

Contributors:

- L. M. Duncan, Los Alamos Scientific Laboratory
Los Alamos, NM 87545**
- W. E. Gordon, F. T. Djuth, D. A. Fleisch, S. Ganguly, A. Frey, D. S. Coco, and A. J. Coster, Dept. of Space Physics and Astronomy
Rice University, Houston, TX 77001**
- R. A. Behrke, National Astronomy and Ionosphere Center
Arecibo Observatory, Arecibo, Puerto Rico 00612**
- R. J. Jost, Johnson Space Center
National Aeronautics and Space Administration, Houston, TX 77058**
- R. L. Showen, SRI, International
Palo Alto, California 94025**
- J. D. Mathews and M. P. Sulzer, Dept. of Electrical Engineering and
Applied Physics, Case Western Reserve University, Cleveland,
Ohio 44106**

SPS IONOSPHERE/MICROWAVE BEAM INTERACTIONS: ARECIBO EXPERIMENTAL STUDIES

CONTENTS

1.	RESULTS AND CONCLUSIONS	1
2.	PHYSICS OF IONOSPHERE/MICROWAVE BEAM INTERACTIONS	3
2.1	Experimental Objectives	4
2.2	Facilities	5
3.	ELECTRON HEATING	6
3.1	Enhanced Electron Heating in the Lower Ionosphere	6
3.2	Electron Heating in the F-Region	8
4.	THERMAL SELF-FOCUSING INSTABILITY	9
4.1	Overdense F-Region Experimental Observations	10
4.2	Overdense E-Region Observations	11
4.3	Underdense F-Region Experimental Observations	12
5.	SHORT-SCALE PLASMA STRIATIONS	13
5.1	F-Region Experimental Observations	13
5.2	E-Region Experimental Observations	13
6.	WHAT WE NEED TO KNOW	15

1. RESULTS AND CONCLUSIONS

For all tests, under conditions similar to the Satellite Power System (SPS) microwave beam operation, no nonlinear ionospheric interactions have been excited that can be associated with clearly unacceptable environmental or communications impacts. Based on these results, we recommend that serious consideration be given to increasing the SPS microwave beam maximum power flux density above the current design limit of 23 mW/cm^2 . These studies are not definitive because of power, frequency, and pulsing limitations in the existing facilities. However, they do represent the best current experimental assessment of the physics of ionosphere/microwave beam interactions.

- 1.1 Using available Arecibo UHF facilities, heating of the lower ionosphere at SPS-equivalent power densities was measured in a series of short-pulse experiments. The observed heating was significantly less than originally predicted, but is in general agreement with subsequently revised theoretical models. Additional studies of underdense ionospheric heating using high-power, high-frequency radiowaves (3 to 10 MHz) at SPS-equivalent power densities within the lower ionosphere yielded electron temperature increases up to a factor of two above ambient. Enhanced electron heating is expected in the lower ionosphere within the SPS beam. However, no directly associated telecommunications impacts have been observed in past experiments. Without experimentally simulating this enhanced heating throughout the ionosphere, we cannot determine if secondary temperature-dependent instabilities will be excited.
- 1.2 Thermal self-focusing of high-power, high-frequency radiowaves has been observed in the upper ionosphere. Scale sizes, thresholds, and growth rates of the accompanying irregularities have been measured for heating in an overdense upper ionospheric plasma. The observations agree with theoretical predictions. Efforts have been made to detect thermal self-focusing in natural sporadic-E regions found in the lower ionosphere. Heating of an overdense sporadic-E plasma has not produced any clear indications of thermal self-focusing; however, focusing by naturally occurring sporadic-E irregularities has been observed. Self-focusing in an underdense ionosphere has been detected through

scintillation observations. Thermal self-focusing of the SPS microwave beam is predicted, although the size and intensity of the accompanying ionospheric irregularities has not been determined. In addition, the associated environmental impacts and possible mitigation strategies have not yet been experimentally demonstrated.

- 1.3 Short-scale plasma striations producing strong field-aligned scatter have been generated in the upper and lower ionosphere in overdense HF ionospheric heating studies. Several theoretical models have been proposed to explain their development. Short-scale plasma striations have not been detected during underdense ionospheric heating experiments; these studies do not predict their formation in the SPS microwave beam.
- 1.4 Parametric or resonant plasma instabilities are a common feature of overdense ionospheric heating experiments. These interactions are not observed for heating in an underdense ionosphere. Although there exist several differing theories for parametric and resonant interactions, it is generally agreed that they should not develop in the SPS microwave beam.

2. PHYSICS OF IONOSPHERE/MICROWAVE BEAM INTERACTIONS

The ionosphere is commonly defined as that portion of the earth's upper atmosphere where sufficient numbers of free electrons exist so as to affect radiowave propagation. Electromagnetic radiation propagating through this region is collisionally damped by the free electrons. For microwave frequencies, the fraction of wave energy absorbed by the plasma is expected to be relatively small. However, the resulting heating of the plasma can significantly affect the local ionosphere thermal budget. Strong microwave radiation can initiate rapid enhancements in electron temperature, also affecting ionospheric densities and structure. In addition, differential heating of the plasma gives rise to electron temperature gradients, convective plasma motions, and macroscopic thermal forces capable of exciting large-scale plasma instabilities.

Numerous telecommunications systems rely on ionospheric reflections or transionospheric propagation as part of the communications signal path. Any system that can significantly modify the ionosphere has the potential to produce wide-ranging telecommunications interference. In addition, the role of the ionosphere in solar-terrestrial coupling and climate change is not well understood. As a result, modification of the ionosphere by the SPS microwave beam is of general concern.

The ionosphere is commonly discussed in terms of three distinct regions: the D, E, and F regions. The D-region, roughly 60 to 85 km, is characterized by low electron densities and collision dominated processes. Ionospheric heating from the SPS microwave beam is expected to be greatest in this layer. The altitude range from 85 to 140 km is designated the E-region. Collisions and conduction exert relatively equal control on the dynamic processes in this region. The F-region, extending from 140 to approximately 2000 km contains the greatest electron concentrations in the ionosphere. The large-scale processes in this region are controlled by plasma conduction, and therefore are strongly affected by the geomagnetic field. Because of the differing characteristics of these regions, the physics of ionosphere/microwave interactions can vary greatly.

A further distinction in our experimental studies is whether the local ionosphere is overdense or underdense compared to the incident heating radiowaves. Overdense ionospheric heating involves electromagnetic radiation with frequencies less than the ionospheric penetration frequency. These waves

reflect in the ionosphere and can excite parametric and resonant interactions that are not directly related to thermal forces. Radio waves with sufficiently high frequency to propagate through the ionosphere, such as the SPS microwave beam, produce underdense ionospheric heating. The physics of nonlinear interactions are substantially different for heating in an overdense and underdense ionosphere. Interpretation of experimental observations must carefully consider these differences.

2.1 Experimental Objectives

The purpose of this program is to determine the environmental impacts associated with the operation of the proposed SPS microwave power transmission system. We obviously would prefer to achieve this goal without actually constructing such a system. As a result, the experimental program must find ways to simulate the SPS microwave beam interactions with the ionosphere.

It is expected that thermal effects will provide the dominant force driving the nonlinear ionosphere/microwave beam interactions. Collisional damping of radio waves, producing ohmic heating of the ionospheric plasma, depends inversely on the square of the radio wave frequency. Therefore, equivalent heating and equivalent thermal forces can be generated at lower radiated power densities by using lower radio wave frequencies. This principle is fundamental to a large part of our experimental program. Although this frequency scaling relationship is well-accepted, its verification is a critical part of our study of the physics of ionospheric interactions.

An understanding of the physics of the specific interactions excited by the SPS microwave beam is also an important part of the assessment program. This program is designed to determine instability thresholds, the growth rates and spatial extent of the resultant ionospheric disturbances, and the frequency and power dependences of the interactions. We need to know how these interactions are affected by variations in the natural ionospheric conditions, how different instabilities occurring simultaneously may affect each other, and how distinct microwave beams might mutually interact. In addition, if necessary, a detailed understanding of the interaction physical processes will be pursued in order to develop mitigation strategies.

2.2 Facilities

The experimental studies of the physics of ionosphere/microwave beam interactions have been conducted primarily using the facilities of the Arecibo Observatory (National Astronomy and Ionosphere Center, Arecibo, Puerto Rico). The new high-power, high-frequency ionospheric heating facility is capable of producing continuous SPS-equivalent heating in the lower ionosphere. However, at higher heights, the delivered power flux density is significantly less than the frequency-scaled SPS microwave beam. A full complement of ionospheric diagnostics is used to monitor the atmospheric response to the ionosphere/radiowave interactions. The principal diagnostic is an incoherent backscatter radar, capable of measuring electron densities, electron and ion temperatures, ionospheric winds and currents, and ion composition as functions of altitude and time. This radar is also capable of SPS-equivalent ionospheric heating in a very narrow beam, but cannot reach heating equilibrium because of a maximum 10-ms pulse-length limitation. Other supporting diagnostics include periodic ionosonde measurements, airglow observations, scintillation studies, and off-site 50-MHz radar investigations of field-aligned scatter.

A comparable high-power, high-frequency, ionospheric heating facility is located in Platteville, Colorado. Although a lack of ground-based diagnostics restricts studies of the physics of the ionospheric interactions, this facility is excellently located for studies of the effects of the associated ionospheric disturbances on existing telecommunications systems. The Arecibo and Platteville experimental studies are yielding complementary results, which together form the basis of our SPS environmental-impact assessment.

3. ELECTRON HEATING

Solar photoionization in the ionosphere produces free electrons with an effective temperature usually exceeding that of the background neutral gas. As electrons gain energy through solar photoionization, they also lose energy by collisions with the much heavier atoms and molecules of this background gas. The electron temperature is therefore an energy balance between these heating and cooling processes.

The collisional heating and cooling interactions of the ionospheric plasma are all dependent on the electron temperature. Under certain conditions, the rate of heating may temporarily dominate the normal cooling losses, initiating a rapid increase in the electron temperature that continues until compensating cooling processes develop, limiting the temperature rise. The net result is a phenomenon originally described as an electron thermal runaway. We now understand that the compensating processes that saturate the heating develop quickly enough to preclude an actual runaway in electron temperature, although significantly enhanced electron heating can occur. This enhanced electron heating can affect the electron-ion recombination rates, thereby changing ionospheric densities, or drive secondary nonlinear ionospheric interactions, further disturbing the ambient plasma. These disturbances can produce potentially serious telecommunications impacts.

3.1 Enhanced Electron Heating in the Lower Ionosphere

Initial tests of the enhanced electron heating theory were made in two series of experimental studies using the 430-MHz radar system at the Arecibo Observatory. The rapid electron heating and cooling initially predicted for the lower ionosphere suggested that pulsed heating experiments using high peak powers would be sufficient to initiate enhanced electron heating. The 430-MHz radar system at Arecibo operates with 2.5-MW peak pulse power and a maximum 10-ms pulse length with a 6% duty cycle. Coupled with the gain of the 305-m Arecibo reflector, this system delivers $\sim 1.5 \text{ mW/cm}^2$ in the center of the radar beam (SPS frequency scaled $\sim 50 \text{ mW/cm}^2$) to 100-km altitude. This is roughly twice the estimated threshold for exciting enhanced electron heating.

The 430-MHz radar system also serves as the principal ionospheric diagnostic in this experiment. Performing as an incoherent backscatter radar, a sensitive receiver system detects the radar signal power backscattered by free electrons in the ionosphere, recorded as a function of time. In this

manner, ionospheric electron density altitude profiles were measured before and after a long (0.4- to 9-ms) radar heating pulse. On these short time scales, electron number density variations are very small. As a result differences in these "hot" and "cold" profiles can be interpreted as due to changes in the electron scattering cross section. Because of the known temperature dependence of this cross section, the effective electron heating averaged across the beam could be determined. The long heating and short diagnostic radar pulses were separated slightly in frequency to avoid signal contamination, providing an altitude resolution of 3 km. Figure 1 shows results of this experiment.

Although more than 100-K increases in electron temperature were typically observed, this was much less than the predictions of enhanced electron heating theory at the time. This discrepancy was resolved by explicitly computing the heating time dependence as a function of power, and accurately treating the radar power distribution across the heating and diagnostic beam. Using these improvements, agreement between theory and observations is good, as shown in Fig. 1. The remaining differences at the lowest altitudes result from complications in interpreting the radar backscatter data when the local plasma Debye length and the radar wavelength become comparable.

Although these experiments usefully provided the first test of enhanced electron heating theory, the results are limited by the restriction to 10-ms pulsed heating. As shown in the current theoretical heating predictions, this heating would not have achieved equilibrium throughout the beam.

This experiment has been supplemented with a recent series of incoherent scatter spectral observations, extended to measure temperature changes in the D-region ionosphere. The underdense heating was provided both by the Arecibo 430-MHz radar system and by the new HF facility. SPS-equivalent heating was produced within the D-region by both systems. Temperature increases by up to a factor of two were detected below 75 km, as shown in Figs. 2 and 3.

For a vertically incident radiowave this represents approximately 30 dB/MHz^2 absorption for a two-way path. This is consistent with observations of 4 to 6 dB of absorption for a 2.4 MHz vertically incident radiowave. Evidence of a significant change in electron temperature is also provided by observations of about 6 dB absorption of a 23-kHz signal incident nearly vertically on the heated mesosphere, with the heated volume a small portion of the overall earth-ionosphere waveguide system. The SPS impacts on

telecommunications signal propagation due to heating of the lower ionosphere are expected to be less than or equal to those effects measured in this experiment.

In addition, a wave interaction study of D-region heating at 430 MHz was conducted. Results of heating-induced changes are shown in Fig. 4. The data indicate generally good agreement between observations and theoretical predictions below 85 km.

3.2 Electron Heating in the F-Region

High-power HF radiowaves have been used to heat the overdense F-region plasma. The radiated power flux density near the HF reflection altitude was estimated at $20 \mu\text{W}/\text{m}^2$ (SPS frequency-square scaled $\sim 0.5 \text{ mW}/\text{cm}^2$).

Electron temperature increases of several hundred degrees were observed near this height of reflection, as shown in Fig. 5. The temperature measurements were made using the 430-MHz incoherent backscatter radar.

The electron temperature increases observed for overdense ionospheric heating cannot be directly related to underdense plasma heating models. Parametric or resonant interactions at the HF reflection height produce anomalous absorption of HF radio waves and increased electron temperatures. As discussed previously, these parametric or resonant interactions are not expected in the SPS microwave beam.

Underdense heating of the F-region ionosphere has been studied at incident frequency-scaled power densities much smaller than the SPS microwave power beam. No F-region heating was measured in these experiments; no detectable electron temperature changes were predicted for the small power densities available in existing facilities for underdense F-region heating. As a result of the high heat conduction along geomagnetic field lines in the F-region, the SPS microwave beam is not expected to produce significant enhanced heating in the upper ionosphere.

4. THERMAL SELF-FOCUSING INSTABILITY

The collective plasma process that has received the most attention with respect to potential ionosphere-microwave interactions is the phenomenon of thermal self-focusing. Small natural density fluctuations in the ionosphere cause a variation in the plasma index of refraction. As a result, an electromagnetic wave propagating through the plasma is slightly focused and defocused, with the local electric field intensity increased as the incident wave refracts into regions of comparatively underdense plasma. Differential ohmic heating of the plasma gives rise to a temperature gradient, driving plasma from the focused region and amplifying the initial density perturbation. This self-focusing instability continues until hydrodynamic equilibrium is reached, creating large-scale ionospheric irregularities similar to natural spread-F conditions.

It is appropriate to mention some equivalent terminologies that can be found in the open literature. Thermal self-focusing has also been referred to as thermal diffusive scattering, thermally-driven stimulated Brillouin scattering, or collisionally-coupled, purely growing, parametric instability in ionospheric modification theories. In nonlinear optics, it is called stimulated Rayleigh scattering; as applied to laser technology, it is described as beam filamentation. The effect of the self-focusing instability, which we call ionospheric irregularities or plasma striations, is frequently referred to as "hot spots" in laser-plasma coupling, "solitons" in astrophysical and controlled fusion research, and "cavitons" in some laboratory plasma studies. Nevertheless, despite subtle differences, the physics of self-focusing is essentially the same for each of these applications.

The SPS microwave beam is predicted to generate large-scale ionospheric irregularities. The environmental and system impacts of this process will depend on the degree of beam self-focusing, the size of the resulting large-scale density striations, and the magnitude of the density fluctuations within the irregularities. Secondary instabilities may develop along the striation density gradients. Ionospheric striations may cause scintillation of radiowaves using transionospheric propagation through the perturbed region, including the SPS pilot beam. In addition, HF radio waves will undergo multiple reflections in the striated region, resembling a natural spread-F environment.

Theoretical studies of thermal self-focusing instabilities have derived a frequency-cubed threshold dependence. However, this frequency dependence is less universally accepted than that of ohmic heating described in the previous section. As a result, experimental verification of this dependence is a programmatic necessity. Furthermore, the frequency-cubed instability threshold scaling is not intended as an unrestricted equivalent power scaling. The frequency-cube scaled "equivalent" powers may produce vastly different irregularity density fluctuations. Therefore, although frequency-cube scaled HF experiments may be used to investigate self-focusing threshold phenomena, they are not expected to generate equivalent telecommunications effects.

4.1 Overdense F-Region Experimental Observations

Intense HF electromagnetic radiation incident on an overdense ionospheric plasma excites parametric instabilities, enhancing electron-plasma oscillations observable by incoherent backscatter radar. These instabilities continue to be the subject of intense experimental study. Of importance here is the fact that, above instability threshold, the strength of enhanced plasma waves directly depends on the local power of the pump electric field. In addition, because of exact frequency and wave-number matching conditions for both the parametric wave-plasma interaction and the radar incoherent backscatter process, these enhanced waves are detected at only one altitude. As a result, systematic scanning of the narrow radar beam across the ionospheric interaction region of the enhanced plasma waves yields a two-dimensional cross section characteristic of the electric-field intensity. These maps of electric-field strength clearly show self-focusing striations and large-scale structuring of the illuminated plasma.

The results of a self-focusing experiment conducted at Arecibo from June 2 through 17, 1977, are shown in Fig. 6. When the radar beam is fixed (Fig. 6a), signal modulations are induced by the natural $E \times B$ drift of striations through the beam. Immediately afterward, rapid scanning of the radar beam (as shown in Fig. 6b) detected a series of striations in the interaction region. Typical striation dimensions deduced from observations over many such scans are 1.2 km in the north-south plane and 1.0 km in the east-west plane, in good agreement with thermal self-focusing theory. Striation velocities are on the order of 25 m/s, with components of 20 m/s to the east, and smaller than 15

m/s in the north-south direction. North-south velocity measurements are complicated by the strong spatial dependence of the striation width in the magnetic meridian plane.

In a more recent experiment using the new HF ionospheric heating facility, the radiated power flux density near the HF reflection altitude was estimated at over $100 \mu\text{W}/\text{m}^2$. The resultant ionospheric striations were studied by measuring signal scintillations as radio stars drifted over the heated region. Large scintillations were detected at 430 MHz, while smaller scintillations were observed at 2.38 GHz. Power spectral densities of the irregularities showed a dominant large-scale size of 500 to 1000 meters, in agreement with the radar striation scans previously described. Signal fluctuations at the center of the HF beam were observed to be as large as 50%, as shown in Fig. 7. Atmospheric Explorer satellite passes through field lines connected to the HF interaction region also detected large-scale field-aligned density irregularities.

4.2 Overdense E-Region Observations

Experimental observations similar to the overdense F-region self-focusing studies described in the previous section have not been performed in the E-region because of past restrictions on low-frequency heating at the Arecibo Observatory. However, experimental results are available for heating by a reflecting HF wave in sporadic E, using a technique similar to that employed for F-region studies.

Radar measurements have been made at Arecibo in which the intensity of the HF-enhanced plasma line in sporadic E was recorded as regions of sporadic E drifted across the radar field-of-view. At E-region heights, the radar beam width is ~ 300 m in diameter. Sporadic-E drift velocities commonly range from 50 to 100 m/s. In Fig. 8a, the plasma line signal strength is shown as a function of time for a typical sporadic-E observation. The altitude of the plasma line enhancements, which corresponds to an altitude of constant electron density, is plotted in Fig. 8b. In comparison with F-region observations, where plasma line signal strengths commonly vary 2 to 3 orders of magnitude over time scales of a few minutes (Fig. 3), the plasma line signal in sporadic E maintains a relatively constant level. The implication is that at experimental power densities (approximately $20 \mu\text{W}/\text{m}^2$), thermal self-focusing similar to that found in the F-region does not take place during

overdense sporadic E heating. The incident HF power density at which thermal self-focusing becomes important in sporadic E is not known.

While plasma-line enhancements in sporadic E do not in general exhibit a behavior characteristic of strong thermal self-focusing, sudden peaking in plasma line intensity has been observed on a few occasions. This peaking is indicative of HF focusing; however, in these cases the focusing is thought to be initiated by naturally occurring sporadic-E irregularities. One such example is illustrated in Fig. 8c. The peaking in plasma line intensity is accompanied by a temporary rise in the signal altitude (Fig. 8d). This corresponds to the passage of a cavity in electron density through the radar field-of-view. The extent to which heating by the focused HF wave has contributed to the final shape of the observed cavity is not known.

4.3 Underdense F-Region Experimental Observations

In addition to striation studies for HF radiowaves reflecting in the F-region ionosphere, several irregularity observations were made for conditions of underdense F-region heating. The electron density at the peak of the F-region was determined through spectral analysis techniques. On one occasion of underdense HF ionospheric heating, a disturbed spectrum was observed, indicative of strong ionospheric irregularities. Near sunrise the spectrum abruptly recovered to its normal state. Typical density variations within the structure were measured to be on the order of 2% $\Delta n/n$, with some disturbances showing changes as large as 4%. There is a strong possibility that these irregularities were not HF-induced, but were a natural spread-F condition, perhaps enhanced by the underdense ionospheric heating.

Radio-source scintillation studies also were conducted for underdense ionospheric heating conditions. Weak scintillations were detected at 430 MHz when the HF was operated at 8.195 MHz and the ionospheric critical frequency was approximately 7.2 MHz. These observations of weak underdense irregularities were confirmed by Atmospheric Explorer satellite measurements.

5. SHORT-SCALE PLASMA STRIATIONS

Short-scale (meter-size) striation generation has been observed during overdense HF ionospheric modification experiments. These irregularities can affect not only HF communications links, but also many VHF and UHF systems. Several theories have been proposed to explain the development of short-scale striations. All of these theories require resonant or parametric interactions between the exciting electromagnetic wave and the ionospheric plasma. As a result, short-scale plasma striations are not expected to be produced by the underdense SPS microwave beam. The underdense HF ionospheric heating experiments have demonstrated that the short-scale striation cross-sections, if they are formed, are scattering below 0.01 m^2 .

5.1 F-Region Experimental Observations

Short-scale field-aligned plasma striations have been observed during overdense ionospheric modification experiments at Arecibo using a portable 50-MHz backscatter radar. This radar was located on the island of Guadeloupe such that it was capable of receiving direct backscatter from 3-meter field-aligned irregularities approximately 250-km above Arecibo. Although the overdense plasma heating produced some interesting results, no signals were detected for underdense ionospheric heating.

A comparison of short-scale field-aligned scatter observations with HF-radiated power and plasma-line enhancements measured by the Arecibo incoherent scatter radar is presented in Fig. 9 for overdense ionospheric heating. The results indicate a threshold for the short-scale striation formation at approximately 10 kW/m^2 . In addition, the short-scale striations are observed to drift with velocities comparable to the large-scale, self-focusing irregularities.

5.2 E-Region Experimental Observations

It is possible that electron heating by a wave penetrating the E-region will generate local plasma turbulence and trigger the formation of small-scale ionospheric irregularities. While no observations designed to detect irregularity formation in an underdense E-region plasma were made in early HF experiments at Platteville, these results show that short-scale (1 to 6 m) field-aligned irregularities are generated during resonant heating of the E-region by a reflecting HF wave. More recently the 50-MHz radar previously

located on Guadeloupe was operated from St. Croix, V.I., such that it was capable of receiving direct backscatter from 3-meter field-aligned irregularities in the E-region approximately 105 km over Arecibo. For underdense ionospheric heating no heater-related signals were observed above the noise level of the system. An upper limit of 0.01 m^2 has been set for the scattering cross-section for irregularities produced by HF waves penetrating the E-region. Verification of pointing and proper operation of the 50-MHz radar was established by heating in the overdense mode. Signal-to-noise ratios sometimes exceeded 20 dB for this case, indicating scattering cross sections of greater than 10 m^2 for overdense E-region heating.

6. WHAT WE NEED TO KNOW

Experimental tests designed to simulate SPS heating have been performed at Arecibo Observatory using short pulses at 430 MHz and a continuously operated radio beam at HF frequencies (3 to 10 MHz). The average heating rate across the 430-MHz beam exceeded the proposed SPS power density of 23 mW/cm^2 in the D- and E-regions, but the transmitted pulses were too short to simulate the thermal equilibrium operating conditions of the SPS. At HF frequencies, the continuously transmitted SPS frequency-scaled power was equivalent to 23 mW/cm^2 only in the lower ionosphere. Thus, SPS equivalent heating has not yet been fully simulated throughout the ionosphere. A definitive SPS environmental-impact assessment of the ionosphere/microwave beam interactions requires the comprehensive simulation of SPS heating of the entire ionosphere. Upgrading of current facility capabilities is needed to satisfactorily meet this requirement.

Since no significant telecommunications effects have been experimentally demonstrated at frequency-scaled SPS equivalent power densities in the lower ionosphere, additional studies are needed to determine the threshold level of SPS heating at which induced ionospheric modifications do have unacceptable impacts on communications/navigation systems. Based on these results, serious consideration should be given to increasing the maximum power flux density allowed within the SPS microwave beam from the current design limit of 23 mW/cm^2 . Several of the potentially important SPS effects that are in need of further investigation are the SPS-equivalent enhanced electron heating studies, underdense thermal self-focusing observations, and short-scale plasma striation measurements in the upper ionosphere. We need to understand how these phenomena depend on upper atmospheric conditions, natural disturbances, or man-made ionospheric perturbations. In addition to their independently assessed effects, the interactive nature of these phenomena must be investigated. Finally, test programs have been designed to produce heating effects comparable to the SPS by scaling the experiments to lower frequencies and therefore to lower transmitted powers. Since confidence in the frequency scaling of the SPS simulation is essential, frequency scaling laws must be tested and verified experimentally.

FIGURE CAPTIONS

1. Electron heating of the E-region ionosphere at 430 MHz and SPS-equivalent power flux density in a 6-ms pulse.
2. Electron heating of the D-region ionosphere at 430 MHz and a frequency-scaled power flux density exceeding the SPS microwave beam. The electron temperature is determined using two separate measurement techniques.
3. Electron heating of the D-region ionosphere at 5.1 MHz. The electron temperature again is determined using two different techniques.
4. HF wave interaction coefficient following pulsed heating at 430 MHz. Theoretical prediction is shown as solid curve.
5. Electron heating of the overdense F-region ionosphere at much less than SPS-equivalent power flux density.
6. Experimental observations of self-focused HF electromagnetic waves in the overdense F-region ionosphere. a) Signal modulation induced by the natural drift of striations through the fixed radar beam. b) A series of striations observed from rapid scanning of the radar beam across the interaction region, immediately following the drift measurements. The unstriated HF beam is approximated by the dashed curve.
7. Scintillations at 430 MHz generated during overdense F-region HF heating. HF operation was continuous at 7.3 MHz and full power, with the ionospheric critical frequency approximately 9 MHz.
8. HF heating in overdense sporadic E. a) and b) show no apparent self-focusing by the HF wave. c) and d) indicate wave focusing by natural sporadic-E structure.
9. Short-scale plasma striations in overdense F-region HF heating. a) Short-scale striation scattered signal strength using 50-MHz radar. b) HF radiated power. c) Enhanced plasma-line intensity in the heated region, indicating large-scale density irregularities.

FIGURE 1

FIGURE 2

FIGURE 3

Figure 4
BEAM AVERAGED WAVE INTERACTION COEFFICIENT MULTIPLIED BY 1000

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9