Initial Assessment

Electromagnetic Compatibility Aspects of Proposed SPS Microwave Power Transmission System (MPTS) Operations

February 1978

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INITIAL ASSESSMENT
ELECTROMAGNETIC COMPATIBILITY ASPECTS OF
PROPOSED SPS MICROWAVE POWER
TRANSMISSION SYSTEM (MPTS) OPERATIONS

(Including Radio Frequency Interference, Electromagnetic Interference and the
Effects of Possible Ionospheric Modification on Communications and Other Elec-
tronic Systems)

February -- 1978

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PREFACE

This presentation is intended to provide the general reader with an analysis of major concerns raised by the proposed SPS Microwave Power Transmission System (MPTS) with regard to other radio and electronic systems. No attempt has been made to present a comprehensive technical analysis of the various points. Extensive technical discussions of most of the points raised can be found in the references.

SPS EMC "POINTS"

- I. Incidental energy from a SPS microwave power transmission which falls outside the rectenna area could produce harmful effects on some electronic systems throughout the hemisphere from which the SPS is visible.
- This appears to be an unavoidable result of any practical SPS microwave power transmission system due to fundamental limitations on the confinement of the transmission beam.
 - Power levels produced throughout a hemisphere could degrade the performance of microwave receivers. The degree of degradation would range from negligible to catastrophic.
 - Affected receivers could be modified to mitigate the problem but the cost and effectiveness of the modifications have not been determined.
 - Effects on a variety of other electronic systems are expected within a radius of 20 to 30 km from the center of rectenna and may occur at much larger distances. Modifications to subject systems may be required.
 - The severity of the problems increases as the total power transmitted from SPSs is increased and if SPSs are allowed to operate with substantial faults in their microwave power transmission control systems.

SPS EMC "POINTS" (Continued)

- I. • This incidental energy could provide secondary benefits if it could be used for limited communications purposes such as distribution of standard time and frequency information or as a navigational aid.

Further evaluation of this point will require a detailed determination of the consequences to potential victim systems, including the cost and effectiveness of possible modifications.

SPS EMC "POINTS"

II. Spurious emissions, at frequencies outside a band presumed to be allocated to SPS microwave power transmission, could cause harmful interference to existing or planned uses of the microwave spectrum.

- Spurious emissions are strongly dependent upon engineering details which are not yet determined.
- Available estimates indicate that some limits set by existing international rules and recommendations for the prevention of interference might be exceeded.
- Control of spurious emissions may have a significant effect on the design and cost of the microwave power transmission system.
- The severity of the problem increases directly with total transmitted SPS power.
- The impact on potential victim systems has not been evaluated in detail.

Further evaluation of this point will require additional information on expected SPS spurious emissions and detailed study of the impact on potential victim systems.

SPS EMC "POINTS"

III. SPS microwave power transmission operation will modify properties of the natural ionosphere and might substantially alter the propagation of radio signals over a wide range of frequencies.

- Possible effects include disruption of television broadcasting, shortwave and other communications, interference with some radar systems and degradation of accuracy of navigation aids.
- The occurrence of significant problems depends very strongly on the microwave power beam intensity. There may be a value at which SPS operation is practical and ionospheric effects are small.
- The interaction of microwave beams of the intensity proposed for the SPS power transmission with the ionosphere is not understood well enough to provide an adequate prediction of effects.

Further evaluation of this point will require extensive further study of interactions between the ionosphere and high power microwave beams including experiments that simulate SPS MPTS operations. Significant new facilities or additions to existing ones will probably be required for these experiments.

SPS EMC "POINTS"

IV. SPS microwave power transmission will require modification of existing international radio rules.

- There is at present no provision for MPTS operation and logical extension of existing rules might preclude it.
- Considering points I, II, and III above there may be technical objections to SPS microwave power transmission operations.
- International political considerations are involved.

Further pursuit of this point will require a careful assessment of points I, II and III, including selection of a candidate frequency band for SPS operations, and an organized effort on the part of some agency to obtain international agreement on a frequency allocation.

SPS EMC "DISCUSSION OF POINT I"

Due to natural and technical limitations it is not possible to concentrate all the power transmitted from an SPS into a finite area. A small fraction of the power will inevitably be transmitted in undesired directions. This represents a loss from the microwave power transmission system and is to be minimized for economic and other reasons. Because of the very high total power transmitted by an SPS the incidental sidelobe or scatter radiation may have a significant effect on microwave receiving equipment throughout the area from which the SPS is visible, nearly an entire hemisphere. Figure A shows the power levels computed for a typical current SPS design (from Reference R-39) for a single 5 GW system. At the edge of the earth as seen from the SPS the power level is approximately 0.3 microwatts/cm². Figure A is to some degree idealized. Details of the pattern would vary due to small design changes or tolerances in an actual transmitting antenna assembly and partial failures of the transmission control system could result in higher power levels outside the main lobe. An increase in the total power transmitted from SPSs, either by the addition of more stations or an increase in power per station, would increase the average power level throughout the hemisphere. In the case of many SPSs using a common frequency, the actual distribution of stray energy would be quite complex and would vary with time as relative satellite positions changed slightly.

The power levels predicted in Figure A are sufficient to degrade the performance of a wide range of microwave receiving systems operating at frequencies removed from the SPS transmitting frequency due to overload and

Fig. A. SPS Microwave Energy Distribution (after R-39)

SPS EMC "DISCUSSIONS OF POINT I" (Continued)

nonlinear effects. The degree of degradation could vary from negligible to catastrophic depending on such factors as the type and orientation of receiving antenna, receiver frequency and details of the receiver design.

At one extreme, a low-altitude satellite or airborne system passing through the main beam peak power density of 23 MW/cm^2 would be severely affected. A low-gain omnidirectional antenna designed for any frequency near the MPTS main beam frequency will intercept and deliver to the receiver approximately $1/4$ watt of power. This is above the damage level for many microwave components, and can be expected to interfere with or damage any receiver not specifically designed to reject the MPTS frequency.

Even at the edge of the hemisphere from which the SPS satellite is visible, where the power density from a single satellite is expected from Fig. A to be $0.3 \text{ microwatt/M}^2$, a 2M diameter antenna pointed toward the satellite would intercept and deliver to a receiver one microwatt, enough to overload a low noise parametric amplifier.

In principle it would be possible to add filters to affected receivers to reject the SPS power frequency, but in practice the rejection may not be completely effective in all cases and may introduce other problems, e.g., increased noise temperature in very low noise receivers or phase distortions.

The subject of responsibility of potentially affected systems for rejection of interference from the SPS power transmission frequency will be

SPS EMC "DISCUSSION OF POINT I" (Continued)

significant in obtaining the necessary international agreements for SPS microwave power transmission operation (see Point IV).

Detailed evaluation of the total impact of SPS stray power and the effectiveness and cost of means for mitigating this impact will be a very large task considering the number of potential victim systems and the complexity of the evaluation and testing that will be required.

The overall impact, and cost of mitigating it, may depend on the exact frequency chosen for SPS transmission so this point should be evaluated as part of the SPS frequency selection process.

Power levels at and near the rectenna area will be sufficient to affect the operation of a variety of electronic equipment, including, but not limited to, receiver systems. This Electromagnetic Interference (EMI) or "High Power Effects" should be no more than a nuisance if adequately anticipated.

Prediction of the type and severity of effects to be expected on equipment which was not designed to interact with electromagnetic radiation is extremely difficult due to the large number of variables involved. The susceptibility of systems can vary widely due to minor details of a particular device or installation. We have calculated that typical computer circuits might malfunction if exposed directly to the microwave intensities expected (from Figure A) at 20 to 30 km from the center of the

SPS EMC "DISCUSSIONS OF POINT I" (Continued)

rectenna. Effects have been noted from radar systems at similar intensities (Reference B-3*). In general, electronic systems would be shielded to some degree by their usual metallic enclosures and would thus be expected to function properly in higher intensity fields. The sensitivity of a number of systems and types of equipment must be investigated to assess the potential for important EMI problems at larger distances from the rectenna.

A considerable body of knowledge is available for dealing with EMI and, with proper precautions and appropriate modifications, it should be possible to operate virtually any desired equipment, except possibly microwave receivers, in the highest intensity fields SPS will produce on or near the earth.

Transmissions from the SPS will be easily detectable throughout roughly a hemisphere. The frequency of these transmissions must be closely controlled for proper operation of the transmitting antenna system and so might be used as a standard frequency. If suitable modulation could be applied the power transmissions might also provide a time reference. Either of the above, or other possible limited communications' uses, which might be compatible with the prime purpose of SPS could provide significant secondary benefits. This point has apparently not been explored in detail.

* Pan American Special Investigation Report 508 as quoted in B-3, p. 29-38.

SPS EMC REFERENCES FOR POINT I

The detailed plot of power beam intensity as a function of angle is from R-39. R-10 provides details on design considerations for the transmitting antenna and other components of the microwave power transmission system. R-31 and R-24 also consider antenna design. Power beam propagation is considered in R-31, including scatter due to weather or the ionosphere.

SPS EMC "DISCUSSION OF POINT II"

The SPS MPTS will inevitably radiate power at frequencies other than the intended power transmission frequency. Exactly what the extent of these spurious emissions will be and what power spectral densities will be produced at the surface of the earth depend strongly on engineering details which are not yet determined. Preliminary estimates, based on components similar to those proposed for SPS DC to microwave converters, antenna system designs representative of those now planned and the use of filters believed to be practical for SPS have indicated problems in complying with current international rules limiting interference with other uses of the microwave spectrum. Interference radiated by an SPS transmitter would be particularly significant as it would affect most of a hemisphere.

The spurious emissions expected from a SPS MPTS transmitter are of two basic kinds. Random noise sidebands will be produced at frequencies adjacent to the nominal transmission frequency and, due to non-linearities, appreciable power will be produced at harmonics of the transmission frequency. The spurious emissions seen at the earth depend strongly on the choice of DC to microwave converter, use of microwave filters, and overall system design.

Figure B indicates the spurious power spectral flux density in noise sidebands expected at the ground for two candidate systems as calculated in R31. Also shown are limits, established by international rules and recommendations, to prevent interference to various systems. (The interference limits shown differ in some cases from those of R31, in part because of different assumptions about receiving antennas of victim systems.)

Fig. B. SPS Noise Sideband Levels at Earth (after R-31)

- ▨ CCIR 74, VOL. II RPT. 387-2 (LINE-OF-SIGHT MICROWAVE LINKS)
- ITU REGULATION 470NF (LINE-OF-SIGHT MICROWAVE LINKS)
- ▤ ITU REGULATION 470NI (LINE-OF-SIGHT MICROWAVE LINKS)
- ┌ ITU REGULATION 470NGA (TROPOSPHERIC SCATTER, 40 db ANTENNA ASSUMED)
- CCIR 74, VOL. II RPT. 224-3 ANNEX 1 (RADIO ASTRONOMY) DOTS MARKED ASSIGNED BANDS. BROADBAND INTERFERENCE SOURCES LOCATED BETWEEN BANDS CAN CAUSE HARMFUL INTERFERENCE TO COMMON OUT-OF-BAND OBSERVATIONS
- CCIR 74, VOL. II RECOMMENDATION 365-2 (DEEP-SPACE RESEARCH) 45 db ANTENNA ASSUMED

SPS EMC "DISCUSSION OF POINT II" (Continued)

An assumption generally made in evaluating radio frequency interference that might be produced by SPS is that a frequency band 100 MHz wide will be allocated for microwave power transmission and that only interference outside this frequency band need be considered. In Figure B it has been assumed that 2400 to 2500 MHz, which is available for Industrial, Scientific and Medical (ISM) uses in the United States, will be allocated. In fact there is no present frequency allocation which would allow SPS operation (see Point IV). Even with this assumption the noise sidebands shown in Figure B would exceed acceptable interference levels for low noise receiving systems especially in cases where receiving antennas might be pointed toward or near a SPS. In particular, Radio Astronomy, Deep Space Research and Tropospheric Scatter Communications Systems are provided specific protections, in International Telecommunications Union (ITU) rules or International Radio Consultative Committee (CCIR) recommendations, which might be violated by SPS microwave power transmission.

Figure C shows estimated levels of harmonic power (from Reference R-31) with recommended interference limits. Because of uncertainties in antenna gains and appropriate bandwidths comparison of the two is not entirely straightforward. Note particularly that the vertical scale of this figure is simply power flux with no bandwidth information.

(Bandwidths of 4 kHz were assumed for communications systems and 10 MHz radio astronomy.) The presentation is intended to be conservative--

Fig. C. SPS Harmonic Levels at Earth (after R-31)

SPS EMC "DISCUSSION OF POINT II" (Continued)

interference could be experienced at levels below those shown--but indicates that, according to the preliminary estimates, SPS harmonic radiation would exceed established recommendations and in some cases (3.g., 3rd harmonic) violate ITU radio regulations.

The above does not indicate that SPS spurious emissions cannot be controlled to meet most appropriate limits, only that in the case of the preliminary design investigated in R-31 it did not. As stated above, spurious emissions are extremely sensitive to design details. Other estimates may be found in Appendix I, and References R-24 and R-53. All suggest interference problems.

In addition to spurious emissions from the SPS transmitter other components of the MPTS system, notably the rectenna array, may contribute harmonic radiation and possibly noise. The rectenna elements are necessarily non-linear and will generate and radiate harmonics at levels yet to be determined and which would be expected to vary with several factors such as accuracy of matching to the rectenna load. At the power levels involved in SPS MPTS, imperfect metal-to-metal junctions in any part of the system may also, due to non-linearity of their electrical conductivity, generate significant harmonics. Spurious radiation from the rectenna system, either from rectenna elements or miscellaneous metallic structures, could be a significant source of RFI near the rectenna site.

SPS EMC "DISCUSSION OF POINT II" (Continued)

The total of spurious emissions would be proportional to the total power provided by SPS and would thus increase as a larger number of SPS are activated.

Any spurious emissions, whether or not they exceed present regulations, would degrade the usefulness of parts of the already crowded radio spectrum. Emissions from a SPS in synchronous orbit could have an important impact on the growing number of systems which receive weak signals from space.

Communications satellites, and possibly broadcast satellites which have been assigned frequencies near those proposed for SPS, would share the limited arc of synchronous orbit accessible from the United States, so receiving antennas would be aimed in the general direction of SPS transmitters. Satellite signal strengths are limited both by regulation and basic technological considerations.

Radio and Radar Astronomy and Deep Space Research deal with signals that approach the weakest detectable, using large antennas which it may be necessary or desirable to point near SPS locations. In particular, Radio Astronomy has been assigned certain protected bands but as a matter of practice uses a wide range of other frequencies subject to existing interference. SPS spurious emissions would further limit the frequencies available for observations.

Detailed investigation of the effect of SPS MPTS emissions at unauthorized frequencies may have some influence on choice of operating frequency

SPS EMC "DISCUSSION OF POINT II" (Continued)

to minimize adverse impact. No exact determination of impact is possible, however, without more extensive information on expected spurious emissions. This information will not be available until representative components, which in some cases do not exist yet, have been tested and SPS system design and testing have proceeded further. The extent of spurious emissions will presumably have an important influence on the difficulty of obtaining necessary international agreement for SPS operations and further design effort toward reducing these emissions seems appropriate.

SPS EMC REFERENCES SECTION OF POINT II

Computations of estimated SPS spurious emission are found in R-31, R-24, and R-53. Interference limits are found in ITU Radio Regulations (S-1), in particular article 7, footnote 470, and in CCIR XIIIth Plenary Assembly (B-5), Volumes II and IX.

A general discussion of SPS interference impacts appears in R-39. For further information on interference considerations for Radio Astronomy see R-12, R-8, and R-11.

SPS EMC "DISCUSSION OF POINT III"

A small part of the energy in the microwave power beam will be absorbed in passing through the ionosphere. The loss of energy will be insignificant in terms of the efficiency of the power transmission system but will result in appreciable modification of the ionosphere. This will produce, among other effects, changes in the propagation of radio waves through or reflected from the ionosphere. Present understanding of the ionosphere and its interactions with radio and microwaves is not adequate to predict the severity of all effects that might result.

Use of the radio spectrum at frequencies below several hundred MHz is strongly influenced by ionospheric properties which SPS MPTS operations might modify. The situation is complicated by the fact that the minimum power densities apparently required for an economically practical SPS are thought to be approximately at the threshold for production of ionospheric irregularities caused by intense heating.

Even if irregularities are not produced, systems using frequencies normally reflected by the ionosphere, including low frequency navigation systems and shortwave communications, would be affected.

If ionospheric irregularities are produced, shortwave communications could be disrupted over some paths and undesirable ionospheric reflection of

SPS EMC "DISCUSSION OF POINT III" (Continued)

higher frequencies, not normally reflected, including TV broadcast frequencies, could produce interference over wide areas, within a radius of perhaps 2000 km from the SPS receiving point.

Prediction of ionospheric modifications that might be caused by SPS, and of the consequent effects on communications and other systems is complicated by natural variability of the ionosphere.

Experiments have been conducted which produced substantial modification of the ionosphere, including irregularities, by means of absorption of radio energy in the high frequency portion of the frequency spectrum. One significant conclusion from these experiments has been that the theoretical predictions of ionospheric behavior resulting from intentional heating have not been entirely accurate.

Experiments done to date have not adequately approximated SPS MPTS operations. Significant ionospheric modification has only been produced by the use of frequencies specifically chosen for maximum energy transfer to the ionosphere, i.e., in the high frequency band. These frequencies are much lower than those proposed for SPS, and because they were chosen to correspond to ionospheric plasma resonances (plasma frequency) the experimental conditions do not approximate SPS operations. Experiments using frequencies which better represent SPS operations have not been able to provide more than a small fraction of energy that SPS would deposit in the ionosphere.

SPS EMC "DISCUSSION OF POINT III" (Continued)

Ionospheric modification experiments which literally duplicate SPS operation would require equipment and total power levels approximating those of an actual SPS and thus would be very expensive. Simulation of SPS effects on the ionosphere should be possible however with much lower power levels due to the fact that energy absorption in the ionosphere is strongly dependent upon frequency. For frequencies far enough removed from the plasma frequency power absorption scales as one over frequency squared. Thus, for example, at a frequency of 24 MHz energy could be transferred to the ionosphere at a rate simulating SPS operations at 2450 MHz from a beam on only 1/10,000th the intensity and total energy of an actual SPS. Details of the interactions between the ionosphere and radio waves have other subtle frequency dependencies however so that extrapolation of results of low frequency experiments to SPS operation is not trivial.

There is general agreement that ionospheric modification experiments are needed which appropriately simulate SPS operations. There is not complete agreement as to details of the experiments required, what frequency or frequencies to use, and exactly what measurements need to be made. One would, for example, like to use a high frequency which would closely approximate SPS effects but the amount of power required, and hence cost, rises rapidly with frequency. It also appears that SPS modification of the ionosphere could have other important effects, in

SPS EMC "DISCUSSION OF POINT III" (Continued)

addition to those on radio propagation, and plans for experiments should include consideration of other appropriate measurements.

In view of the above, and the substantial cost of the required experiments (\$4 million is the lowest figure quoted, Reference R47), extensive additional planning is required for research in this area.

SPS EMC REFERENCES FOR POINT III

A basic analysis of SPS microwave power transmission interaction with the ionosphere is begun in R31 and expanded in R36 to provide theoretical predictions of ionospheric modification expected, qualitative estimates of effects on radio propagation, and recommendations for further study.

R47 describes a recent series of experiments in ionospheric modification performed for SPS evaluation, qualitatively describes possible impacts of SPS ionospheric modifications, and makes specific recommendations for further work.

For further information on ionospheric modification experiments and consequences see R9, R62, and R45.

SPS EMC "DISCUSSION OF POINT IV"

Use of the radio spectrum is controlled by international and national regulations. At present there is no provision for SPS microwave power transmission. The closest approximation currently recognized is for Industrial, Scientific and Medical (ISM) purposes. The International Telecommunications Union (ITU), a specialized agency of the United Nations, provides for ISM operations in Article 5, footnote 357 of the International Radio Regulations as follows:

"The frequency 2450 MHz is designated for industrial, scientific and medical purposes except in Albania, Bulgaria, Hungary, Poland, Roumania, Czechoslovakia and the U.S.S.R., where the frequency 2375 MHz is used. Emissions must be confined within ± 50 MHz of the frequencies designated. Radiocommunication services operating within these limits must accept any harmful interference that may be experienced from the operation of industrial, scientific and medical equipment."

The United States Federal Communications Commission (FCC) Rules and Regulations also allocate this band, among others, for ISM purposes and defines ISM equipment (in 18.3(f)) as "Devices which use radio waves for industrial, scientific, medical, or any other purpose including the transfer of energy by radio and which are not used nor intended to be used for radio communication" (emphasis added).

The FCC further notes that "Equipment operating on an ISM frequency may be operated with unlimited radiation on that frequency." (18.102 (b)) but that "No harmful interference shall be caused to authorized communications services from spurious or harmonic radiation" (18.14 (c)).

SPS EMC "DISCUSSION OF POINT IV" (Continued)

It has been tentatively assumed in SPS microwave power transmission design studies and radio frequency evaluations that the ISM band from 2400 to 2500 MHz would be allocated to SPS operations. Such an allocation does not now exist. Two important point must be noted. First the 2400-2500 MHz band is not allocated to ISM purposes throughout the world. Second, SPS microwave power transmission would be a substantial departure from conditions foreseeable when the existing allocation was made. The area of interference produced from an ISM installation at the surface of the earth is limited by line of sight propagation characteristics at microwave frequencies whereas an SPS would cover roughly a hemisphere. There are communication services presently using this band, some but not all of which are in countries where it is not allocated to ISM.

Existing regulations could be changed at a World Administrative Radio Conference (WARC), one of which is scheduled for 1979, to explicitly permit SPS microwave power transmission. In view of the substantial impact SPS could have on radio communications, as outlined in points I, II and III above, approval of a request for such changes could hardly be regarded as assured. Convincing demonstrations would be required that consequences would be acceptable.

The proposed SPS microwave power transmission system raises concerns in a number of areas, beyond radio spectrum allocation, which may well influence any decisions on necessary International Radio Regulation

changes. In particular there is a great deal of sensitivity and concern over possible undesirable modifications of the earth's atmosphere, including the ionosphere, and over the possibility of biologically harmful effects from electromagnetic radiation.

Modification of the international Radio Regulations would require the approval of a majority of the world's nations and it is conceivable that approval might be denied for reasons not directly related to technical concerns.

SPS EMC REFERENCES FOR POINT IV

International rules governing usage of the radio spectrum are contained in ITU Radio Regulations (S-1). See in particular articles 5 and 7. These regulations are principally based on CCIR recommendations. See in particular Volumes II and IX of the XIIIth Plenary Assembly (B-5).

United States regulations are contained in Federal Communications Commission Rules and Regulations (S-2). See in particular Parts 2 and 18.

SPS EMC "RESEARCH PLAN"

Further work on points I and II will require assessment of the impact of microwave radiation from the SPS power transmission system, both at the intended power transmission frequencies and all expected spurious emissions on existing radio communications, radar, radio astronomy services and other electronic systems. This assessment should include a determination of optimum SPS operating frequency to minimize harmful effects and an evaluation of the need for control of spurious emissions. A detailed assessment will require more highly refined estimates of the emissions expected from all parts of the SPS system, estimates which in many cases cannot be made until SPS design and testing are further advanced. Sufficient information is available now however to begin useful basic evaluation. The processes of impact assessment and design refinement are expected to proceed interactively to a technical optimum. Assessment of SPS impacts is closely related to the general concept of efficient radio spectrum utilization, a topic which is of substantial continuing interest. The U.S. Department of Commerce, Office of Telecommunications has played a leading part in work in this area and could be expected to provide substantial assistance in SPS interference assessment.

It is expected that SPS design and testing will be supervised by NASA and that they will be able to provide all, or most, of the data required to estimate emissions from the SPS MPTS. Some additional specific tests for interference assessment may be required from time to time but nothing is

SPS EMC "RESEARCH PLAN" (Continued)

foreseen that would be a major perturbation of overall schedules or budgets.

Specific tests may be desirable to determine the susceptibility of representative electronic apparatus and systems to electromagnetic interference from SPS. There does not seem to be an immediate pressing need for such tests but they could be simple and inexpensive to perform.

As part of a detailed assessment it may be necessary to make both laboratory and field measurements of the severity of overloading problems in microwave receivers and the effectiveness of means for mitigating any problems found. This might require a substantial effort but its scope cannot be planned until the problems to be expected have been assessed in more detail.

The questions raised in point III will require a substantial research effort because basic scientific knowledge is not now adequate to evaluate the potentially very serious consequences of SPS ionospheric modification.

Experiments will be required to simulate ionospheric modifications that would be expected during SPS MPTS operation and extensive measurements will be needed to determine the consequences for radio communications and other systems. Existing facilities are not adequate to perform these experiments and the necessary construction will be expensive. Costs have been estimated at from \$4 million for additions to an existing facility

SPS EMC "RESEARCH PLAN" (Continued)

(in Reference R47) to \$34 to \$126 million for construction of new facilities (in Reference R36). There is at present some divergence of opinion as to details of appropriate experiments. In view of the cost and importance of the work further efforts should be made to reach a consensus before developing detailed plans. A meeting of experts in this area seems highly desirable to define as well as possible the course of appropriate experiments. Measurements of consequences beyond those to communications should also be considered. In view of the schedule of the SPS evaluation this meeting should be scheduled for early 1978.

Further work on resolution of point IV will consist in some sense of efforts directed toward obtaining international agreement on a frequency allocation for SPS MPTS. Studies undertaken for points I, II and III will substantially develop the necessary technical assessment of consequences and could, with relatively little additional effort, provide the needed support in this area. Some agency will, however, have to undertake the advocacy of the required allocation, with due sensitivity to all the considerations involved. It would seem to be desirable that the impact evaluation and advocacy roles be kept well separated.

The cost of research on ionospheric modification effects on radio propagation, responsive to point II, cannot be adequately estimated until details

SPS EMC "RESEARCH PLAN" (Continued)

of the necessary work are determined and the division of effort between these studies and those on other ionospheric effects has been clarified.

APPENDIX I

Notes on the SPS Noise Calculation of R-31

Two frequency-dependent effects neglected in the noise calculation of R-31 will, if included, substantially alter the noise spectrum obtained.

The first is beam scanning and/or breakup for radiated frequency components away from the carrier. The effective off-frequency gain depends crucially upon antenna feed details, and these could be chosen to minimize spurious radiation. In another context Section 6.6.1 of the report calculates for the slotted waveguide radiator proposed a frequency scanning sensitivity of 1 arc minute per 612 Hz frequency deviation. This indicates that a deviation of 300 kHz will scan the main lobe off the earth. Larger deviations will eventually scan a degraded beam back on. At any given location in the beam's scan path there would be particular narrow frequency ranges where noise could be observed possibly as intense as that calculated below, but most of the spectrum would be much quieter.

The second effect is the frequency dependence of coherence in an amplatron cascade. The report's calculation treats the antenna as a collection of independent 10-tube cascades. Antenna gain for each 10-tube coherently radiating assembly is estimated at 33.7 dB based on its share of the array area and an assumed coherence factor of .5. The total power output of the cascade is taken to be ten times as noisy as one tube to account for fed-through noise being cumulative along the cascade. Coherence is taken to be

SPS EMC APPENDIX I (Continued)

frequency independent, and the radiated spectrum shape is assumed to be the same as that of a single tube.

Power density result is $-160 \text{ dBW/M}^2\text{Hz}$ at band center falling off as the single-tube spectrum does.

The coherence length in an infinite cascade depends strongly on the stage gain, and at the -3 dB point is just one tube. From this arise two separate calculations:

A) For out-of-band noise, each tube-and-radiator is treated as an independent noise source whose antenna gain and pattern are that of a single slotted waveguide section, and whose noise output is that of a single tube. The gain is estimated at 21 dB based upon detailed consideration of a center-of-antenna fully dense guide section. This gives for a uniformly illuminated antenna a power density result of $-183 \text{ dBW/M}^2\text{-Hz}$ at band center falling off as the single-tube spectrum does, plus the in-band contribution below. Corrected for 11.5 dB illumination taper it is $-178 \text{ dBW/M}^2\text{-Hz}$, or 18 dB less noisy than the report's result.

B) For in-band noise, the noise originating in any tube is assumed to be present at the same S/N and completely coherent in the outputs of all tubes downstream. A tree is assumed driving 128 8-tube cascades which make up the subarray. If amplitrans are used in the tree, the first one dominates the array noise output and tree

SPS EMC APPENDIX I (Continued)

details are unimportant. Four-way branching was assumed for the first three levels, and a 2-way branch for the fourth stage. The first tree stage's noise appears in all 1024 of the radiating guide sections (a multiplicity gain of 1024) and these sections are all coherent, giving an antenna gain of 1.2×10^5 or 51 dB. Other contributions are all smaller, the next tree stage contributing 1/4 as much because of the smaller area over which coherence is maintained, and so on. The power density result is -151.4 dBW/M²Hz at band center. Away from band center the received noise power density will fall rapidly due to loss of coherence, and due to beam breakup induced by the lumped phase shift of the amplitrans and filters, and eventually become negligible compared with calculation A.

The net effect of considering the frequency dependence of coherence is to increase the predicted noise density near the carrier by about 9 dB, and decrease the predicted noise far from the carrier by about 18 dB.

SPS BIBLIOGRAPHIC NOTES

General Information on Microwave Power Transmission:

R-28 provides a brief, overall review of microwave power transmission technology and potential.

Extensive studies done for a space-to-space microwave power link are documented in R-54, R-60, and R-61.

Studies of microwave power transmission systems for SPS (or similar projects) are found in R-24 and R-53 with R-31 being perhaps the most comprehensive.

In addition, R-65 discusses expected atmospheric effects on an SPS microwave power beam.

Measurements of microwave power transmission efficiency, with particular consideration of the rectenna system are found in R-18 and R-37 which describe laboratory tests and R-20 and R-5 which describe field tests of a 30 KW rectenna.

R-10 provides a wealth of detail on engineering considerations in SPS including microwave power transmission.

R-39 provides a comprehensive, up-to-date, summary of the impacts and benefits of SPS microwave power transmission as currently envisioned.

SPS BIBLIOGRAPHIC NOTES (Continued)

Specific Topics in Microwave Power Transmission:

For general information about microwave to DC conversion tube technology see R-15, for amplitrons R-41, R-54, R-68, for klystrons R-0.

For tubes discussed for particular application in SPS see R-41, R-24, R-31, and R-53.

Antenna designs for the SPS power transmitter are described in R-10 and R-31. R-39 provides a detailed diagram of expected sidelobe levels for a well developed design.

For discussion of propagation of a power beam through the atmosphere, including scatter see R-65, R-31, and R-34. Information about atmospheric effects on microwave propagation in general may be found in R-64, B-4, R-19, R-29 and R-30, R-17, and B-3.

Detailed discussions of rectenna systems are found in R-18, R-37, and field tests are described in R-20 and R-5.

Radio frequency interference that might result from SPS microwave power transmission is estimated in R-31, R-24, and R-53 with a recent assessment of the impact in R-39. For information on radio spectrum usage for radio astronomy see R-12 and R-8.

International radio regulations appear in S-1. B-5 provides the technical basis for many of these rules and includes additional recommendations. S-2 contains U.S. domestic radio rules and regulations.

SPS BIBLIOGRAPHIC NOTES (Continued)

The effects of the SPS microwave power beam on the ionosphere and their consequences for radio propagation are considered in R-31, R-36, and R-47 with a review in R-39.

Modification of the ionosphere by radio waves and resulting effects on radio communications are discussed in R-62 and R-45.

For further information on ionospheric modification and consequences thereof see R-6, R-9, R-11, R-46, R-66, R-69, and R-70.

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 - b BIBLIOGRAPHIES
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- 1-a MICROWAVE POWER TRANSMISSION, GENERAL AND SYSTEM STUDIES
 - b MICROWAVE GENERATORS OF INTEREST
 - c SPS ANTENNA CHARACTERISTICS (Transmitting)
 - d LINEAR (Non-Frequency Converting) SCATTER OF MICROWAVES
 - e NON-LINEAR (Frequency Converting) SCATTER
 - f RECTENNA
- 2-a RADIO RULES, REGULATIONS, POLICIES, Etc. (Includes Frequency Assignments)
 - b RFI GENERAL INFORMATION
 - c RFI IMPACTS ON SPECIFIC SYSTEMS USERS OR SERVICES
 - d SPS/RFI STUDIES
- 3-a IONOSPHERIC MODIFICATION BY RADIO/MICROWAVES
 - b IONOSPHERIC MODIFICATION EFFECTS ON SPECIFIC SERVICES, SYSTEMS OR USERS
 - c IONOSPHERIC PROPAGATION (Radio/Radar, Etc.)
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MRE - Nov. 13-15, 1973; vii+502, il.

WITNESS: Glaser, Peter E., vp. engineering sciences, Arthur D. Little, Inc.

STATEMENT: Assessment of industry's technological ability to develop solar heating and cooling systems; description of typical solar climate control system. (p. 128-158)

DISCUSSION: Problems with H. R. 10952 funding (p. 158-163)

INSERTION: Project Plan for a Program to Develop a Solar Climate Control Industry, Mar. 16, 1973, Arthur D. Little (p. 139-157).

Space Solar Power

Glaser, P. E.

(Arthur D. Little, Inc., Cambridge, MS)

Centre National D'Etudes Spatiales/Bretigny-Sur-Orge, Essonne, France/1973/
Photovoltaic Power and Its Applications in Space and on Earth

CONGRESSIONAL HEARINGS

AN - 74-S121-3

MTI - Space Shuttle Payloads, Part 2

MRE - Oct. 31, 1973; iv+101, p. 11

Continuation of hearings on plans for the space shuttle era. This volume considers potential use of space shuttle for missions relating to energy production and transmission, and to industrial production in space.

WITNESS: Glaser, Peter E., vp. engineering sciences, Arthur D. Little, Inc.

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STATEMENT AND DISCUSSION: Slides presentation and explanation of operations of a satellite solar power station (SSPS) including microwave generation and transmission system; planned space shuttle transportation system for SSPS; estimated cost of program over next ten years.

AN - 74-H441-20

MTI - National Energy Research

MRE - May 16, 23, June 13, Dec. 10, 18, 1973, Jan. 31, Feb. 1, 19

AN - 74-H441-20.7

ARE - June 13, 1973, p. 206-220

ARS - 464

WI

WITNESS: Glaser, Peter E., vp. and head of engineering sciences, Arthur D. Little Co., Inc.

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STATEMENT AND DISCUSSION: Review of U. S. and foreign applications of solar energy; status of, and importance of further development on, satellite solar power stations.

AN - 73-H701-15.12

ARE - May 24, 1973, p. 257-501

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Statements and Discussion: Explanation, with slides, of satellite solar power stations (SSPS) concept and microwave beam radiation effects (technical memo of dev. plans, p. 281-284), analysis of problem areas and requirements; economic factors in evaluating and developing energy options; feasibility of satisfying peak energy demands from space power stations.

Evaluation of space shuttle program and possibility of Apollo mission in geosynchronous orbit possible uses of SSPS for support of space activities; potential consequences of energy sources vulnerability.

Briefing papers, prepared for subcom. including charts, photos, tables, titled:

a. "Power from the Sun via Satellite" by P. E. Glaser; assessment of SSPS feasibility, including technical principles, economic considerations, environmental issues, and list of references (p. 298-373).

b. "Space Technology and Energy" by K. A. Ehricke, focusing on space relaying by microwave beam transmission and power relay satellites (p. 329-373).

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c. Glaser, Peter E. (vp. Arthur D. Little, Inc. et al), "Satellite Solar Power Station: An Option for Power Generation" prepared with Joseph G. Gavin, Jr. (Grumman Aerospace Corp.), William C. Brown (Raytheon Co.), and Eugene L. Ralph (Textron, Inc.) (p. 144-179).

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IONOSPHERIC MODIFICATION BY RADIO/MICROWAVES--3-a

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Task: 975101
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Proj: NR-088 047, SRI-8727

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IONOSPHERIC MODIFICATION BY RADIO/MICROWAVES--3-a

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