CONF-800672--1

LA-UR -80-1562

MASTER

TITLE: SPS ENVIRONMENTAL EFFECTS ON THE UPPER ATMOSPHERE

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SUBMITTED TO: International Symposium on Solar Power Satellites, Toulouse, France, June 25-27, 1980

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SPS ENVIRONMENTAL EFFECTS ON THE UPPER ATMOSPHERE

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Abstract

This paper reviews the ionospheric effects and associated environmental impacts which may be produced during the construction and operation of a solar power satellite system. Propellant emissions from heavy lift-launch vehicles are predicted to cause wide-spread ionospheric depletions in electron and ion densities. Collisional damping of the microwave power beam in the lower ionosphere can significantly enhance the local free electron temperatures. Thermal self-focusing of the power beam in the ionosphere may excite variations in the beam power-flux density and create large-scale field-aligned electron density irregularities. These large-scale irregularities may also trigger the formation of small-scale plasma striations. Ionospheric modifications can lead to the development of potentially serious telecommunications and climate impacts. A comprehensive research program is being conducted to understand the physical interactions driving these ionospheric effects and to determine the scope and magnitude of the associated environmental impacts.

Introduction

The solar power satellite (SPS) concept proposes to collect solar energy in space and microwave beam this energy to ground-based receiving antennas where it can be converted to electrical power.[1] A network of these solar-power satellites, each generating 5 to 10 GW of power, could make a substantial contribution toward satisfying our future energy needs. The US Department of Energy is currently directing research programs to determine the feasibility of a satellite power system.

The ionosphere is frequently defined as that part of the earth's upper atmosphere where free electrons exist in sufficient numbers to affect radio-wave propagation. Numerous telecommunications systems rely on ionospheric reflections or transionospheric propagation as part of their communications signal path. Any system which 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 just beginning to be investigated. This paper explores the potential ionospheric disturbances and associated environmental impacts accompanying the construction and operation of a solar-power satellite system.

Construction Impacts on the Ionosphere

Construction of a system of solar-power satellites requires many flights of large rockets, called heavy-lift launch vehicles (HLLV).[2] Powered flights of these large hydrogen- or hydrocarbon-burning rockets could cause temporary removal of ions and electrons from the ionospheric F-region. At heights of 150 to 500 km, the normally occurring O^+ ions transfer their charge to the combustion products H_2O and CO_2, forming polyatomic ions that recombine rapidly with free electrons. Severe depletions in ionospheric electron-number density can result. These plasma depletions can produce serious telecommunications effects and may trigger climate modifications. The proposed HLLV launch trajectory currently involves only limited propellant emissions in the F-layer of the ionosphere. The scope and magnitude of associated environmental impacts is being investigated.

Ionospheric Effects on SPS Operation

The microwave power beam responsible for transmitting energy from space to the ground-based rectenna is designed to operate at 2.45 GHz. This frequency represents a convenient compromise between the ionosphere-microwave interactions that are more easily excited at lower frequencies and the increased scattering losses from atmospheric hydrometeors such as rain and hail that occur for higher frequencies. Although no major changes in this operating frequency are anticipated, small changes may be made to reduce interference effects on other electromagnetic systems. An alternative option of laser power transmission is also being considered.

To avoid nonlinear ionospheric interactions, the maximum power flux density within the SPS microwave beam was originally limited to 23 mW/cm^2. Therefore, to deliver 5 GW of power, the downcoming beam would have to be at least 5 km in diameter. The rectenna, equally as large as the beam, then becomes a substantial part of the SPS system cost (estimated at approximately 42%). Any significant change in the maximum power-flux density in the microwave beam results in an associated change in SPS cost efficiency. The SPS economics, thus, are closely related to the ionosphere-microwave interaction thresholds and the magnitude of associated effects. A research program to determine these thresholds accurately and to evaluate accompanying environmental impacts is well underway.

In addition to economic considerations, the ionosphere can also affect the SPS operational performance. The downcoming microwave power beam is directed onto the ground-based rectenna by an upgoing pilot beam. This retrodirective system operates at a frequency close to that of the power beam and is centered in the rectenna. Thus, the upgoing pilot beam propagates through the same ionospheric plasma as does the downcoming power beam. Any disturbances generated in the ionosphere could then lead to pilot beam scintillation or scattering, resulting in wandering or defocusing of the microwave power beam. A detailed study of beam control is an important part of the SPS ionospheric research program.

Microwave Beam Effects on the Ionosphere

Electromagnetic radiation propagating through the ionosphere is collisionally damped by free electrons. For microwave frequencies, the fraction of wave energy absorbed by the plasma is expected to be extremely small. Nevertheless, because this absorbed energy goes directly into the free electrons, which have a very small effective heat capacity, the resulting ohmic heating can significantly affect the local ionospheric thermal budget. Strong radiation can initiate significant enhancements in electron temperature, also affecting ionospheric densities and structure. Furthermore, the resulting thermal forces can drive additional ionosphere-microwave interactions leading to beam self-focusing and the development of ionospheric striations.

Most of the changes in the ionosphere induced by the SPS microwave beam are believed to be restricted to an area near the beam. However, even localized changes in ionospheric structure, density, and temperature can cause serious wide-ranging telecommunications effects. The magnitude and scope of these effects depends both on the specific telecommunications system characteristics and on the nature of the ionospheric disturbances. A vigorous research program is underway to establish the thresholds for exciting nonlinear ionosphere-microwave interactions, to determine the effects of these interactions on the ionosphere, to define the scope and magnitude of associated telecommunications impacts, and to devise mitigation strategies to suppress their occurrence, if necessary.

HLLV Propellant Emissions

Depletion Chemistry

Ionospheric depletions in electron and ion densities are predicted to occur following HLLV launches for the construction of solar-power satellites.[3] The injection of rocket exhaust products, primarily H_2O and H_2, leads to an enhancement of the effective electron-ion recombination rate through the substitution of polyatomic ions H_2O^+, H_3O^+, and OH^+ in place of the normally occurring O^+. The depletion effect is apparently confined to the F-layer ionosphere above 200-km altitude where O^+ is the dominant positive ion. The main reactions are

$$O^+ + H_2O \rightarrow H_2O^+ + O \qquad (1)$$

followed by

$$H_2O^+ + e^- \rightarrow H + OH \quad . \qquad (2)$$

Reaction (1) is much faster than either of the normally occurring F-layer charge transfer reactions

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad (3)$$

or

$$O^+ + N_2 \rightarrow NO^+ + N \quad . \qquad (4)$$

Reaction (1) is about 10^5 times faster than the direct recombination of electrons with O^+, viz:

$$O^+ + e^- \rightarrow O + h\nu \quad . \qquad (5)$$

In addition, the OH radical formed in Reaction (2) can react further with O^+,

$$O^+ + OH \rightarrow O_2^+ + H \quad , \qquad (6)$$

which is followed by rapid neutralization of the O_2^+,

$$O_2^+ + e^- \rightarrow O(^1D) + O \quad . \qquad (7)$$

The $O(^1D)$ is a metastable electronically excited oxygen atom that decays primarily by emission of 6300-Å radiation.

As a result of these two cycles, each H_2O molecule can induce rapid recombination of two electron-ion pairs. Similar processes occur with other common rocket exhaust products, such as H_2 and CO_2.

The spatial and temporal scale of the ionospheric depletion is influenced by diffusion and convection of the exhaust products from their initial point of deposition. A portion of the water deposited in the F-region ionosphere will form ice and fall to D-region heights (65 to 90 km), where its interaction with the normal ionospheric chemistry is much less serious. When the H_2O concentration along the rocket trajectory has decreased by diffusion to levels below the normal F-layer ion concentration (10^6 cm^{-3}), the local ionization should be replaced by sunlight-induced photoionization of atomic oxygen in about four hours.

Relevant Observations

The launch of Skylab I (Saturn V rocket, 1230 EST, 14 May 1973) involved an unusually long second-stage burn through the ionospheric F-region. Nearly simultaneous observations of the formation of a large ionospheric hole were reported.[4] The ionospheric total-electron column density was observed to be reduced by 50% or more over a period commencing within 10 minutes after the launch and persisting for about 4 hours, as shown in Fig. 1. The depletion apparently extended over a region approximately 2000 km in diameter. These observations were made in the course of routine Faraday rotation measurements of VHF signals from geostationary satellites ATS-3 and -5, as obtained from the Sagamore Hill Radio Observatory in Hamilton, Massachusetts. The ionosphere may have recovered from the depletion in the observed four-hour event duration, or the hole structure may simply have drifted beyond the observational line-of-sight. In either case, the large depletion in ionospheric electron density can be attributed directly to the rocket propellant emissions during launch.

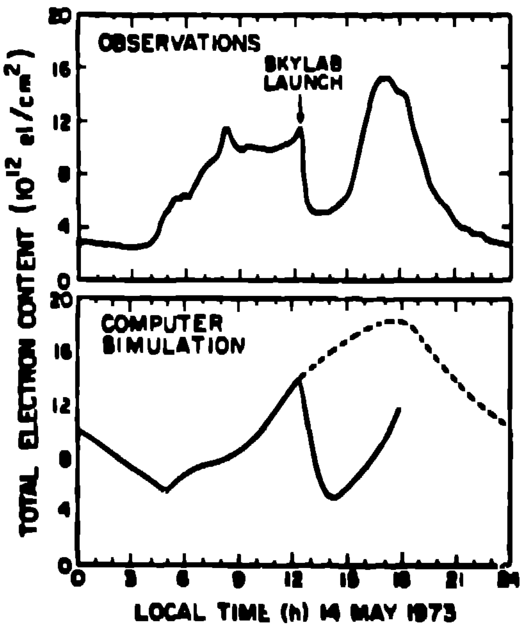

Figure 1
Measured total electron content[4] vs time following Skylab I launch on line-of-sight from Sagamore Hill Observatory to ATS-3; model computation of TEC vs time for same line-of-sight for the 24 hours preceding and 4 hours following the Skylab launch.[3]

Because of the potential impacts of these depletions on telecommunications systems, Los Alamos National Scientific Laboratory and Sandia Laboratories jointly sponsored two rocket experiments (code-named Lagopedo) to investigate the expected chemistry modifications produced by H_2O and CO_2.[5] The experiments generated ionospheric depletions by many of the same processes that are active following the deposition of rocket-propellant emission products; consequently, the Lagopedo data are directly pertinent to the SPS problem. The rockets' explosive payloads deposited detonation products H_2O, CO_2, and N_2 into the F-region ionosphere.

Both experiments successfully produced ionospheric depletions. The first experiment, fired in local daylight, produced a visible ice cloud as a result of adiabatic expansion of the H_2O which expanded to a diameter of over 100 km within 30 s. The cloud was visible due to scattered sunlight. No cloud was seen in the second shot, fired after local sunset. Both releases were accompanied by measurable airglow emissions at 6300 Å [$O(^1D)$] and 5577 Å [$O(^1S)$].

It is also probable that the launch of large spacecraft produces similar global disturbances of electron density in the ionosphere. At observation points approximately 2000 km from the launching site, fluctuations in electron density of 5 to 10% were detected following the launch of Soyuz 19 and Apollo spacecraft.[6] A decrease in density was recorded several minutes after each launch, followed by a quasiperiodic recovery with a period of about 90 minutes and persisting for several hours. Multiple reflections of HF radio waves were observed during the ionospheric disturbance. These disturbances resemble the ionospheric response following a sudden commencement of a magnetic storm.

The High-Energy Astrophysical Observatory satellite HEAO-C was launched from Cape Canaveral at 0530 GMT (0030 local time) on September 20, 1979, aboard an Atlas-Centaur rocket. The launch trajectory, which was almost due eastward, was unusual in that the Centaur second-stage engines burned to an altitude of 466 km, depositing large quantities of exhaust gases directly into the F-layer. Experimental observations confirmed that, as predicted by computer models, a significant F-layer depletion did occur over a region roughly 600 km in north-south extent. The depletion persisted until dawn. High-altitude density profiles measured using the Arecibo Observatory incoherent-scatter radar indicated that electron density in magnetic-flux tubes directly connected to the depleted region showed no apparent rocket-induced changes.

Predictions for SPS

Details of rocket-exhaust induced ionospheric depletion processes depend on many factors, including vertical and horizontal diffusion and convection, sunlight-induced photoionization and photodissociation, and a large number of chemical reactions. Large computer models that incorporate these many factors affecting ionospheric chemistry are being constructed to predict the effects of the HLLV launches envisioned as part of the SPS transportation system.[3] Preliminary results indicate the potential for substantial reduction of the total ionosphere, as shown in Fig. 2.

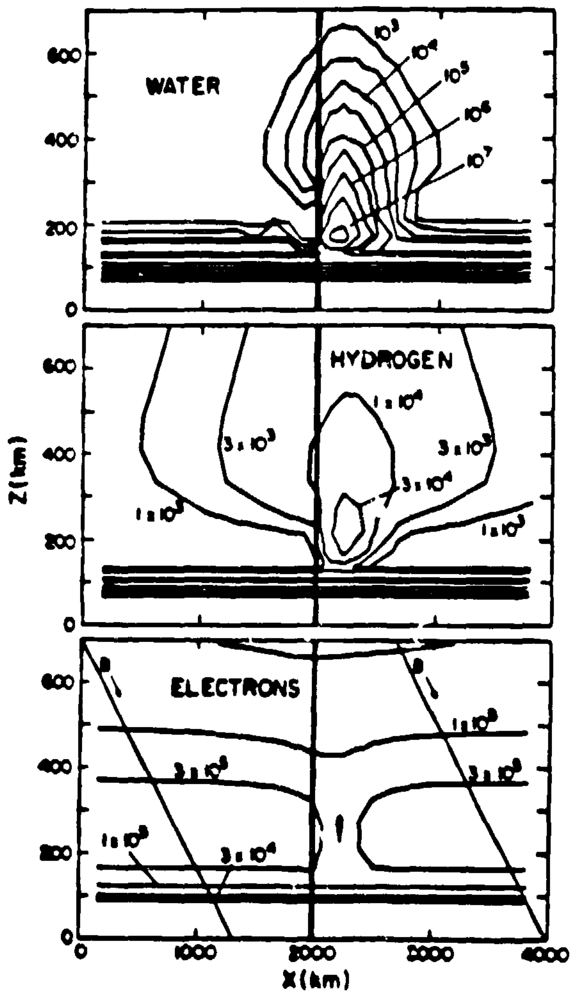

Figure 2
Computed concentration contours[3] for H_2O, H_2 and electrons (number per cubic centimeter)[2] 2.4 hours after a hypothetical HLLV orbit circularization burn over the Philippine Islands. The cross-sectional view is perpendicular to the orbital plane and parallel to the magnetic meridian plane looking back along the trajectory. The original exhaust deposition was in the central plane x = 2000 km, and extends 1400-km lengthwise in that plane.

A single HLLV second stage would emit about 7.8×10^{31} H_2O molecules and 2.4×10^{31} H_2 molecules. If all of these molecules went into the F-layer, they could recombine 1.8×10^{32} ion-electron pairs, or about twice the number present in the entire global ionosphere. However, before reaching any catastrophic conclusions, the atmospheric models must include accurate treatments of diffusion, gravitational settling, and convection effects, as well as a realistic description of the HLLV launch trajectory and associated vehicle effluents.

These large-scale ionospheric depletions could have many consequences. Decreases in ionospheric electron density will directly affect high-frequency (HF) telecommunications systems that depend on radio waves reflecting from the ionosphere. Additional impacts are much more speculative. The ionosperic electron temperature profile, electric conductivities, and wave-particle interactions will be affected to some extent. The ionosphere-magnetosphere coupling may be altered and satellite drag may increase. Auroral behavior and airglow intensities could also change.

Several potentially serious environmental impacts may accompany these modifications of ionospheric structure and behavior. In addition to direct HF radio-wave effects, changes in the ionospheric propagation properties of other electromagnetic waves may lead to impacts on many telecommunications systems. The role of solar-terrestrial coupling in triggering climatic changes is not yet well-understood; however, several theories suggest that changes in the upper atmospheric conductivity and composition may lead to climate modifications. All of these possibilities, as well as many others, must be studied in much greater detail before we commit ourselves to constructing solar-power satellites.

Ionosphere-Microwave Interactions

Enhanced Electron Heating

The collisional heating and cooling processes of the ionospheric plasma are all dependent on the electron temperature. For sufficiently strong radiation, the rate of heating may increase much faster than the normal cooling interactions, initiating a rapid increase in the electron temperature that continues until compensating processes set in that limit the temperature rise. The net result is a phenomenon originally described as an electron thermal runaway.[7] 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 heating then can affect the electron-ion recombination rates, changing ionospheric densities, or drive secondary nonlinear ionosphere-microwave interactions, further disturbing the ambient plasma. These disturbances can produce potentially serious telecommunications impacts.

Electron Heating Theory. Holway and Meltz,[7] investigating the effects of strong radio-wave heating of free electrons in the lower ionosphere, first introduced the concept of an electron temperature runaway. However, because their calculations neglected several important ionospheric cooling mechanisms, their results are not quantitatively accurate and do not predict an electron temperature saturation limit. A computation of electron heating within the SPS microwave beam was described recently by Perkins and Roble,[8] including a comprehensive model for the dominant collisional cooling processes. Their results represent the first thorough analysis of the effects of a thermal runaway in the ionosphere, including a steady-state solution for the electron temperature. Additional studies have verified this analysis and extended the results to lower altitudes.[9]

The electron energy equation in the ionosphere can be expressed as

$$\frac{3}{2} n_e k \frac{dT_e}{dt} = Q^+ - Q^- \quad , \qquad (8)$$

where n_e is the electron number density, k is Boltzmann's constant, dT_e/dt is the rate of change of the electron temperature, Q^+ is the heat source function, and Q^- describes the volume heat losses. Clearly, whenever the energy input exceeds the cooling losses, the electron temperature must increase. Sufficiently strong ohmic heating can produce a continuously increasing electron temperature, saturating only at some level where the increased ohmic heating is balanced by additional cooling processes.

The rate of energy input to the atmospheric free electrons resulting from the absorption of microwave or radiofrequency radiation can be attributed entirely to ohmic heating, given by[9]

$$Q^+ = \frac{E^2}{8\pi} \frac{f_p^2}{f^2} (\nu_{ei} + \nu_{en}) \quad , \qquad (9)$$

where E is the wave electric field amplitude, f_p is the local plasma frequency, f is the electromagnetic wave frequency, and ν_{ei}, ν_{en} are the electron-ion and electron-neutral collision frequencies. In the lower ionosphere, the electron-neutral collision frequency dominates and can be approximated by[10]

$$\nu_{en} \sim 2.3 \times 10^{-11} \, n(M) \, T_e \quad , \qquad (10)$$

where n(M) is the total molecular number density (cm^{-3}) and T_e is the electron temperature (K).

As the electrons gain energy from the microwaves or from solar UV radiation, they also lose energy by collisions with atoms and molecules of the background gas. In the collision-dominated lower ionosphere, thermal conduction is not an important cooling mechanism. The most effective kinds of energy transfer collisions are inelastic interactions with O_2 and N_2, producing rotational and vibrational excitation, and collisions with atomic oxygen, producing excitation of hyperfine levels of the ^3P ground state. In the upper atmosphere, thermal conduction is the principal cooling process, rapidly diffusing excess heat along the geomagnetic field lines.

The electron temperature is a sensitive balance between heating processes and cooling interactions. As shown in Eqs. (9) and (10), as the electron temperature rises the electron-neutral collision frequency also increases, thereby increasing the ohmic heating. Electron cooling also becomes more efficient as the electron temperature increases above its ambient value. The time it takes a plasma to self-consistently reach an equilibrium between these competing processes is called the heating time scale. After the ionospheric wind has swept this plasma beyond the heating beam, the electron temperature relaxes to its ambient level on a cooling time scale that is not very different from its heating counterpart. In the lower ionosphere, both heating and cooling equilibria are reached in tens of milliseconds or less.

Relevant Observations. No present facilities can continuously irradiate the ionosphere at the SPS frequency of 2.45 GHz with the SPS power-flux density of 23 mW/cm^2. To construct such a facility would be extremely costly. However, at least for the study of ionosphere-microwave interactions, this does not seem necessary. The SPS frequency is many times greater than normal plasma frequencies in the ionosphere, which are typically smaller than 10 MHz and usually do not exceed 20 MHz. Therefore, resonant ionosphere-microwave interactions are not expected to occur. Instead, thermal forces should drive any phenomena that develop. As can be seen in Eq. (9), this heating scales inversely as the square of frequency. Thus, by using lower experimental wave frequencies but still avoiding resonant interactions, the SPS microwave beam can be accurately simulated at much lower radiated powers.

Initial tests of the enhanced electron heating theory were made in two series of experimental studies using the 430-MHz radar system of the Arecibo Observatory (National Astronomy and Ionosphere Center).[11] Preliminary results measured only about 100 K increases in electron temperature at 100-km altitude for SPS-equivalent power, compared to theoretical heating predictions of several times this. Experimental results are shown in Fig. 3. The

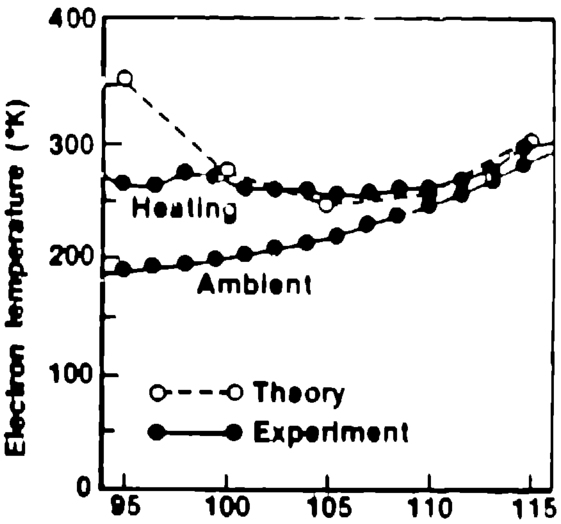

Figure 3
Experimental measurements of electron heating following 6 ms of 430-MHz heating on June 11, 1978. The SPS frequency-scaled power flux equals 25 mW/cm^2 at 85 km. Theoretical predictions are from G. Meltz (1980).

heating pulse length for this experiment was limited to 10 ms. Although this is several times the normal heating time constant, we discovered that the enhanced heating time scale is nonlinearly dependent on the heating power-flux density. New time-dependent heating calculations yield predictions in general agreement with the experimental observations. In addition, unexpected natural variability in the ionospheric behavior was observed to affect the heating balance. No explanation for this variability is yet available.

A detailed research program is planned using high-frequency (HF) ionospheric modification facilities at Arecibo, Puerto Rico, and Platteville, Colorado. These facilities currently produce SPS-equivalent heating only in the D-region ionosphere, but anticipated upgrading will extend this to cover all ionospheric heights. Studies to determine the threshold and magnitude of ionosphere-microwave interactions and to demonstrate the validity of extrapolating results of these frequency- and power-scaled experiments to the SPS microwave beam will be complemented by representative generic telecommunications tests designed to directly demonstrate the ionospheric interactions impacts on communications systems. If necessary, this research will also investigate possible impact mitigation strategies.

Predictions for SPS. At the SPS frequency of 2.45 GHz, the threshold power-flux density for producing significant nonlinear heating is now thought to be approximately 40 mW/cm^2. However, even for small power fluxes, enhanced electron heating is predicted to occur, as shown in Fig. 4. This heating is restricted to the neighborhood of the microwave beam.

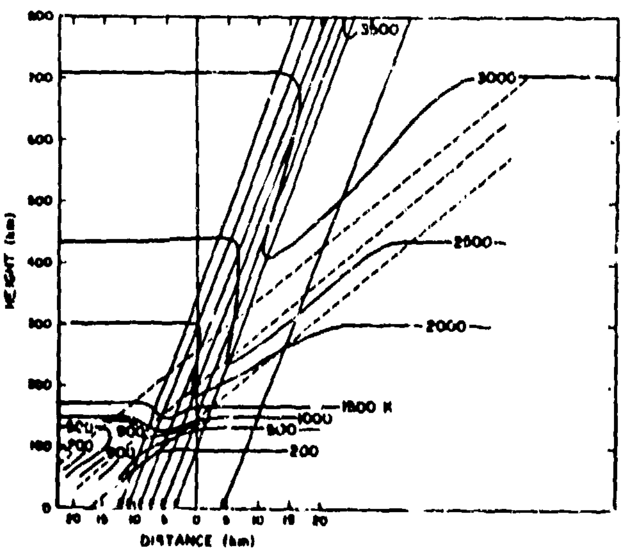

Figure 4
Contours of theoretically calculated electron temperature over Boulder, Colorado for microwave heating by the solar power satellite power beam. The dashed lines give the beam direction and the light solid lines indicate the geomagnetic field direction (from Perkins and Roble, 1978).

Large electron temperature increases in the ionosphere may produce several important environmental effects. Enhanced electron temperatures will increase HF radio-wave absorption in the lower ionosphere. The associated thermal forces can drive potentially serious nonlinear interactions, resulting in beam self-focusing and further development of ionospheric irregularities. If generated, these irregularities can scatter HF, VHF, and UHF radio waves, producing widespread communications interference on many systems using transionospheric propagation.[12] In addition, accompanying changes in ionospheric density and conductivity may induce climate modifications through effects on upper-atmospheric solar-terrestrial coupling mechanisms.[13]

Despite identification of these potential environmental impacts, much more research is needed before any definitive statements can be made. At this point in our very limited studies, no significant environmental impacts associated with enhanced ionospheric heating have been experimentally demonstrated.

On the basis of these preliminary experimental results, we believe the instability threshold for SPS excitation of nonlinear ionospheric interactions is greater than the current microwave beam power-flux density design limit of 23 mW/cm^2.

Collective Plasma Phenomena

Differential ohmic heating of the ionosphere gives rise to electron temperature gradients, convective plasma motions, and macroscopic thermal forces capable of exciting plasma instabilities. The large-scale ionospheric responses to these induced heating effects can generally be described as collective plasma phenomena. This large-scale plasma behavior is driven by dynamic macroscopic thermal forces, as opposed to the microscopic kinetics of resistive heating effects.

Beam Self-Focusing Theory. A considerable amount of attention has recently been directed at wave self-focusing, a macroscopic plasma phenomenon. Natural density fluctuations cause small variations in the index of refraction of a 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[14] and the electric-field ponderomotive force[15] then drive plasma from these focused regions, 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 Fig. 5.

Thermal self-focusing has been shown to develop at much lower power fluxes than those required for self-focusing driven by the ponderomotive force.[16] Thermal self-focusing theories are currently limited to threshold calculations and usually involve geometric restrictions. In

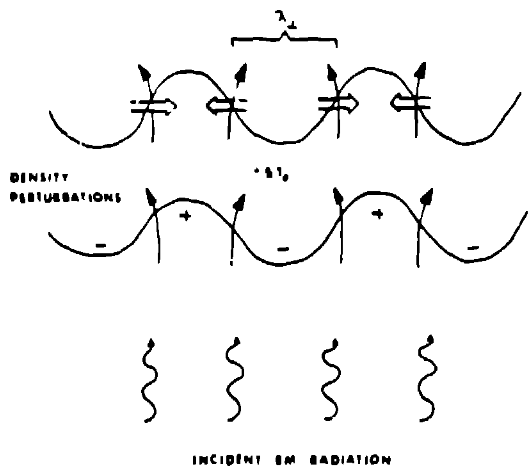

Figure 5
Schematic description of the thermal self-focusing process. Increased electron heating in the focused regions produces a temperature gradient that drives plasma out of the region, further focusing the beam.

the magnetic meridian plane, the thermal self-focusing threshold power flux can be expressed as[17]

$$P_{thresh}(W/m^2)$$

$$\simeq (6\ W/m^2)(10^6/n)^3(T_0/1000\ K)^4(f/2.4\ GHz)^3 C_F\ , \qquad (11)$$

where n is the ambient electron density, T_0 is the ambient electron temperature, f is the microwave frequency, and C_F is roughly unity, depending on spatial and temporal growth rates. This expression is valid for underdense ionospheric heating ($f > f_p$), which is the case for the SPS ionosphere-microwave interactions.

It is not possible to determine a threshold power in the usual sense for thermal self-focusing because the instability threshold power depends nonlinearly on the excited striation width. As the incident power flux increases, smaller striations can become unstable. Also, the power flux necessary to amplify any particular striation size becomes very small when the self-focusing beam nearly parallels the geomagnetic field. The instability threshold depends on the cube of the incident wave frequency, so that once again SPS-equivalent experiments can be conducted at lower heating frequencies with much less radiated power.

Relevant Observations. Thermal self-focusing of high-frequency electromagnetic radiation has been observed in overdense ionospheric modification experiments. These observations will be extended to the appropriate underdense regime in similar experiments scheduled for the near future. The overdense self-focusing instabilities are observed to develop with the theoretically predicted threshold fields, scale lengths, and growth rates.[18] Associated density irregularities form on time scales of seconds to tens of seconds and decay on time scales of minutes.

A schematic of a self-focusing experiment conducted at the Arecibo Observatory is shown in Fig. 6. Results of this study, presented in Fig. 7, indicate that the measured striation widths agree with the theoretical predictions of $\lambda \sim 1$ km for the experimental parameters used.[19] However, the thermal self-focusing theory predicts that all irregularities with widths of 1 km and greater should be amplified. Apparently the saturation state of the self-focusing instability preferentially selects the smallest striation width compatible with a given threshold power for growth. In the plane perpendicular to the magnetic field, the striation widths are predicted to be approximately 500 m,[20] again in relative agreement with the observations.[19] Electron-density perturbations due to the field self-focusing are experimentally estimated at about 5% of the natural background density.

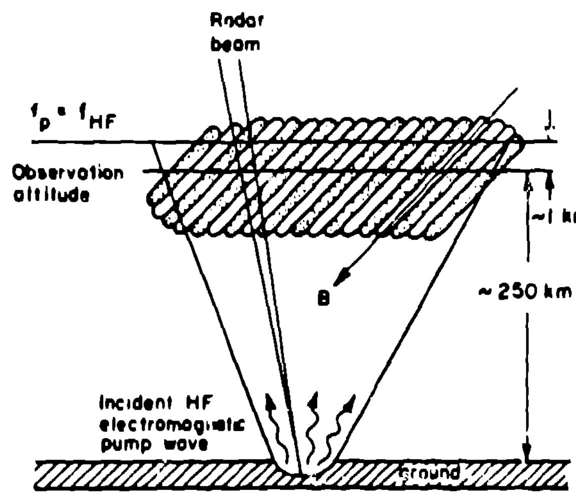

Figure 6
The experimental configuration for incoherent backscatter radar mapping of plasma striations, attributed to thermal self-focusing. Radar scans across the interaction region yield two-dimensional measurements of the local electric field strength.

In addition to these large-scale electron-density irregularities, overdense ionospheric heating is observed to produce short-scale (meter-size) plasma striations.[12] However, they are believed to be produced through some type of resonant interaction,[21] and thus are not predicted to be excited by the SPS microwave radiation.

Predictions for SPS. Thermal self-focusing is expected to occur for the SPS microwave power beam. The environmental and system impacts of this process will depend on the degree of beam focusing, the size of the resulting large-scale

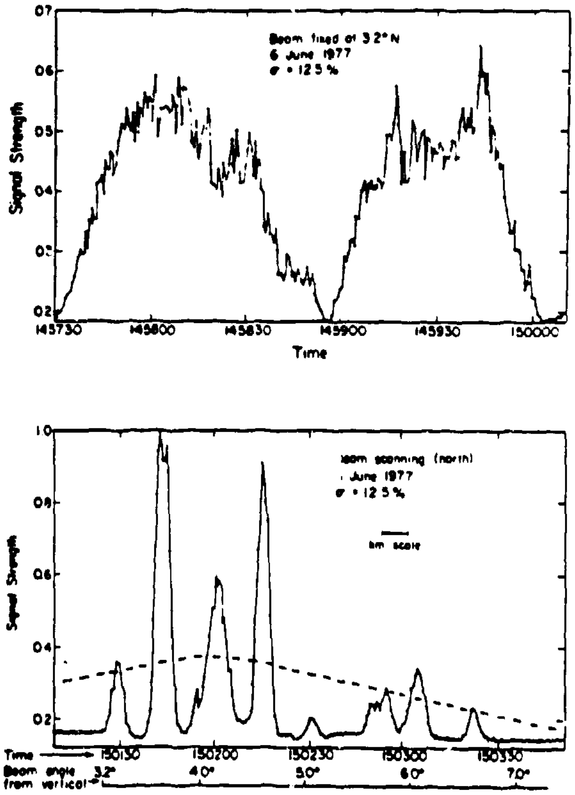

Figure 7
Experimental observations of wave self-focusing. The top figure shows the backscattered signal modulation induced by the natural drift of self-focusing striations through the fixed radar beam. The lower figure presents a series of striations as observed from rapid scanning of the radar beam across the interaction region immediately after the drift measurements. The dashed curve estimates the unstriated beam.

density striations, and the magnitude of the density fluctuations within these irregularities. Best estimates are that the solar-power satellite microwave beam should excite ionospheric striations with scale sizes of about 100 m and density fluctuations of $\Delta n/n \sim 10\%$.[17] These irregularities may cause scintillation of radio waves using transionospheric propagation, including the SPS pilot beam. In addition, HF radio waves will undergo multiple reflections in the striated region. The modified ionosphere will resemble a natural spread-F environment.

If short-scale plasma striations develop in this region, much more serious and wide-ranging communications effects may occur. Coherent scattering of HF, VHF, and UHF radio waves can produce interference in many telecommunications systems, including television and radio. Detailed experimental studies scaled to SPS-equivalence are planned to verify the initial predictions that such short-scale plasma striations will not be generated in the SPS microwave beam.

Conclusions

Although we have presented a simplistic review of a number of distinct ionospheric phenomena, it is clear that for a complete evaluation of the solar-power satellite impacts, we must investigate a complex, coupled set of problems. HLLV propellant emissions may produce large depletions in the ionospheric electron density; collisional damping of the SPS microwave beam will significantly enhance electron temperatures in the lower ionosphere; beam self-focusing can generate large-scale density irregularities in the upper ionosphere. In addition to their independently assessed effects, the interactive nature of these phenomena must be considered. A comprehensive research program to perform the SPS environmental impact assessment has been organized and is being administered by the US Department of Energy.

Historically in the study of ionospheric physics, theory has been relatively poor at predicting experimental results, although quick to explain observations once they have been made. For this reason, it is premature to draw conclusions based on the ionospheric studies to date. Although theoretical investigations have identified several potentially serious SPS environmental impacts, no effects have yet been experimentally demonstrated. Furthermore, we cannot extrapolate the results of current ionospheric research to the SPS studies without also verifying the theoretical assumptions that those extrapolations are based on. All of these considerations have been incorporated into the DoE research program plan. In addition to directly measuring the environmental impacts of ionospheric HLLV emissions and SPS-equivalent ionospheric heating, this program is designed to determine the physics of the interactive mechanisms driving these effects. With this approach, the proposed ionospheric research will yield a thorough understanding of the environmental impacts associated with the solar-power satellite construction and operation.

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