

Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program-Electromagnetic Systems Compatibility

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EXECUTIVE SUMMARY

The effects of the Satellite Power System (SPS) and its microwave power transmission system (MPTS) on other electromagnetic and electronic systems were analyzed as one of the five tasks of the Environmental Assessment part of the SPS Concept Development and Evaluation Program. The very large quantities of electromagnetic power that would be transmitted by SPS prompt important questions as to its compatibility with electronic systems on which our modern society is heavily dependent. Electromagnetic compatibility (EMC) analysis is a well-developed discipline and existing techniques are adequate for an accurate prediction of SPS effects. The SPS EMC Assessment is limited at this time by two major factors: incomplete data on some important aspects of the MPTS performance and the unusually wide scope of potential effects, which has precluded an exhaustive analysis.

There were two major phases in the EMC Assessment: computations of the changes that SPS would produce in the electromagnetic environment and evaluation of the effects of these changes on other electromagnetic and electronic systems. The electromagnetic environment would be changed both by direct emissions from SPS and by modification of these emissions by other factors such as scattering in the atmosphere. Computation of emissions has been based as far as possible on the system described in the Reference System Report of October 1978 (DOE/ER-0023), with some additional information from later NASA concept development efforts. In some important areas, it has been necessary to extrapolate SPS performance from that of existing systems that use similar technology. Although some of the quantitative conclusions such as geographic ranges of particular effects are specific to the Reference System, the assessment was done parametrically so that conclusions can easily be re-evaluated as SPS concepts evolve or new data become available.

Satellite power system EMC emissions can be grouped into four categories: those at the intended power transmission frequency, spurious microwave emissions at frequencies outside the intended bandwidth, emissions from warm space structures, and sunlight scattered from those structures. Some microwave power will unavoidably escape from the power transmission system. The amount and spatial distribution of this lost power have been analyzed in detail because of their importance to SPS performance. This lost power is also the basis for most of the EMC concerns that are peculiar to the SPS concept. The assessment focused on the effects of emissions at the power transfer frequency both because of their unique relation to the SPS and because they are relatively well defined at the present stage of SPS concept development. The high total power transmitted by SPS means that the escape of even a small percentage can be a source of significant interference to other systems. The density of escaping microwave power is highest near rectenna sites, falling off rapidly with distances from the rectenna.

Emissions outside a bandwidth assigned to power transmission are of concern because of the unprecedented power levels of an SPS which could cause potential interference to other spectrum users over a hemisphere. Most spectrum use is controlled and protected by detailed international agreements which include limits on interference (International Telecommunication Union Radio Regulations). There is, at present, no provision in these agreements for space-to-earth microwave power transmission. The EMC assessment has assumed that a frequency band from 2.40 to 2.50 GHz would be assigned to SPS. The strength and spatial distribution of SPS emissions outside this assumed band is not now known and could only be determined with confidence by building and testing representative SPS components. Because firm data are lacking and because potential problems from SPS spurious emissions are similar to those from other systems, the assessment in this area has been confined to identifying major potential problems and recommending that limitation of spurious emission to noninterfering levels be an SPS design goal. A further assessment of this area would be needed if the SPS concept is to be pursued.

The large photovoltaic arrays and other components of SPS structures would emit broad-band thermal and microwave radiation. This radiation could, according to present estimates, be a significant source of interference to sensitive receiving systems such as are used in radio astronomy, deep space research, and some satellite communications when the directional antennas of these systems are pointed near an SPS.

Sunlight scattered from the very large areas of the SPS solar collectors can cause the structures to appear as very bright objects in the night sky. For the Reference System, with an estimated 4% diffuse reflectivity for the photovoltaic cells, each structure would be as bright as the planet Venus ever appears, brighter than any object in the sky except the sun or moon. This amount of scattered light would have a severe impact on scientific observations requiring dark night skies.

The effects of SPS-produced changes in the electromagnetic environment on other systems were evaluated in two closely related studies. Electromagnetic compatibility problems at five hypothetical rectenna locations were analyzed to illustrate site-specific problems, and effects on representative items in important categories of electronic systems were determined to ascertain the overall extent of SPS EMC problems. At the first hypothetical rectenna site considered in California's Mojave Desert, unacceptable impacts on military test facilities were identified which could only be mitigated by changing the rectenna location.

Electromagnetic compatibility was thus demonstrated to be an important factor in rectenna site selection. Specific recommended separation distances of from 50 to 150 km between rectennas and sensitive facilities such as nuclear reactors and radio astronomy observations have been provided for rectenna siting studies.

Tests and analyses of the interference susceptibility of important categories of electronic systems and equipment including radar, communications, computers, and sensors were performed to obtain a general assessment of EMC problems. Systems include current designs and to the extent practical, evaluation of the impacts on advanced electronic technologies. Techniques for mitigating potential effects were also evaluated. It was found that many items would be affected at ranges up to about 50 km from rectenna sites, and some particularly sensitive equipment would experience interference at greater ranges. In many cases, straightforward modifications such as improved shielding or minor circuit changes could substantially eliminate interference. Some sensitive microwave receivers would require more extensive changes such as additional filters to reject SPS inputs.

Many of the satellites in orbits lower than SPS position would occasionally pass through an SPS power beam and thus encounter intense microwave fields for periods of a few seconds. Some of the electronic systems on these satellites would experience interference and a temporary degradation in performance during this period. Improved electromagnetic shielding and other minor modifications would be expected to eliminate or substantially reduce effects to allow normal performance.

Satellites in geosynchronous earth orbit (GEO), if sufficiently separated from a solar power satellite, should not be affected. The allowable spacing between an SPS and other satellites in GEO would probably not be less than 1°, but this is based on approximate analyses that will require refinement as the SPS technology develops. Scientific observations of very low levels of electromagnetic radiation, such as are made in optical and radio astronomy, would be particularly sensitive to SPS additions to the electromagnetic environment. In many cases, these observations are already limited by existing sources of radiation, and any additions would further limit capabilities. The only clearly effective mitigating technique would be to conduct the observations from unaffected regions, i.e., the far side of the earth if SPS satellites are deployed over a hemisphere or less, or from space. The added expense and difficulty, especially for the space option, might have an undesirable impact on the scope of observations.

The SPS concept was thus found to have a wide range of potential EMC effects. Microwave power unavoidably escaping from the power transmission system could affect a wide range of electronic equipment within about 50 km of rectenna sites. Effective mitigation is available in most cases, but it is recommended that rectennas be separated by distances of 50 km to 150 km for various sensitive facilities, such as military operational and test/evaluation areas, radio and optical astronomy sites, and nuclear research and power generation operations. For military equipments, separation is mandated because mitigation methods would modify the normal performance characteristics of military equipments when operated outside SPS environments. Astronomy and nuclear facility separation is considered necessary because of the extreme sensitivity of astronomy receivers and sensors, and the safety risks inherent with complex nuclear instrumentation systems operating in any additional environment. Microwave emissions from SPS outside a presumed assigned bandwidth have the potential for interfering with uses of the radio spectrum over a hemisphere. Whether, or to what degree, such interference would occur cannot be determined without construction and tests of components of SPS microwave systems. Finally, large sunlit SPS structures would, unless much darker than the present reference design, brighten the night sky significantly, impairing astronomical and other scientific observations.

If the SPS concept is to be pursued further, more detailed consideration of EMC will be required. The following areas will be of particular importance:

- a) development of complete and accurate data on all SPS electromagnetic emissions; and
- b) specific SPS design studies of means for controlling offending emissions.

1.0 INTRODUCTION

The SPS concept has been suggested as a possible new energy source which, if fully developed, could provide a source of power equal to all the electrical energy generated in the United States in 1975. The energy would be collected by building and operating satellites equipped with large solar arrays in geostationary orbits around the earth. In the present version, solar energy would be converted to microwaves and transmitted from space to earth. Earth receiving stations would convert the microwave energy to electricity, which could be fed directly into utility networks. Each satellite/receiving station combination would provide approximately 5 GW of electric power. Other transmission systems, such as lasers, also are being considered, but the current evaluation considered only the microwave version.

The SPS design concept considered in the Concept Development and Evaluation Program is described in the "Reference System Report" of October 1978 (DOE/ER-0023). The Reference System's purpose is to serve as a common basis for further technological development (systems definition and critical supporting investigations), environmental and societal assessments, and comparative analyses of the SPS concept and other national energy ventures. For the most part, the Reference System is based on fully-matured engineering precepts (methods, materials, practices, etc.) and realizable projections of future improvements. However, it is by no means an optimized engineering design, and does not account for newly emerging technologies which might become standard practices in the post-2000 era. Continuing systems definition undoubtedly will change many of the current characteristics of the Reference System. Some of those changes can already be reasonably perceived, but others most likely will occur that cannot yet be appreciated. Thus some potential problems associated with the present Reference System may subsequently become moot, and new ones will be recognized as developed continues. Despite its current limitations, the Reference System is an important tool for identifying and evaluating significant side effects which conceivably could accompany SPS.

The current satellite power system (SPS) concept proposes the transmission of approximately 400 GW of microwave power to the earth from 60 stations in geostationary orbit. Most of this power would be captured by rectifying antenna arrays ("rectennas") on the ground, delivering a total of approximately 300 GW to the electrical utility grid. The unavoidable escape of energy from the microwave power transmission system provides the potential for a wide range of effects to electronic and electromagnetic communications, control, and measurement systems.

The electromagnetic compatibility (EMC) of the proposed concept with present and anticipated electronic systems has been assessed as part of the SPS Concept Development and Evaluation Program (CDEP) carried out by DOE and NASA. This report is a summary of that work, the technical details of which will be presented in a number of separate topical reports.

The EMC analysis was the fifth of five tasks of the Environmental Assessment area of the CDEP. The other tasks were:

- 1) Microwave Health and Ecological Effects,
- 2) Non-Microwave Health and Ecological Effects,
- 3) Atmospheric Effects (extending up to the spacecraft orbit), and
- 4) Effects of Ionospheric Heating on Telecommunications (which considered the possible effects of the microwave power beam on the ionosphere).

The EMC analysis addressed only the direct effects of electromagnetic emissions from the SPS on other technological systems. Emissions were defined quite broadly, including not only those from the microwave system, but also thermal blackbody emission and scattered sunlight from the satellite. Figure 1 shows the SPS from an EMC perspective and schematically identifies the major emissions. The analysis is based on the design for an SPS as described in the Reference System Report and some quantitative conclusions, e.g., ranges from rectenna sites at which effects are expected are specific to that design. The methodology and qualitative conclusions, however, apply to any SPS concept using microwave power transmission. Quantitative conclusions have been obtained parametrically and can be adjusted as SPS designs change.

The balance of this summary report presents an overview of the assessment. Section 2, Methodology, explains the organization of work, procedures followed, and the constraints and limitations of the assessment. The electromagnetic environment that the Reference System would produce, and in which other systems would have to function, is described in Section 3. As an early part of the EMC Assessment, the problems expected for a hypothetical rectenna site, in the Mojave Desert of southern California, were analyzed in detail. This effort provided an initial quantitative indication of the scope of potential EMC problems and indicated the importance of EMC considerations in rectenna site selection. The results of this analysis are presented in Section 8. The effects of SPS microwave emissions on important categories of electronic systems and equipment are summarized in Section 4, with many examples of test results and demonstrated techniques for mitigation of problems encountered. SPS effects on other satellite systems are presented in Section 9. Astronomical research frequently involves measurement of

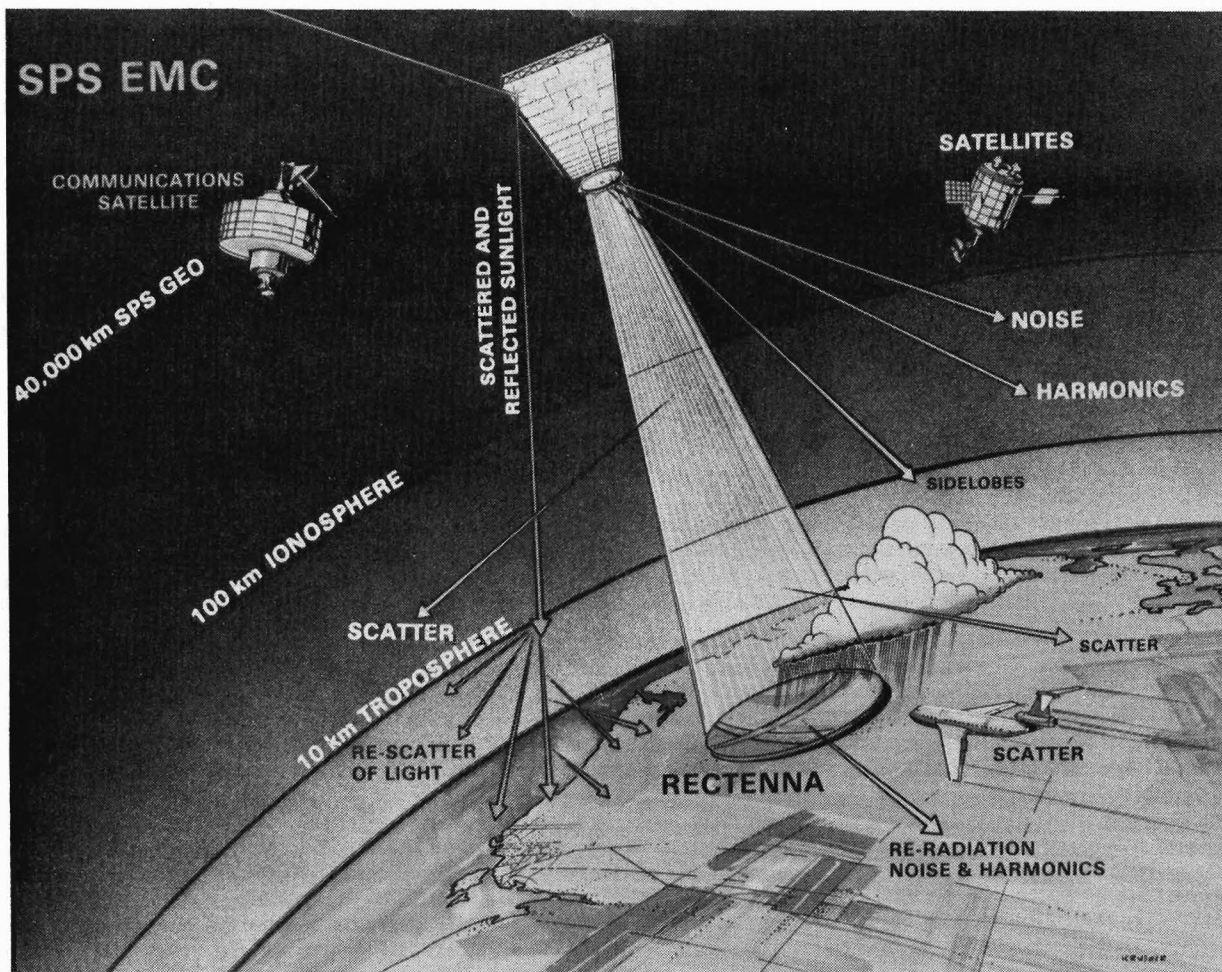


Figure 1. Electromagnetic Emissions from the Satellite Power System.

extremely low levels of electromagnetic radiation and is thus very susceptible to interference. The concerns of both radio astronomy with microwave emissions from SPS and optical astronomy with sunlight scattered from SPS spacecraft are discussed in Section 10. Brief summaries of mitigation techniques, cost estimates, and conclusions complete the report.

In addition to this summary document, the EMC Assessment Task is documented by the following ITS-published reports:

- 1 Satellite Ground Terminals,
- 2 EMC Analysis of Mojave Rectenna Site,
- 3 EMC Analysis of Four Hypothetical Rectenna Sites,
- 4 Systems Degradation,
- 5 Analysis of Higher Operating Frequencies,
- 6 Sixty-Satellite System Field Intensity Maps with Population Overlay,
- 7 Microwave Fields in Habitable Structures,
- 8 GEO/LEO Satellites,
- 9 Cost of Impacted Systems and Mitigation.

2.0 METHODOLOGY

Electromagnetic compatibility analysis is a well developed field having become of increasing importance as the number, complexity, and transmitted power levels of electronic systems have increased dramatically in the last 30 years. The SPS EMC Assessment requires no major new developments in technique or understanding, but is a problem of unusually wide scope. Because of the large area potentially covered by SPS microwave emissions and high total power involved, a very large number of systems and pieces of electronic equipment of a wide variety of types are potentially affected. It has thus been necessary to select representative items in important categories for analysis.

Assessment of the electromagnetic effects of SPS required two distinct types of data: the changes in the electromagnetic environment that SPS would produce and the response of existing or anticipated systems and equipment to the new environment. The environmental changes result from electromagnetic emissions from the SPS and the effects of other phenomena, such as weather, that could modify the emissions or at least their geographic distribution. In considering the response of equipment to SPS, it was necessary to consider the potential, which is substantial in many cases, for mitigating anticipated problems. Finally, the actual significance of changes in equipment performance to the user must be evaluated. Figure 2 shows the relations between the major elements of the assessment.

INPUT:

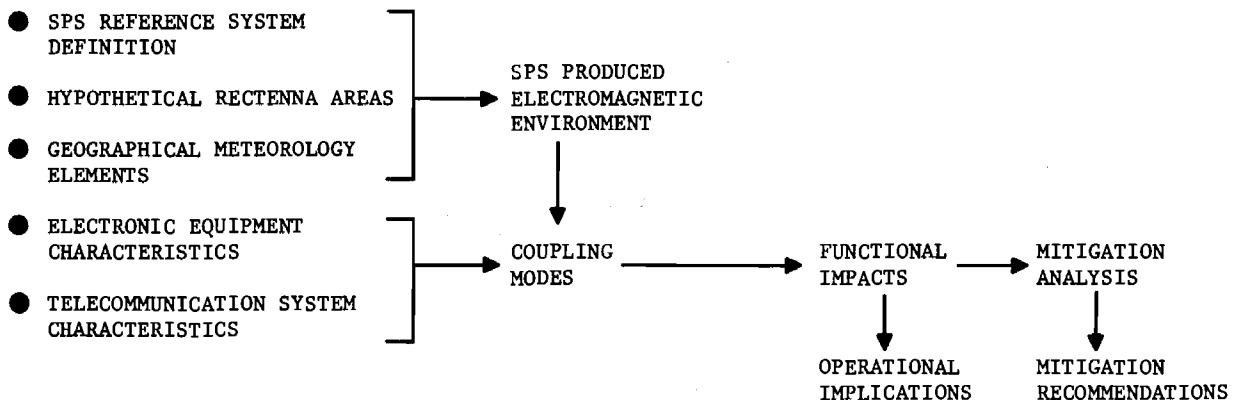


Figure 2. SPS EMC Analysis Evaluation

The major limitation on the present assessment is the limited knowledge of some of the electromagnetic emissions from SPS. More accurate data on these emissions will not be known without further examination. As noted above, much of the electromagnetic compatibility assessment completed during the Concept Development and Evaluation Program is parametric, and conclusions could easily be adjusted if new data on SPS preferred systems become available in the future.

Present knowledge of the electromagnetic environment that SPS would produce is based on the Reference System. The Reference System is, however, only a conceptual design, as mentioned earlier, and is incomplete in some areas important for an EMC Assessment; for example, the details of the performance of the devices used for conversion of direct current (DC) power to microwaves on the satellite are unknown. The Reference System uses klystrons for DC to microwave conversion, but several other devices, including solid state components, are being considered. The basic performance of the Microwave Power Transmission System (MPTS) has been studied, since it is critical to total SPS performance; as a result, the spatial distribution of microwave power at the intended transmission frequency can be computed with good assurance of accuracy for the far field. The strength and spatial distribution of emissions at other frequencies can now only be estimated by using data on the performance of existing systems.

Effects of the media (atmospheric attenuation, scatter, refraction, rain and hail scatter, etc) on the SPS main beam at 2.45 GHz have been estimated and have not proven to be a major problem (Grant et al., 1980). However, the effects of the media on the complete spacetenna control loop, which would include the pilot beam interactions, are not well known as yet and may present control loop stability problems that will need further study. For the SPS, system control includes beam aiming at the rectenna center, spacetenna sidelobe minimization, and safety actions.

This EMC assessment has concentrated on determining the microwave power levels outside of the rectenna exclusion area due to sidelobes and scattering of energy from the main beam and the impact on electronic and electromagnetic systems operating within 150 km of a rectenna site. These levels were estimated

given the conceptual design of the Reference System. The EMC effort has been directed at establishing the threshold where unacceptable performance begins for a wide variety of electronic and EM systems when subjected to various levels of 2.45 GHz energy. Knowing the estimated EM field outside the rectenna area and the threshold of unacceptable performance, one can determine how far a given system must be from the rectenna to allow acceptable performance or what mitigation techniques must be applied to allow the system to perform satisfactorily when in fields that surpass the threshold level. Solar power satellite concept design changes that will most likely come about as the total systems are studied may alter the spatial distribution of microwave energy, but this would only alter the distance that a system would have to be from the rectenna to perform satisfactorily, or determine the mitigation involved for acceptable performance.

Solar power satellite emissions at frequencies outside the ISM band assumed for the reference system design would present "in-band" interference to users of those frequencies for communications, allocated only in East Europe. For SPS operation in the western hemisphere, western Europe, or most of Asia, this interference mode will not exist. The dominant interference mode for radio receivers will be "out-of-band." The effects of such interference and allowable limits are established and incorporated in the Radio Regulations of the International Telecommunication Union and the Federal Communications Commission Rules and Regulations. This study has adopted the approach of examining possible emission ranges and recommending threshold levels for system design.

The current EMC analysis is dependent on the assumption that the MPTS would operate in the 2.40- to 2.50-GHz industrial, scientific and medical (ISM) frequency band. Although this is a logical choice of frequency, it is not the only possibility and has not yet been allocated for space-to-earth power transmission. Some of the considerations in SPS frequency selection are discussed in Section 7. A substantial change in SPS operating frequency would alter the coupling with other systems, requiring reassessment of many EMC concerns.

In many cases, the response of electronic systems and equipment to the SPS environment could be predicted from existing EMC data. Tests specific to SPS were conducted on important, representative systems and items and, where needed, were run to fill gaps in available data. A total of 57 major systems were tested. The tests concentrated on advanced systems to provide maximum relevance to the 1990-2000 time frame appropriate for SPS startup. Complete system configurations were tested in many cases to determine overall functional impact.

2.1 EQUIPMENT CATEGORIES

The major categories of equipment tested are summarized in Table 1. These cover the principal military, government, and commercial equipment and systems in use in the continental United States (CONUS) and are representative of those used by other industrial nations.

TABLE 1. Major Equipment Categories for SPS EMC Assessment

COMMUNICATIONS	COMPUTERS/PROCESSORS	RADARS
Terrestrial Links	Centralized Mini-Computers/ Microprocessors	Area Monitor
Satellite Links		Target Track
	Distributed Mini-Computers/ Microprocessors	Command/Control
MEDICAL ELECTRONICS	RESEARCH SUPPORT	SENSORS
Diagnostic Systems	Radio Astronomy	Staring Detector Systems
Implanted Devices	Optical Astronomy	Scanning Detector Systems
Patient Telemetry	Space Telescope	EM Field Detection Systems

Evaluation of communications systems emphasized command and control operations in applications including mass transportation, utility and pipeline control, and air traffic control. Long-distance, multinode data networks were evaluated for node or switching center input-output delay and lost messages caused by errors resulting from interference and increased noise levels.

Computers in the mini- and microprocessor classes were evaluated including both military and commercial systems and those implemented with both medium and large scale integrated circuits (MSI and LSI). Complete functional configurations were tested under simulated SPS exposure conditions to determine effects on system interconnections and overall performance. The sensitivity of individual digital integrated circuits to the SPS environment was analyzed separately.

Radar systems for air traffic monitor, military test range instrumentation, and military operational monitor and control systems were evaluated. Effects on detection range, identification delay, tracking error, and tracking lock uncertainty were considered for both passive (skin) and cooperative (transponder) targets.

Pacemakers, and general medical electronics were investigated to find if there were current standards used for EMI susceptibility. Manufacturers were contacted and data obtained where possible. Actual testing was not accomplished, and further study would be warranted.

Scientific research equipment used in studies of extremely weak electromagnetic radiation, at both radio and optical wavelengths, was identified early in the program as a category particularly sensitive to interference from SPS. A workshop was convened in May 1979 to consider potential SPS impacts on optical and radio astronomy, deep space research, and related scientific programs. Proceedings of this workshop have been published as "Workshop on Satellite Power Systems (SPS) Effects on Optical and Radio Astronomy," CONF-7905143 (1980), and a summary of our current understanding of these problems is included in this report.

A wide range of electro-optical sensor systems was evaluated covering both the infrared and visible wavelengths. Staring and imaging sensors using solid state and vacuum tube detectors were included. Effects on video and control electronics were considered as well as primary effects on the sensors. Target detection and feature extraction processes for identification in security and intrusion detection applications were considered, as were track noise or prediction filter coefficient uncertainties in star and aircraft tracking systems. Tested performance scoring points included video noise, scan jitter, dynamic range compression, and alterations in modulation transfer function.

2.2 RECTENNA SITES

As one part of the assessment, the EMC problems associated with hypothetical rectenna sites in regions representing different climates and degrees of urbanization were evaluated in detail to indicate the extent of anticipated effects. The results for the first hypothetical site considered, in the Mojave Desert of southern California, are summarized in Section 8. This first site analysis demonstrated that EMC considerations would be important in rectenna site selection.

2.3 MITIGATION

Consideration of mitigation of anticipated EMC problems was an integral part of the assessment. Many potential problems arise simply because most current electronic equipment was not designed to operate in the electromagnetic environment anticipated near SPS rectennas (or that experienced by satellites transmitting the microwave power beam). Testing to date has indicated that relatively simple modifications of existing equipment can, in many cases, substantially eliminate expected SPS interference. Where safety or similar concerns dictate an extremely low probability of interference, or where state of the art performance of electronic systems is required and would be impaired by modification, geographic separation between rectennas and sensitive systems is recommended.

Specific means of mitigating anticipated SPS problems were evaluated wherever such problems were found. Many of the tests included measurements of the effectiveness of various mitigating techniques. Figure 3 indicates the relationships between identified effects on equipment, evaluation of mitigation methods, and development of design and modification recommendations. The EMC Assessment has provided recommendations, and estimates of the cost of modifications and incremental cost of design changes have been provided.

Mitigation methods considered include shielding improvements, circuit modifications, and changes in the functional use of equipment. Geographic separation between rectennas and some systems may, as noted above, be a required mitigation technique in some cases. Constraints on the rectenna siting to provide this separation have been provided to rectenna site evaluation studies. Redeployment of existing facilities could also be considered if necessary.

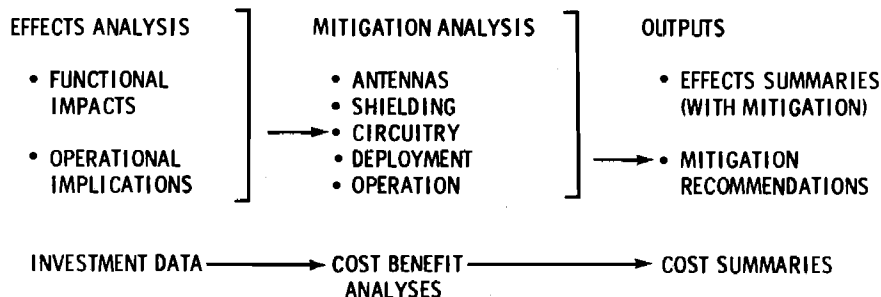


Figure 3. Data Flow in Mitigation Analysis Area of SPS EMC Assessment

3.0 SPS EMISSIONS AND MEDIA EFFECTS

An EMC assessment is based on measured or a range of assumed emissions from a proposed system or concept of operation. The SPS concept presently includes the GEO solar collection -- microwave conversion and transmission platform -- and terrestrial microwave power collector and utility conversion facility. Emission sources include direct and induced components from the GEO platform and reradiation and induced components from the rectenna circuitry and structures.

The SPS emission categories important in the EMC evaluation are listed.

1. Primary frequency (2.4-2.5 GHz band) and the second, third, and fourth harmonic power amplitudes, and spatial distributions from the spacetenna.
2. Noise sidebands generated by multiplying and amplifying devices, and radiated from the spacetenna.
3. Intermodulation products from the GEO platform (i.e., sources represented by multiple frequency illumination of structure composite material junction areas and the solar cells and control/conversion circuitry).
4. Fundamental frequency and harmonic reradiation from the rectenna dipoles.
5. Intermodulation products from the rectenna site structures (e.g., dipole group framework and other metal structures within the rectenna site). Illumination sources include the SPS fundamental and harmonic components and other signals in the locale (e.g., airborne and surface radars, satellite communications, commercial communications).
6. Thermal black body radiation from the SPS GEO platform.
7. Scattered sunlight and moonlight from the SPS GEO platform.

3.1 ELECTROMAGNETIC FIELDS DUE TO THE MICROWAVE POWER TRANSMISSION SYSTEM

In the current Reference System design, the microwave power transmission beam is formed by a 1-km diameter phased-array antenna (spacetenna). The array consists of 7220 subarrays, each approximately 10 meters square, of slotted waveguide radiators. The DC power from photovoltaic collectors is converted to the 2.45 GHz frequency and amplified by more than 100,000-70 kW klystrons. An active phase control system would accommodate mechanical flexing and subarray positioning errors, and maintain beam shape and pointing. This control system will also accommodate beam perturbations and distortions imposed by atmospheric anomalies. Several different phase control schemes are under consideration. The array illumination has a 10 dB Gaussian taper accomplished in ten discrete steps.

Gain patterns for the transmitting array at the fundamental frequency have been computed separately by ITS and NASA. The ITS pattern, shown in Figures 4 and 5, does not include the effects of mechanical tolerances or component failures. [Derivation of this pattern is given in Ott (1979)] The NASA-computed patterns are shown in Figures 6 and 7 (from DOE/ER-0023). The independent computations are in close agreement (differences of about 6-8 dB in the 60°-90° angles from boresight). The grating lobe shown in Figure 6 results from subarray spacings, and would repeat on the earth in a rectangular pattern at intervals of 440 km.

A smoothed, fundamental power-density pattern on the ground for a single SPS is shown in Figure 8. Figure 9 shows power densities in the continental United States for a 60-SPS configuration assuming

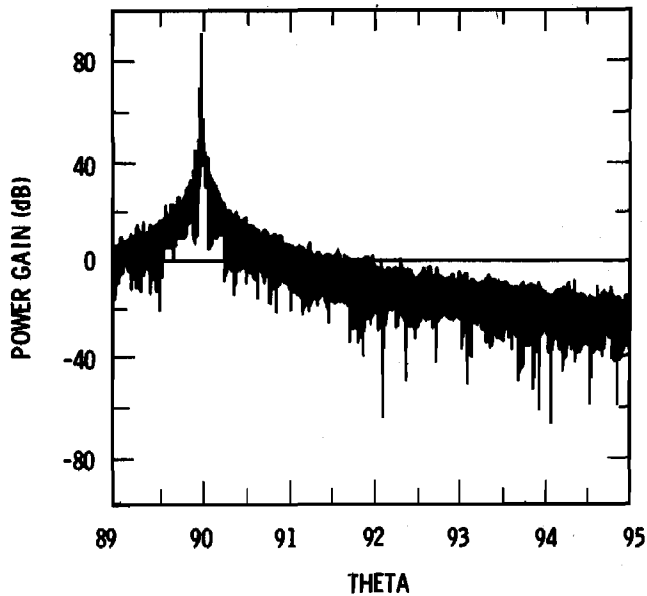


Figure 4. SPS Transmitting Antenna Gain Versus Angle from Antenna Plane. On-axis gain is approximately 87.7 dBi.

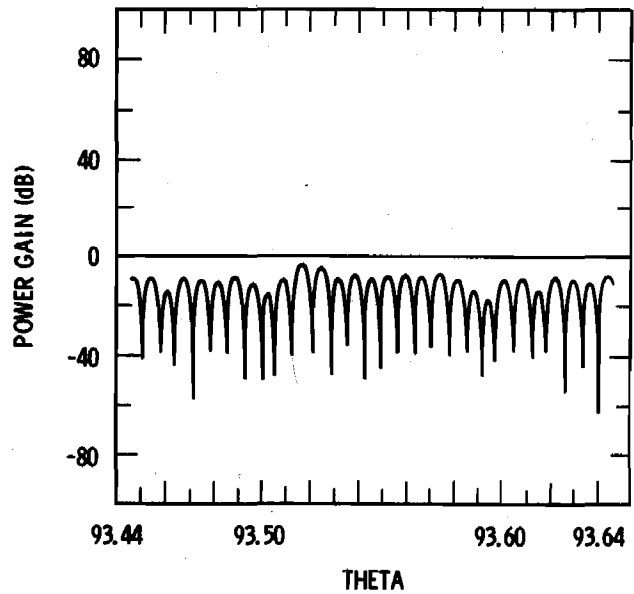


Figure 5. SPS Transmitting Antenna Gain Side Lobe Detail.

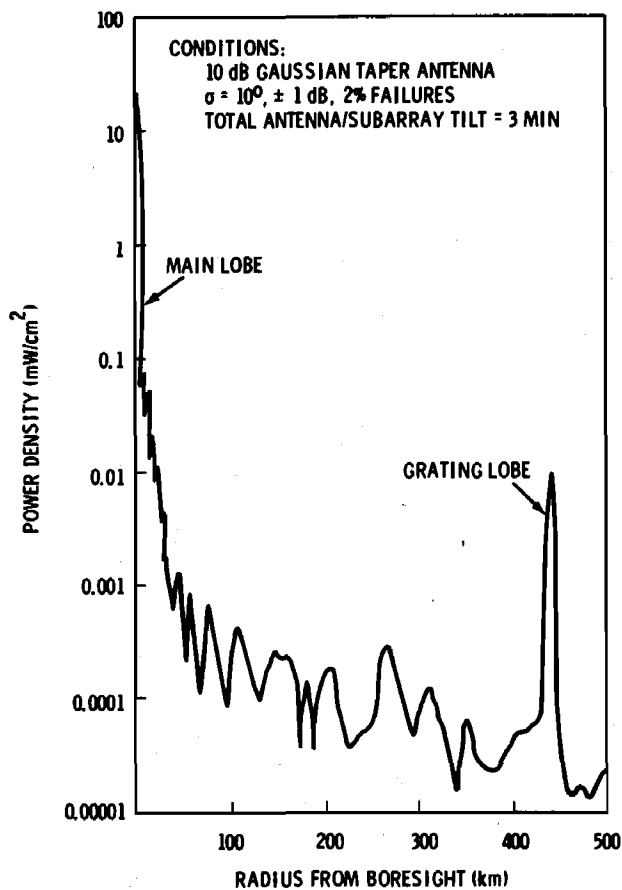


Figure 6. Peak Power Density for SPS Side Lobes and Grating Lobe as a Function of Radial Distance from Rectenna.

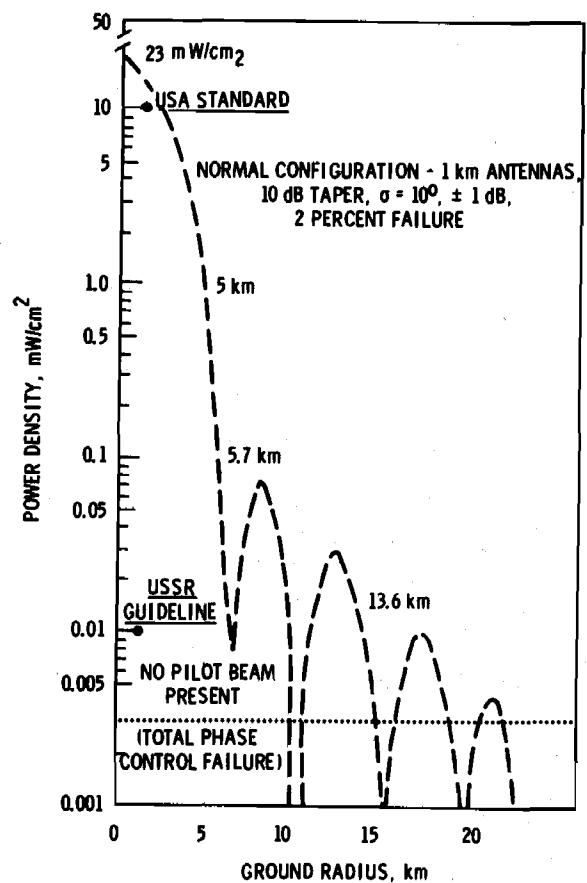


Figure 7. Power Density near Rectenna as a Function of Distance from Center.

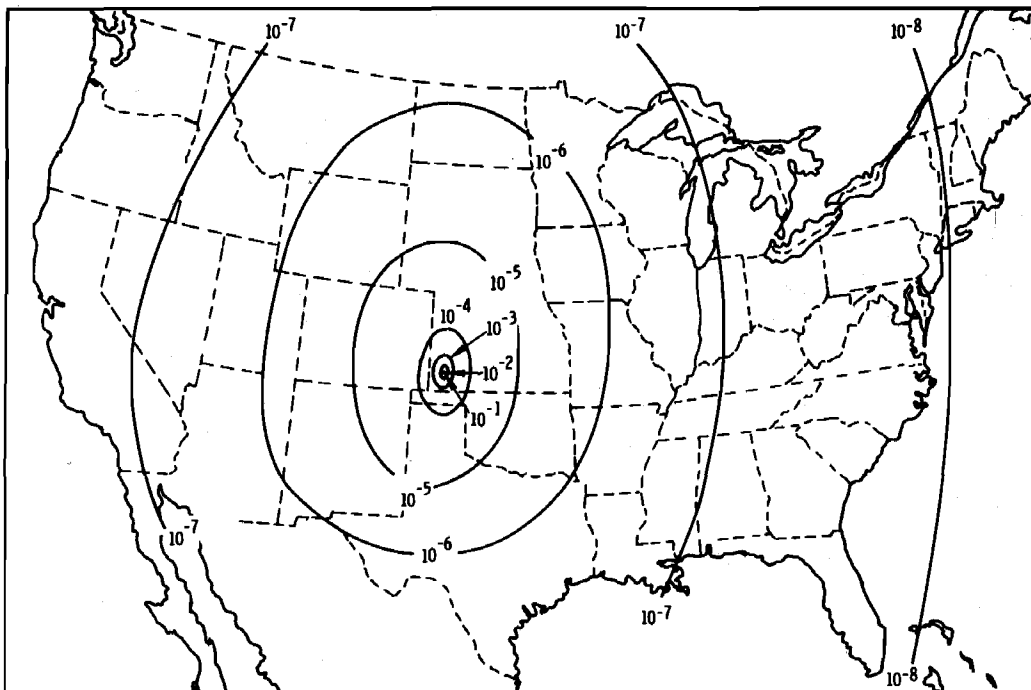


Figure 8. Microwave Power Density (W/m^2) from a Single SPS with Rectenna in Kansas

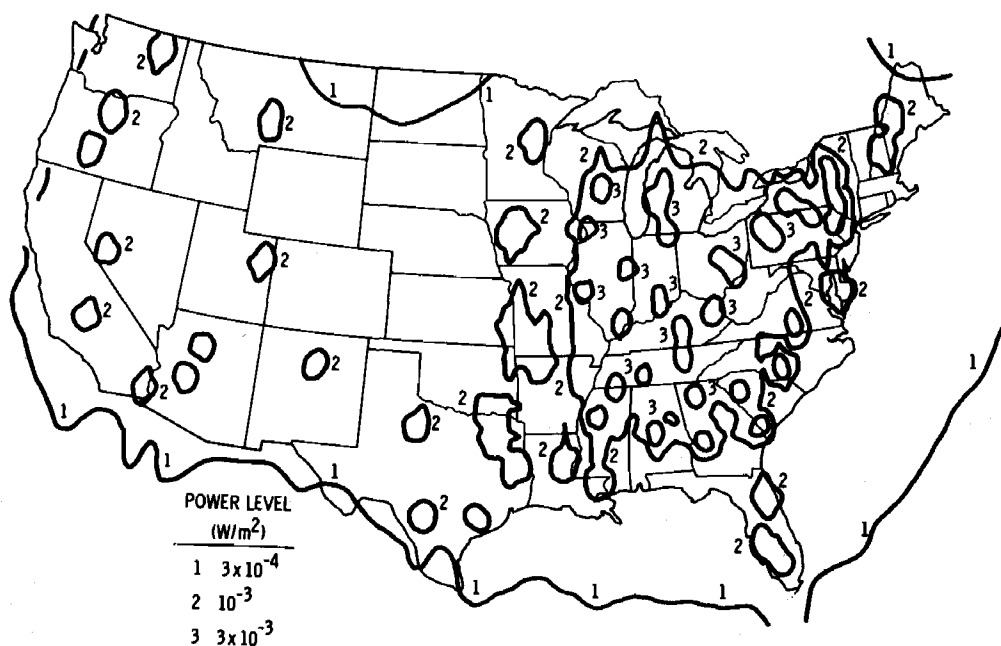


Figure 9. Microwave Power Densities (W/m^2) in the Western Hemisphere for a Configuration of 60 SPSs with Rectennas in CONUS (from Boeing D180-26019-1).

rectenna siting consistent with satellites positioned every 1° from 60° to 120° West longitude. The rectenna sites were identified by the Rice University siting criteria study (Blackburn, 1980).

The estimate of amplifier chain harmonic source amplitudes is presented in Figure 10. Amplifier harmonic emissions plotted represent spectrum signature data for a wide range of klystron amplifiers used for power amplifiers in S, C, and X band communications and radar equipment. The noise sideband plot in Figure 11 is representative of high-power klystron amplifier chains, where the power output is in the 10 kW-50 kW range. These modulation components are important in evaluating potential in-channel interference for communications channels adjacent to the 2.4 - 2.5 GHz ISM band. One operation constraint imposed by these sidebands is the minimum separation between an SPS frequency assignment and the edge of the ISM band. For the sidebands plotted, the minimum SPS frequency separation from the ISM band edge must be 10 MHz. Normal life parameter variations for high power TWT or klystron amplifiers would indicate a 15-20 MHz separation from the band edge.

Noise sidebands from SPS, if held to the levels computed by Arndt and Leopold (1978), would exceed interference limits only for the adjacent satellite broadcast band, which is not now used. If these noise sideband levels are realized, problems in the nearby deep space research and radio astronomy bands would probably be due largely to the effects of high power levels at 2.45 GHz.

Estimates of the spatial distribution of harmonic power from the spaceteenna are plotted in Figures 12 and 13. These patterns were derived by relating fundamental and harmonic spatial frequency distributions for arrays with nonuniform tapers. The envelope of the pattern (dotted line) was used in all SPS environment computations (the uncertainties in harmonic phasing and amplitude variations among power amplifiers do not justify confidence in the spatial variations). The array gain at the harmonic frequencies should be valid within a 10 dB range. The uncertainty is due to the fact that emission power varies according to mode properties and impedance differences between output amplifiers.

The rectenna fundamental frequency reradiation pattern is plotted in Figure 14. This was developed from the effective radar cross-section of a resonant dipole at an average illumination angle of 35° and an impedance ratio of 1.2/1. A cross-section of 300 m^2 is assumed for the metal framework supporting the dipoles. Pattern estimates for the second and third harmonic emissions from the rectenna are plotted in Figures 15 and 16. These were developed for an array of dipoles each having a length of λ for f_2 and $3\lambda/2$ for f_3 patterns. No effects of the ground conductivity or reflections from the metal framework are included.

The second harmonic of 2.45 GHz at 4.9 GHz is very near a radio astronomy allocation. In practice radio astronomy operates below the allocated band and would be impacted by SPS second harmonic radiation unless it was held to very low levels.

The third harmonic at 7.35 GHz falls into a satellite downlink band allocated to government use in the United States. SPS emissions in this band could interfere with communications systems in this band. Many of these are military and resistant to interference but SPS input could degrade their ability to accept additional interference.

The SPS fifth harmonic at 12.25 GHz is adjacent to a satellite downlink band being considered for TV broadcasting. It is possible that this band could be extended upward in the future (in Europe it already extends to 12.5 GHz). In any case, a strong signal from SPS structures could present a serious problem to the use of this band for direct TV broadcasting to inexpensive receivers with small antennas.

3.2 MEDIA EFFECTS

The spatial distribution of SPS microwave power can be modified by phenomena in the beam path which either directly scatter power out of the beam or affect the phase control system which maintains beam shape and pointing. Two areas are of particular concern: the ionosphere and the troposphere. The effects of natural ionospheric conditions, including perturbations from average conditions caused by solar activity, are known and expected to be minor. Potential modification of ionospheric electron density and temperature by the SPS power beam has been addressed by an analytic and experimental program in Task 4 of the Environmental Assessment. This program indicates the degree of possible power beam and phase control effects and the effects on the performance of radio systems that use ionospheric refraction for transmission (e.g., low frequency navigation and shortwave communications). The study also includes satellite communication and navigation systems that transmit through the ionosphere.

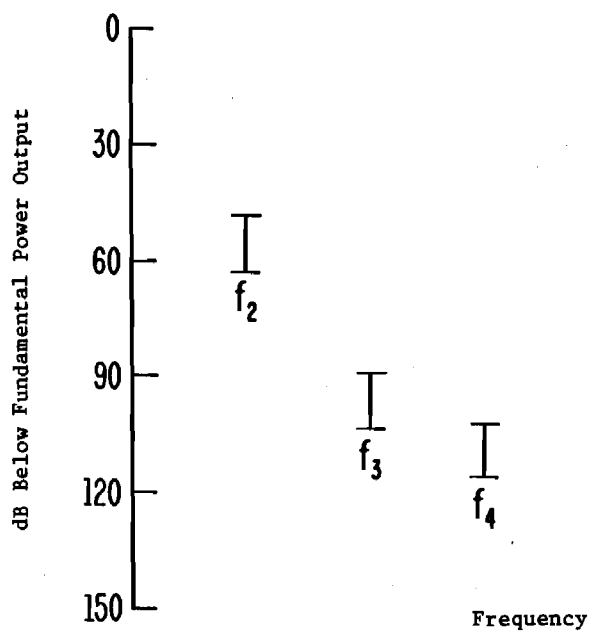


Figure 10. Typical Harmonic Emission from a High Power Klystron.

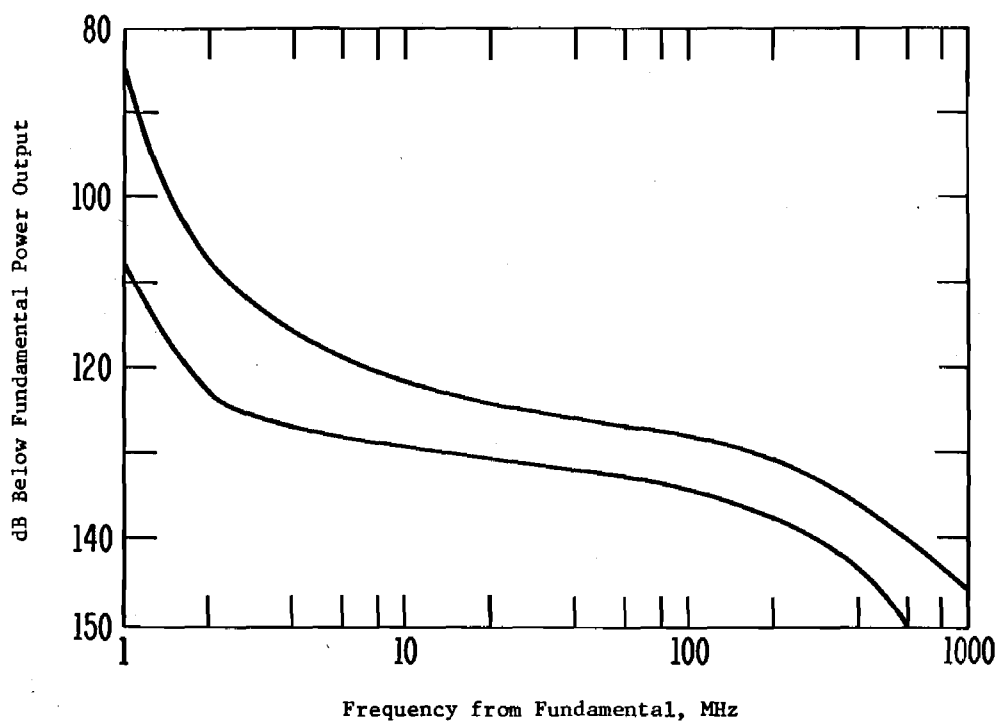


Figure 11. Typical Noise Emissions from a High Power Klystron.

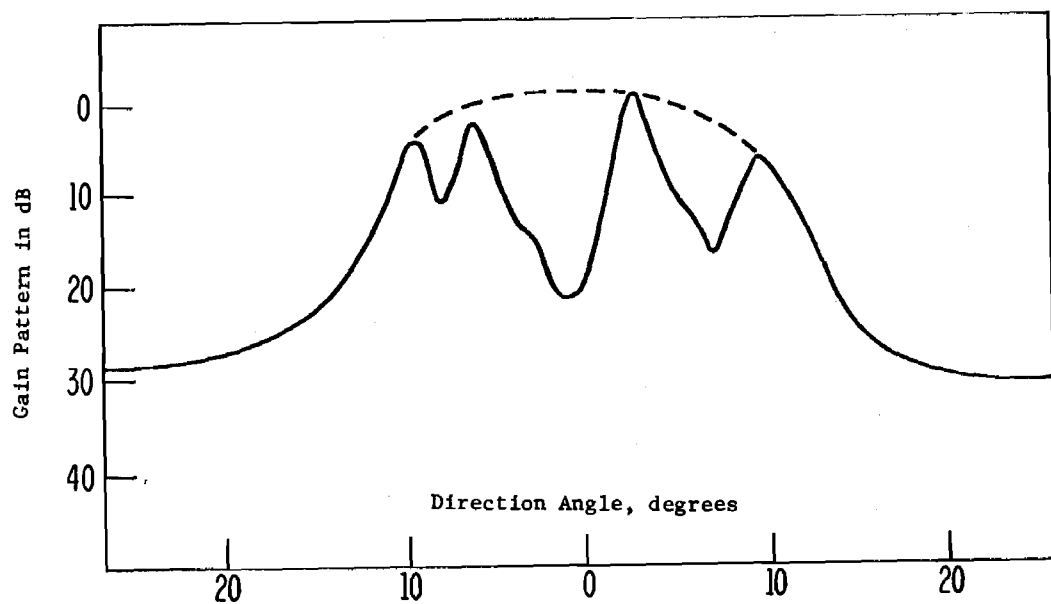


Figure 12. "Spacetenna - f_2 Pattern Estimate"

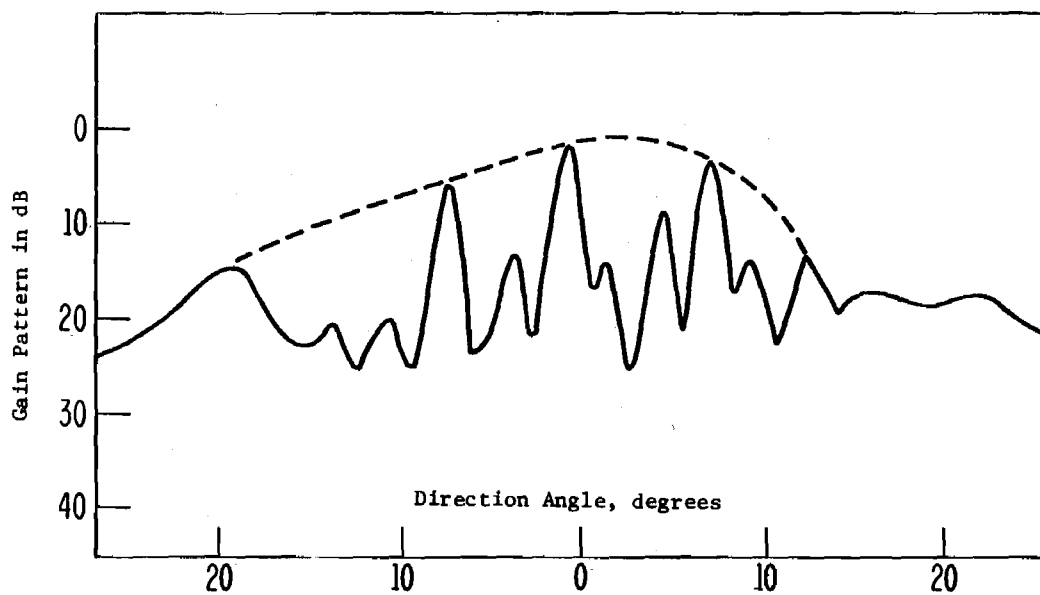


Figure 13. Spacetenna - f_3 Pattern Estimate".

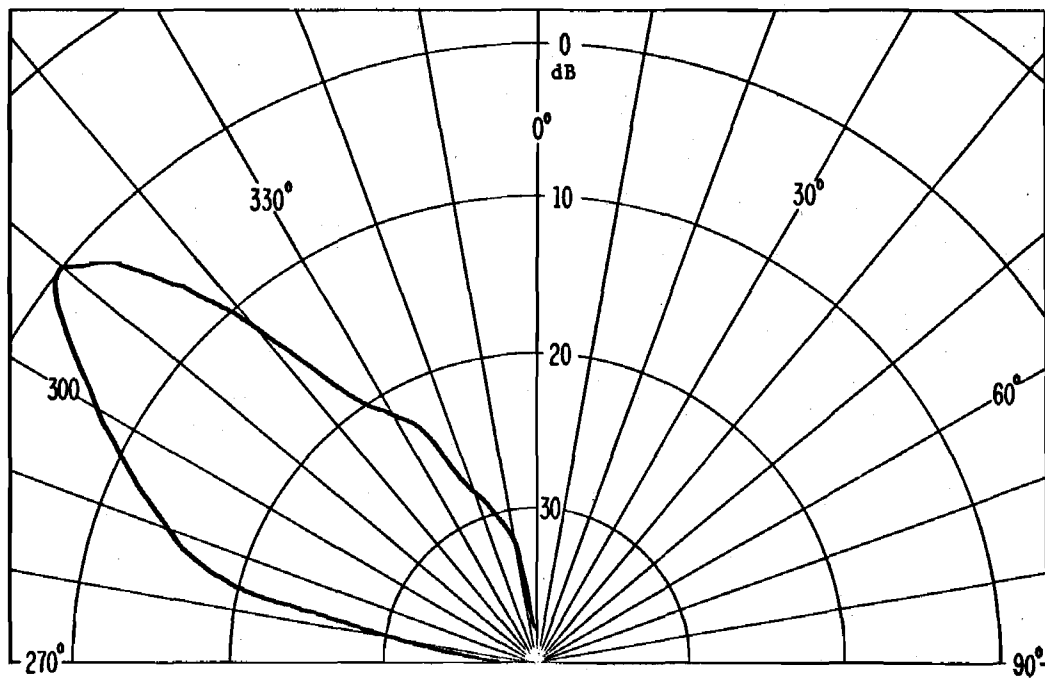


Figure 14. Rectenna f_0 Pattern.

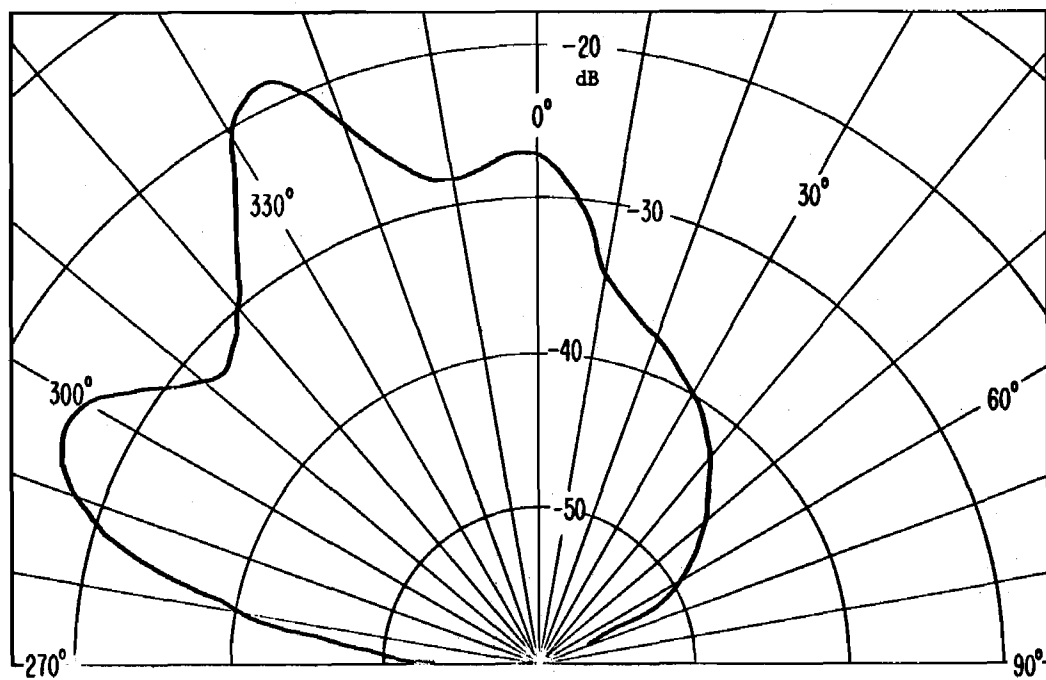
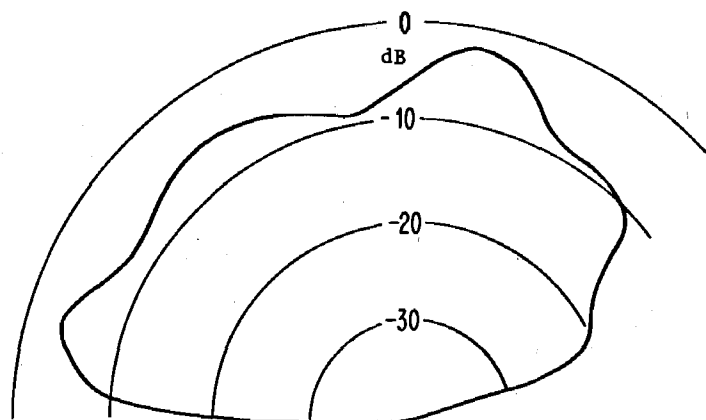


Figure 15. Rectenna f_2 Pattern.



RECTENNA f_3 PATTERN

Figure 16. Rectenna f_3 Pattern.

The troposphere phenomena of interest are

- * hydrometeor (principally rain and hail) scatter of the power beam,
- * scatter of the power beam by dust or other particulates,
- * changes in microwave refractive index with various distance and time scales which might scatter the power beam or interfere with phase control (e.g., layer refraction, dynamic anomalies or radar "angels." and turbulence from rectenna site heating).

The heat island effect has been evaluated by Task 3 of the Environmental Assessment. Results indicate density variations of 0.1% to 1.2% of normal for day and night periods due to rectenna heating. This increased turbulence causes no practical reduction in power to the rectenna, and because it occurs only 50 to 200 meters above the rectenna, it contributes no additional scattered power beyond the rectenna area's boundary.

Dust or sandstorms contribute an insignificant microwave power loss and variation of power densities outside the rectenna. For the larger storms in the U.S. southwest arid areas, the maximum power scattered is expected to be in the range of 10^{-5} to 10^{-4} of the power beam, over an angle range of about $\pm 60^\circ$.

Rainstorms will cause transient power beam scatter, attenuation, and induced modulation of phase control signals. Rain scattering anticipated, as a percentage of beam power, has been computed for hypothetical rectenna sites in nine states. Rain rates and power loss percentages will be equal to or less than values in columns A of Table 2 for 99% of an average year. Columns B provide corresponding values for 99.99% of an average year. That is, for New York most rain storms will be 10.2 m/hr or less but some can be as high as 55.3 m/hr for less than .01% of a year.

TABLE 2. Total Power Loss Expected for Various Rectenna Sites

Hypothetical Rectenna Sites	Rain Rate (mm/hr)		Power Loss (%)	
	A(99%)	B(99.99%)	A(99%)	B(99.99%)
California	2.9	6.3	0.02	0.06
Delaware	18.2	87	1.11	2.55
Tennessee	18	83	1.08	2.43
Florida	42.4	113	1.56	3.1
Montana	5	21.6	0.11	0.63
Nebraska	7.3	70.8	0.7	1.46
Minnesota	9.1	46.7	0.28	1.12
Michigan	8.3	52	0.38	1.4
New York	10.2	55.3	0.4	1.41

(Power loss percentages shown include clean air attenuation.) Rain-scattered power was added to direct-beam power in determining the separation requirements between rectenna sites and sensitive facilities to ensure that these are conservative.

Transient meteorological events and refractive anomalies will produce both amplitude and phase modulation of the power beam and beam control signals. If beam spreading or wander results, the geographic range of EMC problems would be extended. It is thus important to understand the effects of these phenomena on any planned beam-control systems and include realistic data on their amplitudes, rates, and spectral densities in evaluations of system stability. Beam parameter sensors employed for spacetenna control will include processors to extract anomaly modulation components, spectra being in the range of 5 Hz to 20 Hz.

The EMC assessment included scatter from the power beam in addition to sidelobe distributions and the reradiated and harmonic components from the rectenna elements in evaluating the geographic extent of EMC problems. Reflected and radiated components from the rectenna are expected to be about 10^{-4} to 10^{-6} of the amplitude of the direct beam throughout any area in which these components could cause responses in receivers (reference patterns in Figures 14, 15, and 16). Refractive index gradients integrated over the full altitude range are not sufficient to produce significant power densities at any terrestrial, aircraft, or space vehicle location.

In areas that receive comparable amount of power from two or more SPS structures, microwave field strengths will be modified by power-beam interference effects, particularly if all SPS transmissions use the same frequency. Frequency differences between transmissions, due to Doppler shifts associated with orbit perturbations or spacecraft frequency offset and atmospheric anomalies, will result in modulation of the fields. If the SPS orbit position is maintained to 0.1° , modulation frequencies due to Doppler shifts will be less than 10 hertz. Local field strengths will be further modified by reflections from terrain, buildings, trees, and moving vehicles.

This possible interference effect can be eliminated if the SPS power transmissions are assigned to different frequencies within the ISM band. Frequencies could be reused at least 4 times over CONUS and allow adequate geographic separation to eliminate these interference effects. Separation of at least 10° longitude would be satisfactory.

3.3 MICROWAVE FIELDS IN STRUCTURES

It is necessary for the EMC analysis to know the SPS microwave field strengths that would be expected inside various structures, particularly buildings and vehicles. Theoretically, such structures could concentrate incident microwave energy to produce fields more intense than would otherwise be expected. Little work has been done explicitly on this problem, but a substantial body of theoretical and experimental information is available on the coupling of microwaves into enclosures and their behavior therein. An exact, detailed analysis of the microwave properties of habitable structures is not practical because of the tremendous variety of materials and complex geometries involved. The problem of estimating the fields inside habitable structures exposed to microwaves near an SPS rectenna has been analyzed in a topical report by Liebe (1980), with particular attention to the possibility of increases in field strength. That study describes and discusses relevant physical processes, lists measured values for many of the quantities involved, and cites actual microwave field strengths measured inside houses exposed to 2.6-GHz radiation from a satellite. Key results are summarized below.

To determine microwave field strengths inside a structure, the coupling of energy into the structure, and its behavior inside, including reflections (possibly resonant), must be understood. Coupling to the interior could occur via relatively microwave-transparent openings (windows, for example) or through wall materials, which in general do not transmit microwaves as well. The following approximate microwave transmissions for representative structural elements have been measured:

<u>Structure</u>	<u>% Transmission</u>	
	<u>Dry</u>	<u>Wet</u>
Wooden Wall	15	6
Frame Wall	40	15
Window (wood sash)	70	40

Metal walls or screening, or even foil, transmit very little 2.45-GHz microwave energy (less than 1%) if openings or joints are less than an inch long.

Average field strengths inside structures are expected to be less than those outside because of coupling losses. The structure could, however, alter the spatial distribution of energy to produce localized areas of increased field intensity. Reflections within structures are the most likely causes of locally-increased field strength. Metallic surfaces are the most common elements of habitable structures likely to produce significant field increases. In the absence of any absorbing material, a single metallic reflection could increase power density at some locations by as much as a factor of four above that incident on the surface. More complex geometries involving multiple reflections could, in principle, produce larger field increases. However, such large increases require special geometries and very little microwave absorption in the system. Neither of these criteria is likely to be satisfied by real

habitable structures. In particular, it should be noted that the presence of people, who are significant microwave absorbers and reflectors, modifies reflection patterns in a time-varying way; as the people move and absorb energy they reduce the field increases that might otherwise occur.

Ratios of microwave field strength inside to that outside single family houses illuminated by 2.6-GHz microwaves from a satellite have been reported (Wells, 1977). Average fields inside were found to be about 25% of those outside, although interior fields varied substantially from point to point. For the case of highest ratio for average inside fields to outside fields, the probability of encountering a microwave field inside that was larger than that outside was only 15%. Considering both the losses in coupling microwave energy into structures and the low probability of situations that would produce significant concentrations of energy, we conclude that interior field strengths significantly higher than those outside are unlikely. If, in specific cases, interior microwave fields were found to be a problem, they could be reduced by reducing coupling or increasing interior absorption.

Vehicles provide shielding because of the metal construction. Automobiles, airplanes, buses, and railroad cars have metal roofs and side panel areas. The future use of composites and plastics in automobiles will reduce shielding effectiveness by 6-10 dB depending on material. Window areas provide little attenuation for direct and reflected microwave power.

Previous measurements (NBS, 1974; ITS, 1975) of microwave fields inside automobiles indicate an average attenuation of external fields of $\sim 6-12$ dB for frequencies in the 1-4 GHz range. Energy coupling included windows and body area openings. For vertical incidence fields, the passenger area attenuation would be $\sim 9-12$ dB, with the variation primarily caused by the reflection characteristics of nearby roadway or structures.

Commercial aircraft flying through an SPS power beam will have powers reflected from wing surfaces in the range of 20-50 kW, with approximately 60% of this power reflected away from the fuselage because of wing surface curvature and dihedral angle. The short term exposure to passengers is insignificant because of the small window area and the short time exposure ($\sim 0.5-1$ min). Public vehicles would be excluded from a rectenna area, and would not be exposed to more than $0.5-1$ mw/cm².

3.4 THERMAL BLACKBODY RADIATION

The large (approximately 50 km²) photovoltaic arrays on the SPS structure will operate at temperatures of approximately 300°K and are expected to have significant microwave emissivity. The spectral flux density at the earth due to blackbody radiation is approximately -265 dB(W/m²Hz) at 2.45 GHz (increasing 6 dB per frequency octave for a single SPS structure assuming 10% microwave emissivity of the photovoltaic array. (Array emissivity might be as much as a factor of 10 larger or smaller.)

Figure 17 shows estimated levels or ranges of spurious emissions from the MPTS, thermal emission from the photovoltaic arrays for a single SPS structure, and some established and estimated interference levels. This plot illustrates power spectral densities for the most sensitive susceptible systems caused by SPS operations, and indicates limits currently defined by CCIR and ITU regulations. The lower ranges of interference limits shown are generally for antennas pointed at or very near (within 1° of) an SPS structure. The noise sidebands are typical of 5-cavity klystrons (Figure 12) and would vary if different power amplifiers (magnetrons, gyrocons, gyrotrons) were used for SPS.

3.5 SCATTERED SUNLIGHT

Because of the large sunlit area of the SPS structures, they will, unless they are extremely good absorbers, be conspicuously bright objects in the night sky. Using a value of 4% for diffuse scattering from the photovoltaic cells, representative of the darkest present cells, each satellite of the Reference System design would appear at midnight to be as bright as the planet Venus ever appears (-4.3 stellar magnitude) and thus brighter than any other object in the sky except the sun or moon. In addition to the very bright points produced by each spacecraft, large areas of the sky would be bright because of rescattering of light in the earth's atmosphere. The addition of this amount of light to the night sky would seriously affect optical astronomy and other scientific observations requiring dark skies. Scattered sunlight is discussed further in Section 10.2.

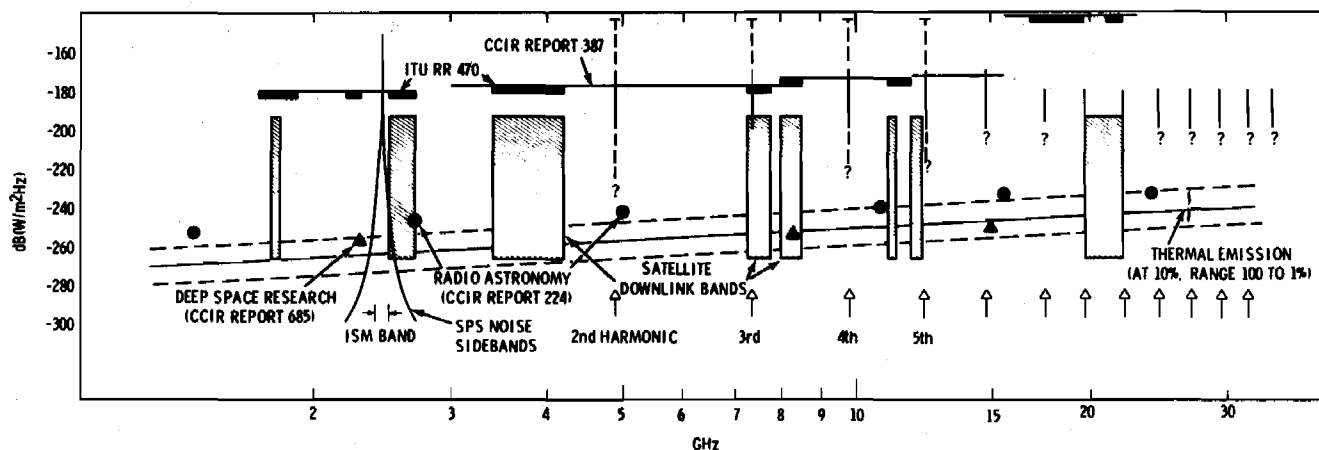


Figure 17. Estimated Microwave Spectral Flux Densities at the Surface of the Earth as a Function of Frequency for One SPS with Relevant Interference Limits.

4.0 EFFECTS ON MAJOR EQUIPMENT CATEGORIES

The evaluation of the degradation in performance of electronic equipment because of SPS interference relied primarily on measurements of coupling modes to circuits and devices, and the resulting effects in operations. Discrete component and integrated circuit configurations of the various system categories were tested to maximize relevance to future equipments. The effects data are relatable to LSI and BLSI configurations that will dominate future electronic equipments, allowing significant increases in processing and control capabilities.

The principal equipment/system categories evaluated include communications and radar receivers, optical and electro-optical sensors, data processors, computers, and special equipments such as radio astronomy receivers and medical clinic diagnostic components.

Specific equipment applications evaluated in this EMC investigation, because of unique sensitivities and future national priority, include GEO and LEO satellite systems; and military test range and operations support, transportation command/control, and terrestrial common carrier communications. Particularly in the satellite services, various equipment categories are represented, including communications and radars, optical sensors for altitude stabilization and earth monitoring, scientific data collection, and computers for station keeping management.

Mitigation techniques to allow these equipment to operate effectively in the SPS environment are discussed in Section 6.0. These mitigation methods include circuit and shielding modifications; and for computer controlled advanced communications and radar systems, the use of processing and control routines to reject or cancel the SPS interference components.

4.1 COMMUNICATIONS RECEIVERS

A general radio frequency communications receiver is diagramed in Figure 18. The configuration includes all functions of a receiver that would be impacted by SPS interference inputs.

Referring to the diagram, the inputs indicated for normal operation include the desired signal and external noise. Typical signal inputs include an unmodulated carrier or an amplitude or frequency (AM or FM) modulated carrier. Familiar communications signals in the microwave spectral region include FM analog voice; AM, FM, or PM single channel or frequency multiplexed voice and data transmission (FM/FM or PM/FM); and time multiplexed analog or digital voice and data channels.

General communications receivers include the antenna, first conversion, and conversion-detection elements of Figure 18. Basic functions include radio frequency amplification with filtering, signal mixing, intermediate frequency amplification, and signal detection, as diagramed in Figure 19. These functions are typical of telemetry terrestrial common carrier, dedicated microwave communications, and space communications equipment.

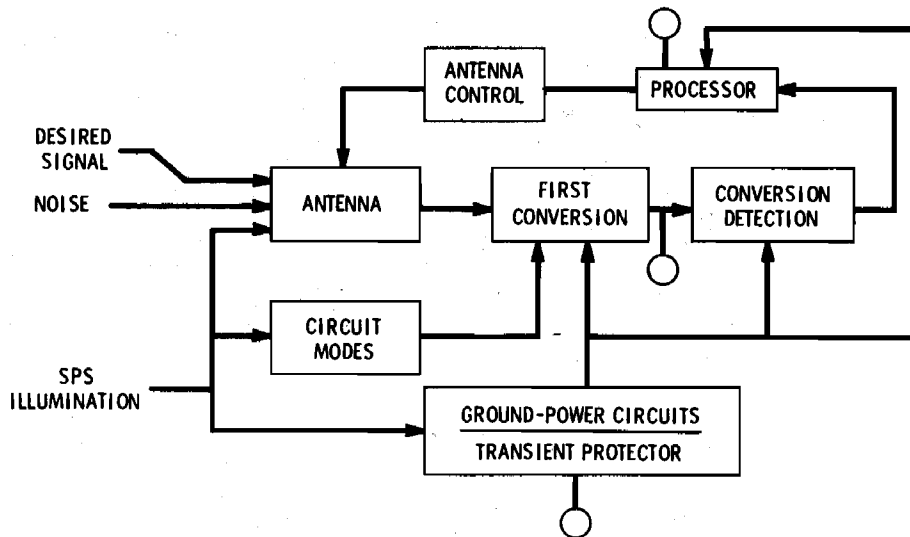


Figure 18. Generalized Block Diagram of a Telecommunication Receiver. Circles indicate EMC performance scoring points.

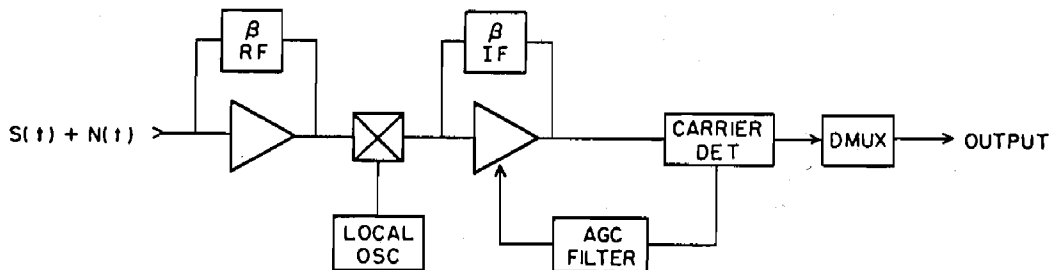


Figure 19. Receiver Functional Diagram

Where a communications receiver is located in a high interference environment, a signal tracking function is necessary to steer the antenna in the direction of the signal source, or steer an antenna null in the direction of the interferor. These tracking functions are represented in the Antenna Control loop in Figure 18. Actual implementation would use nulling antennas in conjunction with the primary antenna; or in future systems utilize a phased array where the acceptance beam width for the desired signal and the rejection beamwidth for the interferor would be accomplished by beam forming and pointing computer routines controlled by detector outputs. Phased array receiver systems can perform these beam control functions.

The SPS interferor is coupled to receivers through the modes listed (refer to Figure 18).

1. Direct entry into the signal channel-antenna, radio frequency amplifier, and the first conversion stage.
2. Coupling to radio frequency or intermediate frequency circuits; energy penetration through nonmetallic areas of module cases.
3. Coupling to ground circuits and transient protection components. The ground circuit mode involves cabling having a modest impedance above a ground point common to other modules ($Z \geq 10 \Omega$), with the junction(s) having a diode characteristic which causes noise transmission in the ground circuits to receiver elements.

These modes are indicated in Figure 18.

The listed types of communications receivers were tested.

1. 30-channel FM/FM telemetry receiver-IRIG subcarrier channels, analog and PCM data formats.
2. 100-channel frequency multiplexed receiver-system used for common carrier and dedicated network services,
3. 10-channel frequency multiplexed spread-spectrum receiver, military data link, satellite, or terrestrial point-to-point links.

The desired signal and SPS fundamental and harmonic components were coupled as indicated in Figure 18. Functional data was recorded at points indicated by the circles. The signal combination and output characteristics recorded are listed in Table 3.

TABLE 3. Receiver Evaluation Parameters

INPUTS		PERFORMANCE DATA
S/N(dB)	S/S _{INT} (dB)	
3	3	First Conversion -
		In-band Intermodulation
		Spectral Density
12	9	Transient Circuit, Ground
		Bus Entry -
		Noise Spectral Density
30	30	Detector/Processor Output -
		Noise Amplitude, Analog
		Signal Error, Bit Error
		Rate.

The desired signal(s) was varied as indicated in the S/N values, replicating the signal format appropriate for the various receiver processors. The SPS interferor (S_{INT}) included the fundamental and second and third harmonics with ratios as defined by the assumed emission spectra in Figure 10.

A representative intermodulation spectra at the first conversion stage output is displayed in Figure 20. The data with the different S/I values relates to an S/N of 12dB. The range of noise generated by transient protectors with two SPS fundamental illumination levels (0.1 mW/cm² and 1 mW/cm²) is presented in Figure 21. These data include ground bus junctions and diode protectors as noise sources.

The composite of communications receiver responses are plotted in Figures 22 and 23. These particular receiver and system metrics indicate the range of SPS interferor effects on communications receiver performance and a typical system level data input-output impact.

The principal functional effects for a communications receiver are listed.

1. Intermodulation products generated by the first conversion stage.
2. Circuit noise coupled from the ground bus and transient protector devices.
3. Direct coupling into high gain intermediate amplifiers, increasing noise levels, and, for the larger interferor levels (~ 1 mW/cm²), causing desensitization because of AGC action.
4. SPS harmonics in a communications band (e.g., third harmonic in the satellite uplink band) cause unacceptable degradation when the S/I ratio is below the 6-15 dB range, depending on data channel bandwidth and modulation employed. If the SPS harmonic amplitudes relative to the fundamental are in the range cited for the klystron tubes in Figure 10, the harmonic in-band interference will affect satellite terminals, GEO transponder receivers, and radio astronomy and deep space communications systems. These latter equipments are discussed separately in Sections 9.0 and 10.0.

4.2 RADAR SYSTEMS

Radar equipment evaluated for SPS interference susceptibility includes fixed site airborne, and future space systems. The applications tested include surface, airborne, space target detection and tracking, velocity control, and various military command/guidance functions. Radar configurations vary significantly for these applications; major functional elements for specific applications are listed below.

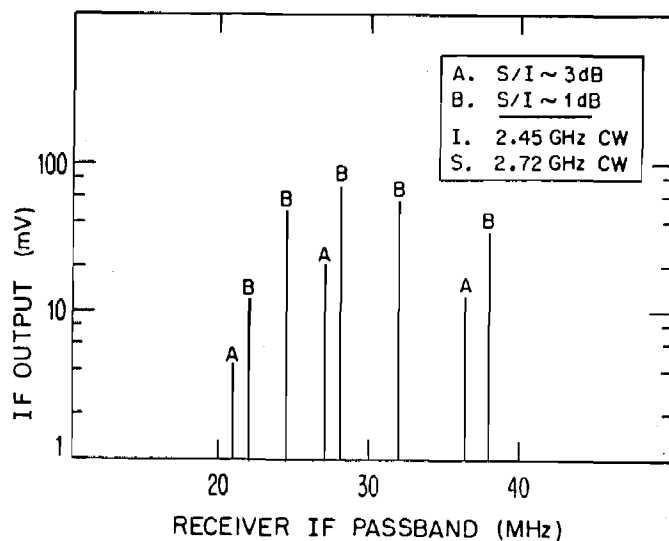


Figure 20. Example Receiver Intermodulation Responses

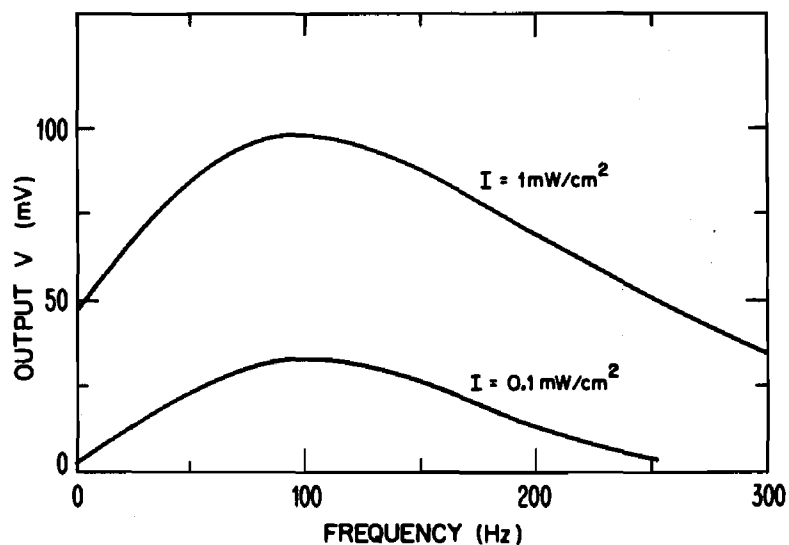


Figure 21. Mean Transient Protector Diode Noise Spectra

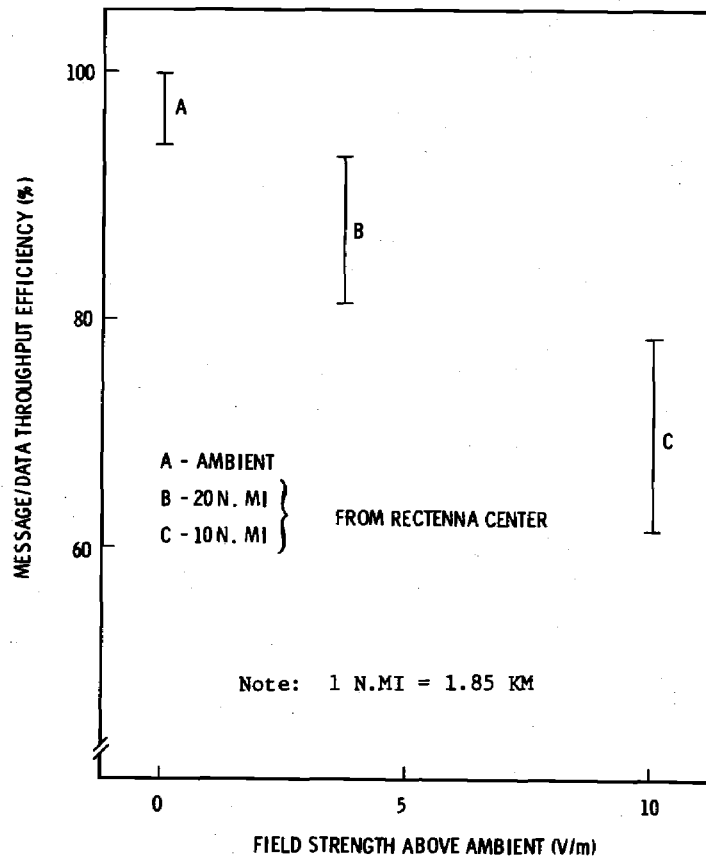


Figure 22. Effects of Microwave Illumination on Throughput Efficiency of Receivers.

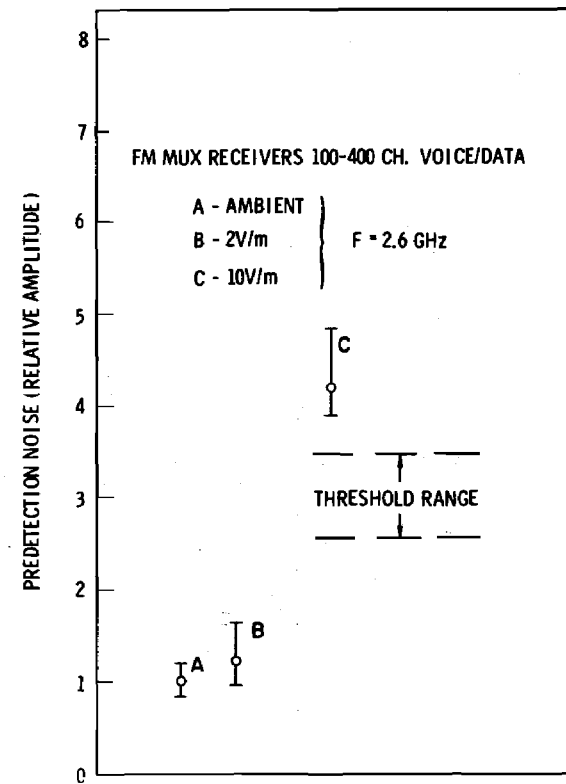


Figure 23. Multichannel Microwave Receiver System Predetection noise Increase due to Microwave Illumination.

<u>APPLICATION</u>	<u>FUNCTIONS/MODES</u>	<u>INTERFERENCE REDUCTION FUNCTIONS</u>
Air Traffic Control Area Surveillance Early Warning/Search	Continuous Scan - Range/Angle Measurement -Code Correlation -Pulse-Time; Conical, Scan, Monopulse Pulse-Pulse Doppler Track-While-Scan CHIRP -	Clutter canceller
Instrumentation/Track Military Test Range, Weapon Guidance	Range/Angle Measure -Code Correlation -Pulse-Time; Conical Scan Monopulse -ON-AXIS -Track-While-Scan, Simultaneous Multi-Target Track Coherent Doppler -Pulse to Pulse Frequency hopping -Pulse Burst, Open Band Doppler Beam Sharpening	Clutter filter ECCM Antenna nulling
Mapping Terrestrial Target Detection	Synthetic Aperture Formation	Doppler beam sharpening

The Interference Reduction Function heading indicates processes included in radar systems for multipath or external signal interference reduction, and which would be degraded by the SPS interferor. For those listed, the primary mitigations would involve computer software modifications.

The performance of the various systems is based on the following characteristics which were used to measure the effects of SPS interference.

- a. Surveillance and Search - Target detection range, target identification time, false target probabilities.
- b. Track and Guidance - Target lock-on time, track error distribution, loss of lock probability, and control action delays (weapon time line actions, interference nulling).
- c. Mapping and Terrestrial Target Detection - Target detection range, spatial resolution, and terrestrial feature resolution.

Because many radar detection and preprocessing functions are similar to those of communications systems, radar systems exhibit interference susceptibilities similar to those of communications receivers. Interference is coupled through the radar antenna and by conduction from external transient protector devices and multipoint ground busses. Figure 24 shows a generalized radar system diagram with EMC evaluation points indicated by circles. The definitions within the PROCESSOR apply specifically to computer controlled array (Track-While-Scan) systems. Similar functions would be implemented by circuitry for a mechanical pedestal system. The principal interference effects are listed below.

INTERFERENCE PRECURSORS:

Predetection Noise
Intermodulation Components
Signal Path Noise

FUNCTIONAL EFFECTS:

Video Pulse Distortion and Jitter
Range and Angle Channel Noise
Target Acquisition Delays and Track Loop Instabilities
Spot Beam Acquisition Delay and Jitter
Code Track Loop Errors and Increased Probability of Loss of Lock
Clutter Filter or Map Noise
-Increased peak of average ratios
Reduced Resolution in Beam Squint and Increased Squint Jitter
Increased Kalman Filter Instabilities

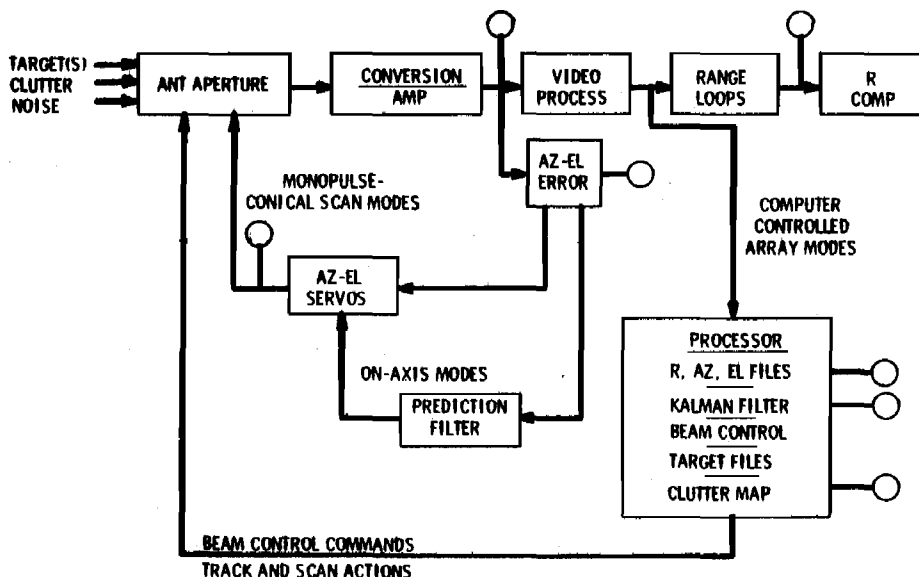


Figure 24. Generalized Block Diagram of a Radar System.
Circles indicate EMC performance scoring points.

Interference tests were conducted on military instrumentation radar systems in the southwestern United States. The following type of radars were tested: FPS-16, FPS-95, MPQ-25, Nike Hercules, and Nike Ajax. These systems represent conical scan and monopulse configurations.

Figure 25 indicates the degradation of range detection capability for two different received power-to-interference ratios (P_r/I) and conditions of cooperative (or transponder) track, and skin track. The interfering signal frequency was 2.45 GHz while the radar operating frequency was in C-band. It is easily seen that the range performance parameter changed by a factor of approximately two (2) for a decrease of 6 dB in the P_r/I ratio. The "worst case" skin track measurements indicate that the maximum radar detection range was decreased by approximately 33%. These data include all orientations of the target relative to the radar. Figure 26 shows the track noise (a contribution to track error) during the same tests.

Figure 27 is similar to Figures 25 and 26, but with different test stimuli and a different receiver response to the interfering signal. The interfering signal was generated at a frequency of 3.1 GHz from an airborne platform (A/C) covering the interference source. The receiver system incorporated an interference canceller (filter) to reduce the off-frequency interfering signal. Here the radar system response was the target lock time in milliseconds (ms). Again, the radar system's performance is degraded by approximately 6 dB in the P_r/I ratio when the noise canceller is used in cases A and B (reference Figures 25, 26, and 27). In situation C where $P_r = I$ the probability of lock is reduced to approximately 38%. A single measurement series was accomplished with SPS fundamental interference to a military phased-array radar. The reduced squint resolution in relation to target echo-interference ratio is indicated in Figure 28. This effect results from signal channel noise for the higher range of S/I ratios, with intermodulation components being the major contribution of the lower S/I values.

The SPS interference effects on a variety of military radar instrumentation used at test ranges near the hypothetical Mojave rectenna site, and other western area test facilities are summarized in Table 4. These tests apply to radar coverage of the full upper hemisphere.

TABLE 4
Military Instrumentation Radars

Cooperative Target Acquisition Range: Reduced by 8 to 20%	Skin Target Track Error: Increased by 22 to 65%
Skin Target Acquisition Range: Reduced by 13 to 28%	Loss of Track Loop Lock (Skin Mode): Probability increased by 10 to 40%
Cooperative Target Track Error: Increased by 15 to 40%	

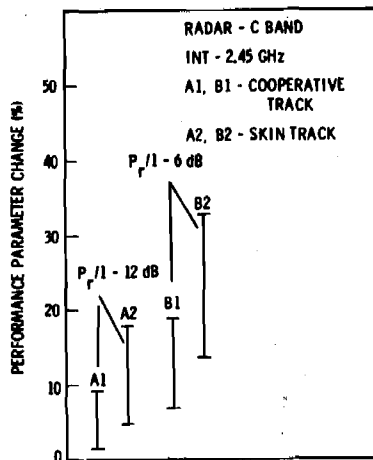


Figure 25. Decrease in Radar Detection Range caused by 2.45-GHz Interference.

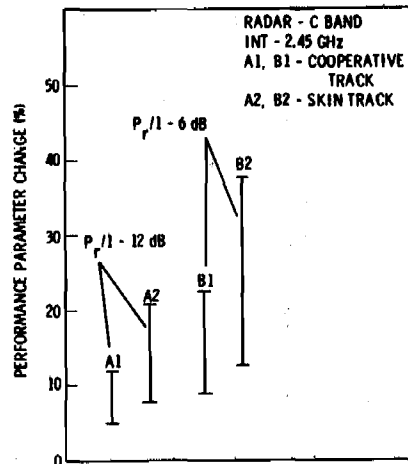


Figure 26. Increase in Radar Track Noise caused by 2.45-GHz Interference.

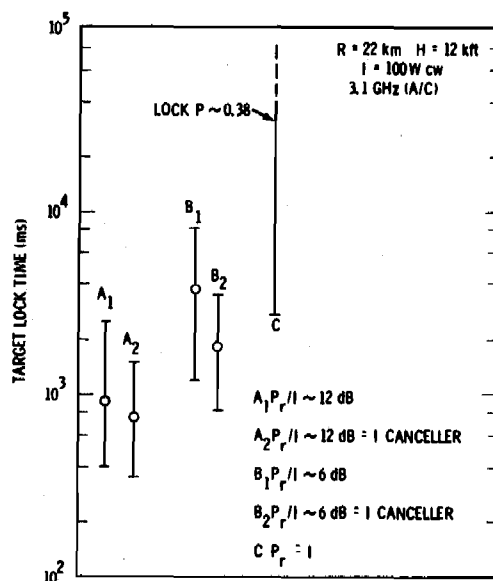


Figure 27. Increase in Radar Target Lock Time caused by Microwave (3.1-GHz) Interference.

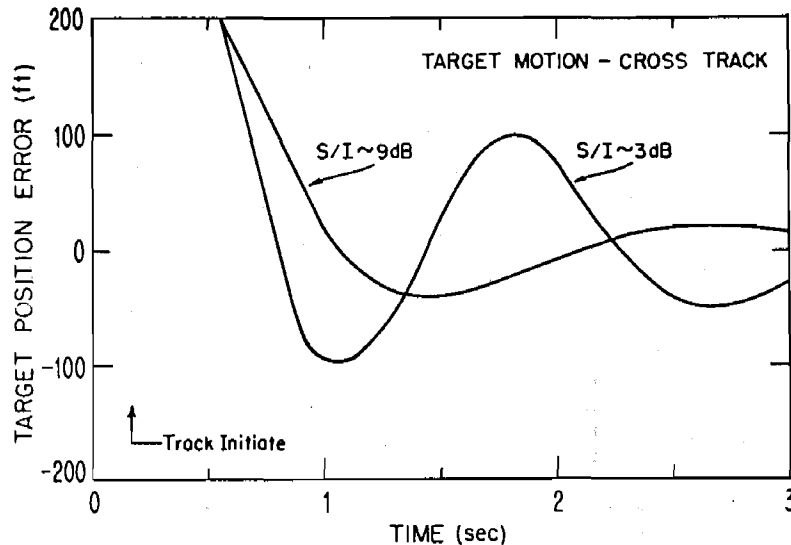


Figure 28. Array Radar Track Characteristic - Squint Software - S/I Sensitivity.

Testing so far has included conical scan, monopulse, on-axis, mechanical steered systems, and a single phased array radar. The phased-array system included software-controlled scan mode control, multi-target (100 maximum) simultaneous track with Kalman prediction routines for the individual track files, and a single channel squint mode. The computer routines used for squint (signal nulling) control would be useful for SPS interference removal with modifications to accommodate the phase modulation of the SPS signal caused by troposphere anomalies. Existing squint routines have been designed for jammer rejection where moving source Doppler or fixed sources are located within a short distance ($\sim 1-5$ km) from the radar. Filter coefficients and possibly a rate compensation may be required to accommodate the media modulation of SPS components, and maintain a null of 40-60 dB.

4.3 COMPUTERS AND PROCESSORS

The primary concern in the susceptibility of computer and data processor systems to SPS interference relates to minicomputers and microprocessors, particularly as employed for remote facility support operations. Areas of application include utility and pipeline command/control, communications network control, transportation service command/control, and military test facility and weapon system control. Computer/processor configurations include centralized units connected to data sources (e.g., remote sensors, entry terminals) and distributed processing systems that interconnect processor modules (central processor, memory, storage) through communications links. Such configurations of microprocessor and minicomputer units are used for a wide range of remote command/control operations.

Discrete component and integrated circuit modules have been tested. Modules include input-output registers and central processor (registers, memory) functions. The noise sensitivity and transfer error data presented herein include both circuit module types.

Microwave coupling is accomplished by penetration through nonmetallic cover or case apertures, to circuit devices and device-component interconnections. Device induced noise is coupled to modules through ground and control lines or cabling, or induced by input-output connecting cabling. Circuit effects include bias shifts in logic and control units (e.g., FET devices, diode level sets), and noise conducted onto ground and control module connectors that cause false logic set/reset transitions. This latter effect increases in sensitivity with transition and clock rates. As cited previously, functions affected include input-output registers and control logic, central processor units, memory (FET, diode), and control and transfer actions for peripheral devices. The basic functional modules are indicated in Figure 29.

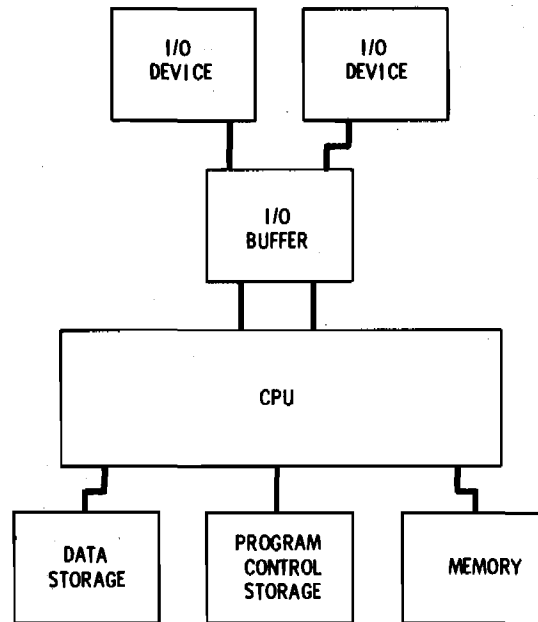


Figure 29. General Mini-Computer or Microprocessor Configuration.

Measurement points for computer modules are listed.

1. I/O register read-in and read-out terminals.
2. Arithmetic register in-out terminals.
3. Ground bus at module interconnections.
4. Memory control gates (OPEN and INHIBIT levels).
5. Register bias levels (discrete component configurations).

Module and system performance criteria include ground bus noise, clock jitter, control channel noise and jitter (gate pulses, register command), and bit-error rates in throughput operations for major modules (e.g., input-output, processor unit, and memory input-output). Figure 30 illustrates the percent increase in control pulse jitter present in the clock and control circuitry of the I/O memory registers for the microprocessors. The spread in data is due to the different responses to the 2.6-GHz interference signal presented by the different manufacturers' equipment and to whether the equipment was designed for military or commercial specifications. The percent jitter under normal conditions is shown as A (reference Figure 30). The jitter increased to 12% in some equipment when illuminated by a 2.6-GHz, 2 V/m field, shown in B. When the interference signal was increased to a 10 V/m field, the control pulse jitter increased by substantial amounts with the worst case reaching 33%, shown as case C. In many circumstances (higher clockrates, large memory fields) the 12% jitter would not be acceptable, and 33% would be beyond acceptable level of performance degradation for all circumstances.

Figure 31 shows the increase in a microprocessor's control bus noise as a function of increased microwave illumination. The threshold is given such that any noise factor above that line would constitute unacceptable performance. In this case the unacceptable interference was coupled through the diode protector circuits on the power supply voltages. With a fairly simple modification, the control bus noise factor could be reduced to an acceptable level (below the threshold line). The figure shows the data from a repeat test using the same field illumination levels but with capacitor bypass modification to the power supply voltages.

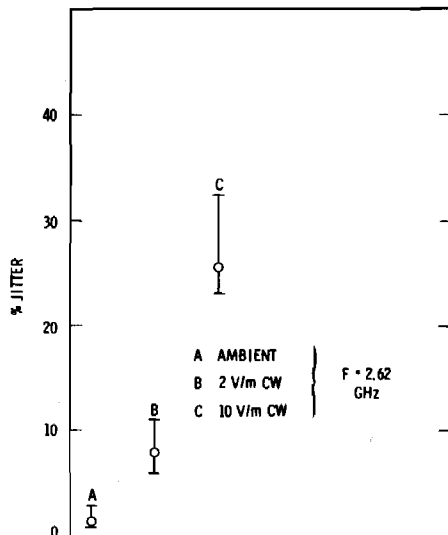


Figure 30. Percent Pulse Jitter in Clock and Control Circuits of Microprocessors illuminated with 2.62 GHz Microwaves.

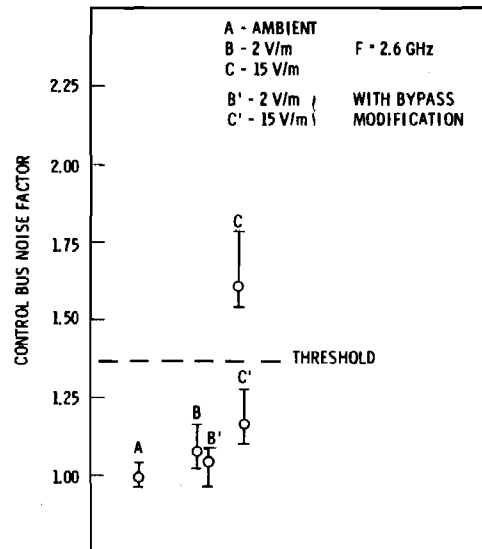


Figure 31. Increase in Microprocessor Control Bus Noise Caused by Microwave Illumination with and Without Mitigating Modifications.

Figure 32 shows the increase in memory transfer errors with increased illumination at the 2.6-GHz frequency. The memory transfer events in the I/O memory register were tracked to measure bit-per-second errors. An additional test with a 200 pulse per second modulation caused unacceptable performance at much lower illumination levels than the CW signals. This has little significance for SPS since the present proposed 2.45-GHz signal is CW. It does demonstrate the effects of pulse modulation interaction with clock, control, and data pulses. Pulse intermodulation events characteristic of medium level interfering levels ($P_{int} \geq 0.2$ clock, control data pulses) are not present with CW interference. For similar effects with CW interference, amplitudes sufficient to cause large bias shifts are required. The figure also shows results from a repeat of the above tests for commercial equipment using a complete wire mesh shield inside the various chassis. Much of the chassis material in modern packaging techniques is plastic. Most of these plastics exhibit very little attenuation of microwave signals. By using the wire mesh with a 9 mm by 9 mm grid size, with single point ground where possible, and completely surrounding the internal electronics, the coupling of the microwave signal was held to an acceptable level. Shielded coaxial cables were also used in place of unshielded or poorly shielded wires for intermodule connections carrying message and control information, further reducing microwave coupling into vital circuitry.

Figure 33 shows the throughput accuracy measured from input port to output port for a normal mini-computer operation when exposed to increasing microwave illumination. The data for cases B and C are given with respect to their proximity to the center of a rectenna site; C, being closer than B to the rectenna, would of course experience a higher exposure level. Twenty nautical miles would correspond to a field intensity of approximately 4 V/m, and 10 nautical miles from a rectenna center would correspond to 10 V/m.

The primary coupling modes for completely shielded modules are ground bus and interconnection cable shielding. Commercial modules exhibited greater susceptibility because of the reduced effectiveness of system shielding. This latter consideration increased susceptibility to direct circuit coupling through unshielded nonmetallic covers. Increased noise (30%-70% range) in unshielded FET circuitry relative to totally shielded was evident.

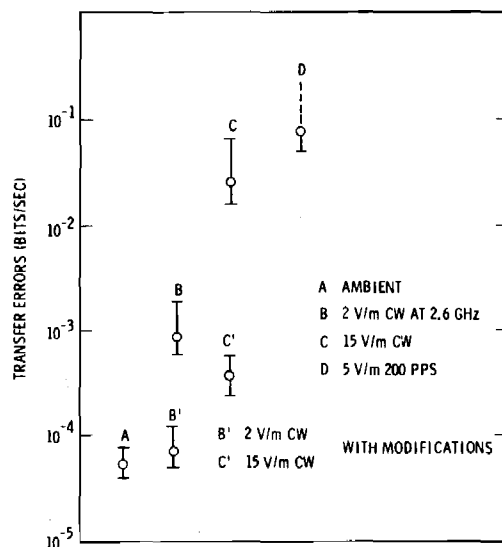


Figure 32. Memory Transfer Error in Microprocessors Illuminated with Microwaves with and without Mitigating Modifications.

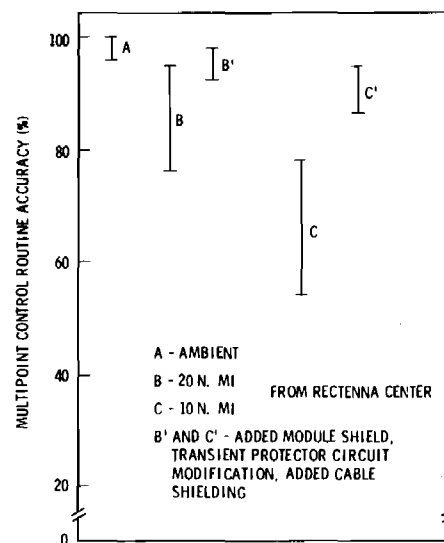


Figure 33. Computational Accuracy of Mini-Computers Illuminated by Microwaves with and without Mitigating Modifications.

4.4 INTEGRATED CIRCUITS

The susceptibility of integrated circuits was reviewed to support measurement planning, analysis of effects, specification of mitigation techniques for computer and control systems and large scale integrated circuits for signal processing in rf receivers and sensor systems.

Interaction between microwave energy and integrated circuits can occur in various ways. Catastrophic failures have been produced in integrated circuits with exposure to rf power levels in the 1 to 100 W range for 500 microseconds. These failures are typically due to bonding wire melting, metallization failure, and junction shorting. However, nondestructive interference generally occurs at power levels far less than those necessary for catastrophic failure.

The most important interference mechanism in integrated circuits is believed to be rectification of microwave energy by the various pn junctions found on all devices. This rectified current can inhibit or induce state changes or change the quiescent operating point of the device. Changes of quiescent operating point can be particularly harmful in noise environments and can reduce the noise immunity of the device.

Basic rectification theory states that the rectified current in a pn junction is

$$I_R = n p_{RF} \text{ (ABSORBED)} \quad (1)$$

where n is the rectification efficiency and p_{RF} is the rf power absorbed into the junction. The theory also tells us that in the microwave frequency range

$$n = \frac{n_0}{f^2} \quad (2)$$

where n_0 is a constant dependent on junction construction and bias conditions, while f is the frequency of the rf energy. That is, junction efficiency is inversely proportional to frequency squared.

This theory allows one to extrapolate measurements made at frequencies other than the SPS frequency of 2.45 GHz. Assume, for example, that a measurement is made at frequency f_1 , where the device absorbs a power p_{RF1} and produces a rectification current I_{R1} . Further assume that this is the level of current where interference effects are first noted (interference threshold). Thus one can write that

$$I_{R1} = \frac{n_o}{f_1^2} P_{RF1} \quad (3)$$

If the threshold measurement were made at a different frequency f_2 , one should expect that the same interference threshold would be reached when

$$I_{R1} = \frac{n_o}{f_2^2} P_{RF2} \quad , \text{ and} \quad (4)$$

$$\frac{P_{RF1}}{P_{RF2}} = \left(\frac{f_1}{f_2}\right)^2 \quad (5)$$

While these formulas are approximate, they do show that interference thresholds can be expected to vary as the square of frequency.

Measurements were made at 0.91 and 3.0 GHz on three types of integrated circuits, a 7400 bipolar NAND gate, a 4011 CMOS NAND gate, and a 5474 flip flop (Roe, 1975). Interference of various power levels was coupled directly into input, output, and power leads of the integrated circuits. The leads were appropriately biased and terminated to simulate normal operating conditions. These measurements are summarized in Table 5 where the interference threshold is defined as that point where deviation in the device normal or quiescent operating conditions are first noted. Note that these measurements were made on a number of devices of the same type and the values shown are representative of those devices that were most susceptible to interference.

TABLE 5. Summary of Interference Threshold Measurements on Integrated Circuits

Device	Measured Interference Threshold	Measurement Frequency	Estimated Interference Threshold 2.45 GHz
7400 NAND GATE	2 mW (3.0 dBm)	0.91 GHz	14.5 mW (11.5 dBm)
4011 NAND GATE	10 mW (10.0 dBm)	3.0 GHz	6.7 mW (8.3 dBm)
5474 FLIP FLOP	20 mW (23.0 dBm)	3.0 GHz	13.3 mW (11.2 dBm)

Before interference estimates can be made, the coupling between the SPS beam and the integrated circuit must be understood. This subject is effectively treated in a report by Ditton (1975), which examines the coupling of microwave energy into shielded and unshielded wires connected to various parts of an integrated circuit, including power supply connections.

The maximum power coupled into an integrated circuit by a connecting wire is given by

$$P_{RF}(\text{MAX}) = P_d \cdot A_e \times SE \quad (6)$$

where

$P_{RF}(\text{MAX})$ = coupled power in mW,

P_d = incident field density in mW/cm^2 ,

A_e = effective aperture of the connecting wire in cm^2 , and

and

SE = shielding effectiveness of any shielding around the wire.

In many instances, the connecting wire is more than $1/2$ wavelength long (a wavelength is 12.2 cm at 2.45 GHz), which means that it exhibits properties similar to an antenna. Thus, the wire can receive energy in a variety of orientations and directions depending on its length and the termination impedances of the wire. The received power will depend on the orientation of the wire in the field. The average received power $P_{RF}(\text{avg})$ is typically

$$P_{RF}(avg) = \frac{1}{10} P_{RF}(max), \quad (7)$$

Another point of interest in the theory of coupling of microwave energy is that the effective aperture, A_e , of a wire whose length is greater than $\lambda/2$ is approximately equal to the aperture of a $\lambda/2$ wave dipole or

$$A_e = 0.13 \lambda^2, \quad (8)$$

where λ is the wavelength of the incident field (Ditton 1975). Note that the effective aperture is not a function of wire length but only the wavelength of the incident field. Thus the absorbed power does not increase with increasing wire length.

The values of $P_{RF}(MAX)$ and $P_{RF}(AVG)$ that can be expected at various locations around the SPS rectenna are summarized in Table 6. This table assumes a shielding effectiveness of 10^{-4} (-40 dB) for shielded wire. Unshielded conditions are represented with a shielding effectiveness of 1.0 or 0 dB. Table 7 presents a summary for the three types of digital integrated circuits results. Forty decibels of shielding should effectively eliminate interference at the module level.

TABLE 6. Estimates of the Maximum Power $P_{RF}(MAX)$ and Average Power $P_{RF}(AVG)$ that can be Coupled into an Integrated Circuit through a Wire of Length Greater than $\lambda/2$

Location	Power Density Pd mW/cm ²	$P_{RF}(MAX)$		$P_{RF}(AVG)$	
		Unshielded	Shielded	Unshielded	Shielded
		dBm	dBm	dBm	dBm
Center of Rectenna	23.0	26.5	-13.5	16.5	-23.5
Edge Rectenna Center	1	12.8	-27.2	2.8	-37.2
Exclusion Fence 5.7 km from Center	0.10	2.8	-37.2	-7.2	-47.2
First Side Lobe 9.0 km from Center	0.08	1.9	-38.1	-8.1	-48.1
Second Side Lobe 13.0 km from Center	0.03	-2.4	-42.4	-12.4	-52.4
Third Side Lobe 17.0 km from Center	0.01	-7.1	-47.1	-17.1	-57.4

In summary, one can conclude that integrated circuits such as 7400, 4011 NAND gates and the 5474 flip flops could be interfered with in SPS field of 1 mW/cm² or greater. This conclusion is true only if the circuits are unshielded. Shielding of the circuits with a shielding effectiveness of 40 dB should eliminate the potential for interference even in fields of 23 mW/cm².

4.5 OPTICAL SENSORS

The high level of power transmitted by SPS could affect a wide range of optical devices used for security monitors, target tracking, communications, resource and atmosphere monitors, altitude control, and astronomy. These sensors are used at terrestrial sites in buildings and field locations, on military aircraft and missiles, high altitude research and surveillance aircraft, and LEO and GEO satellites. Sensors include electron tubes and semiconductors, used singly and in imaging matrices.

Primary applications of optical sensors are:

1. Astronomy-spectrometry, photometry, and telescope control.
2. Space vehicles - astronomical instrumentation, attitude control, secure wideband communications, and terrestrial surveillance and monitoring.

TABLE 7. Summary of Susceptibility of 3 Types of Unshielded Integrated Circuits to 2.45-GHz SPS Interference

Location	Power Density pd mW/cm^2	7400 NAND GATE	4011 NAND GATE	5470 FLIP FLOP
Center of Rectenna	23	Exceeds Threshold, Max and Avg Orientations	Exceeds Threshold, Max and Avg Orientations	Exceeds Threshold Max and Avg Orientations
Edge of Rectenna	1	Exceeds Threshold, Max Orientation Only	Exceeds Threshold, Max and Avg Orientation	Exceeds Threshold Max Orientation Only
Exclusion Fence 5.7 km from Center	0.10	Below Threshold	Below Threshold	Below Threshold
First Side Lobe 9.0 km from Center	0.08	Below Threshold	Below Threshold	Below Threshold
Second Side Lobe 13.0 km from Center	0.03	Below Threshold	Below Threshold	Below Threshold
Third Side Lobe 17.0 km from Center	0.01	Below Threshold	Below Threshold	Below Threshold

3. Airborne platforms - astronomical instrumentation, navigation, terrestrial surveillance and monitoring, and secure communications.
4. Target tracking - multiple staring image systems on fixed pedestals, scanning cameras aiding radar and hyperbolic systems.
5. Security and intrusion alarms - scanning detectors to detect fixed or moving images; classification/identification based on image presence, spatial features, and frame-frame vectors, and spectral features used when visual and one or more IR bands combined in the detection criteria.
6. Target detection and guidance - military target detection using scanning or staring sensors (single or multiple spectral bands), and provision of angle track data for weapon guidance.

Normal inputs to an image sensor system (Figure 34) are the target image and the background noise. The SPS illumination can couple into the optical aperture, any physical apertures such as cooling holes and louvers, plastic cases and unshielded cables, and control lines and supply coupling. Open circles on the diagram at the scan control, video circuit output, and power circuits indicate the signal to interference (S/I) scoring points. The S/I scoring parameters included SPS induced video noise, scan jitter, and related spatial resolution, and dynamic range effects. Bar targets with a maximum resolution of 2000 lines per inch were used for testing the visual scanners. The IR bar targets include reflectance elements in the optical range 2 to 6 microns with a resolution of 1000 lines per inch, and differential temperature targets for thermal sensors from 8 to 13 microns with a resolution of 800 lines per inch.

Specific sensor types tested are listed.

1. Vidicon and plumbicom cameras.
2. Orthicon cameras.
3. Forward looking infrared receivers (FLIR).
4. Image dissector tube.
5. Charge coupled device (CCD) matrices.
6. Photomultiplier tubes - in cassegrain telescope applications for star tracking and photometry.

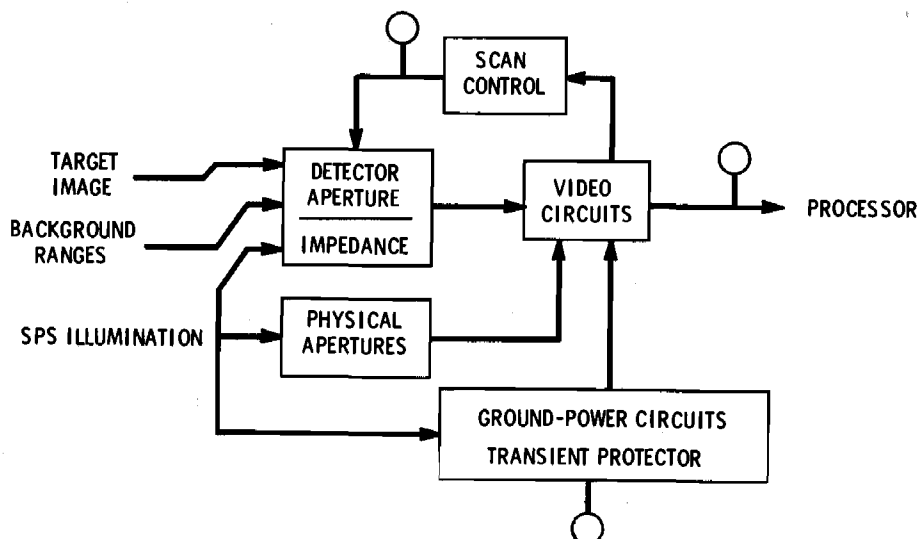


Figure 34. Generalized Block Diagram for EMC Evaluation of Optical Sensor Systems. Circles identify evaluation points.

Energy penetration into optical sensors is primarily through optical apertures, gaps in metal enclosures that exceed 7 to 12 cm in any dimension, and unshielded module interconnections. Vidicon or orthicon cameras and photomultiplier detectors permit coupling into electron tube anodes and collector surfaces, and into high impedance video and signal amplifiers which are generally collocated with the detector tubes. (These amplifiers are moderate to high gain - bandwidth product circuits using FET circuits in the input stage.) Jitter in scan circuitry results from energy coupling into sync and sweep oscillator circuits from the control gates and matching amplifiers with common interconnections between video and scanning modules, and through common ac return circuits having an effective impedance in the range of 100Ω. Coupling to staring and scanning IR detectors occurs by direct exposure of the semiconductor detectors and wideband-moderate gain matching circuits and video amplifiers. Optical filters provide no useful attenuation of microwave energy penetrating the optical aperture. As indicated in the performance data, increased video noise and reduced spatial resolution are the primary effects.

Specific effects for the various sensors are indicated in Table 8.

TABLE 8. Interference Effects for Optical Sensor System.

<u>SENSOR TYPE</u>	<u>INTERFERENCE COUPLING</u>	<u>RESPONSE EFFECTS</u>
Vidicon-Plumbicon Orthicon	Video Amplifier Scan Generator Sensor Collector	Video Noise Scan Line Jitter Reduced Sensitivity Reduced Resolution
Image Dissector	Video Amplifier Sensor Collector	Video Noise Reduced Sensitivity Increased Track Error
CCD Matrix	Video and Gate Amplifiers Matrix Detectors	Video Noise Reduced Sensitivity Reduced Resolution
Photomultiplier	Sensor Collector Video Amplifier	Reduced Sensitivity Video Noise
FLIR - IR Semiconductor DET	Sensor Detector Video Amplifier	Video Noise Reduced Resolution

Figure 35 shows a typical level of degradation in spatial transfer function of a vidicon camera subject to microwave illumination. With illumination by a 10 V/m, 2.6-GHz signal the relative amplitude degraded as shown by the lower curve of the figure. This affects the ability to detect object movement from frame to frame as time snapshots are received from a target, degrades the ability to identify targets quickly and increases the false-target or missed target probabilities.

Figure 36 shows degradation of the total imaging characteristic as a function of distance from the center of a rectenna. These data cover a number of both TV and IR scanning, high resolution sensors, and they represent degradation from induced video noise, scan jitter, spatial resolution and dynamic range due to simulated SPS illumination. The B and C cases indicate that the overall degradation increases dramatically from 20 n mi to within 10 n mi of a rectenna site. The distances correspond to illumination levels of 4 V/m for 20 n mi and 10 V/m at 10 n mi. A typical ambient and interference illuminated response for a CCD row is presented in Figure 37. Resolution and sensitivity effects are indicated. Representative signal noise data for a photomultiplier tube under ambient and one interferon illumination level is plotted in Figure 38. Exemplary illumination effects on an image dissector are indicated in Figure 39.

Most TV and IR sensor systems should not be seriously affected if sited beyond 50 km from a rectenna site depending on how accurate the resolution must be. Certain extremely sensitive military applications may require a distance of 50 to 75 km.

4.6 MEDICAL ELECTRONIC DEVICES

To assess the possibility of adverse SPS electromagnetic interference with medical electronic devices, an exhaustive literature search was conducted and contacts established with manufacturers, testing organizations, and government agencies concerned with EMC standards.

The initial analysis focused on cardiac pacemakers, patient telemetry, and the electronic instrumentation associated with mobile clinics and emergency vehicles (EKG, EMG, and possibly EEG). Federal health agencies are planning mobile and remote diagnostic facilities to expand preventative medical services. Since rectennas will be sited so as to avoid urban areas and thus most hospitals, these clinical facilities are the areas of medical electronics most subject to SPS interference.

4.6.1 Cardiac Pacemakers

Based on their immediate importance to cardiac patients, the large numbers now in use, and the fact that interference related failures have been observed, it is clear that cardiac pacemakers are prime subjects for a study of compatibility with the SPS power beam. Pacemakers are classed as asynchronous or synchronous. The asynchronous pacemakers pulse in response to internal circuit control and are relatively insensitive to external electrical stimuli. The synchronous or demand pacemakers pulse in response to small electrical stimuli from the user's body and are therefore more susceptible to small external electrical stimuli.

Failures related to interference (failure to pulse within design specifications) in demand pacemakers have been attributed to such diverse rf sources as radar, small electrical appliances, lightning strokes, microwave ovens, and motor vehicles. To identify potential hazards for pacemaker users, the frequency, field intensity and modulation of rf sources that cause failures must be quantified. Fortunately, many pacemakers have been laboratory tested, and it is now possible to identify important trends in the thresholds of failure of pacemakers as a function of frequency, field intensity, and modulation. These trends aid in evaluating the potential adverse effects of the SPS power beam to pacemakers.

Table 9 indicates the test conditions employed in establishing levels of potential hazards for pacemakers. Very early work on highly specific testing has been omitted here in favor of later work which tends to identify important trends.

The field intensities or thresholds at which demand pacemakers malfunction increase with frequency. For example Mitchell and Hurt (1975) found that the average threshold increased from less than 50 V/m at 450 MHz to nearly 600 V/m at 3200 MHz even when the pulse rate and width of the test source were maintained constant (Figure 40). This observation is qualitatively supported by some earlier work (Figure 40) of Bonney et al. (1973), which shows that the potentially hazardous field intensity level increases from about 75 V/m at 915 MHz to 250 V/m at 2810 MHz. Since the SPS power beam is at a 2.45-GHz frequency and the field intensity outside the receiving area is expected to be less than 20 V/m, pacemakers are not likely to be affected by the SPS power beam.

Pacemakers are more likely to fail in low frequency pulsed rf fields as opposed to cw fields. Data taken by Mitchell and Hurt (1975) indicate that the average failure threshold decreased from 117 V/m at a pulse width of 10 μ s, to 33.8 V/m at 1 ms and to 18.6 V/m at 20 ms, when the PRF and frequency were constant. Denny et al. (1977) found that failures are more likely to occur if the rf source is pulsed at a rate of 10 PPS or less. Some demand pacemakers, by design, revert to an asynchronous mode of pulsing if they are subjected to an intense rf source pulsed at a high rate.

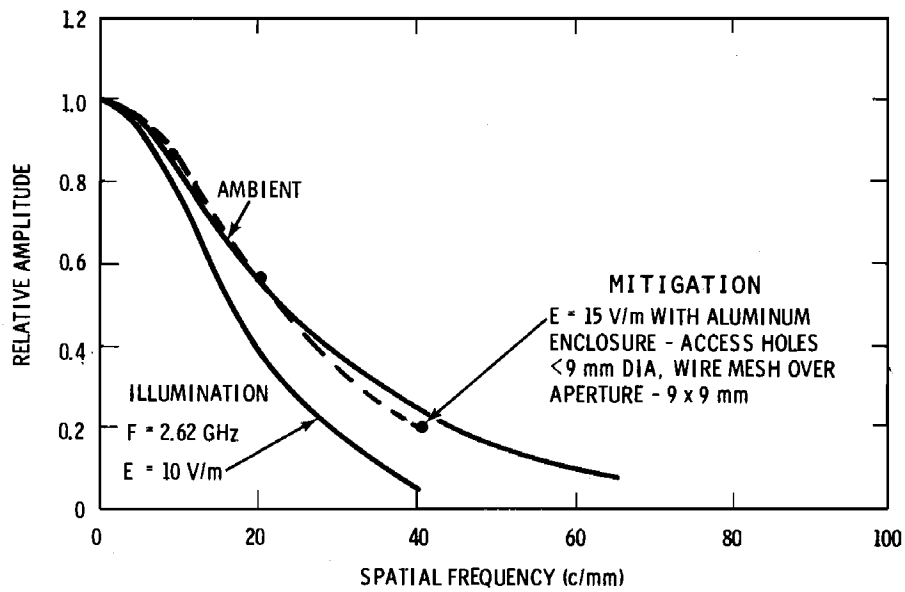


Figure 35. Effect of Microwave Illumination on MTF of a Vidicon Camera with and without Mitigating Modifications.

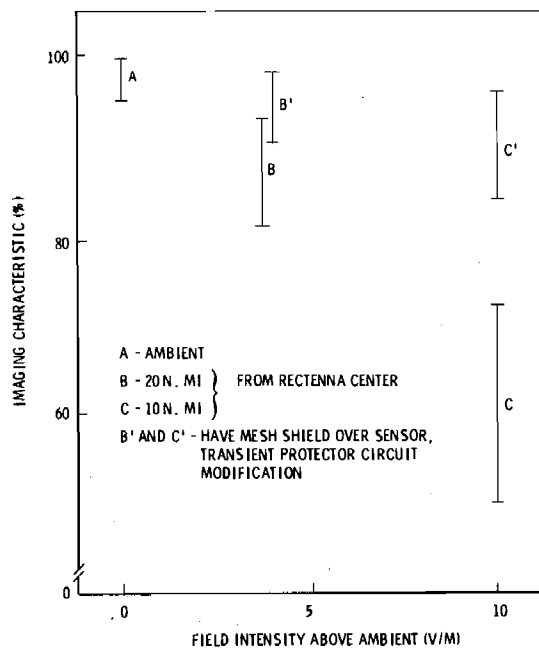


Figure 36. Degradation in Performance of High Resolution TV and IR Scanning Sensors with and without Mitigating Modifications.

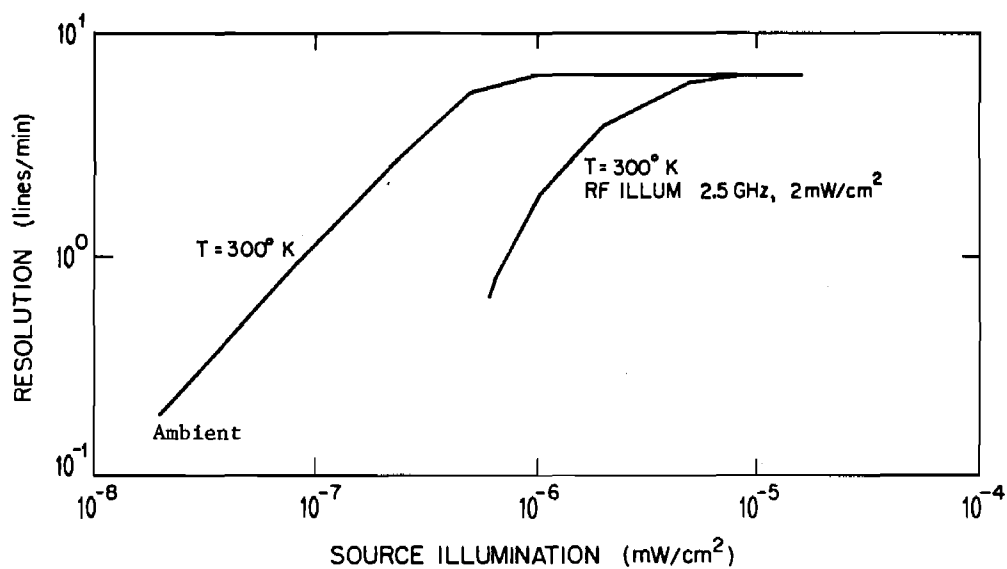


Figure 37. Representative CCD Response Characteristics

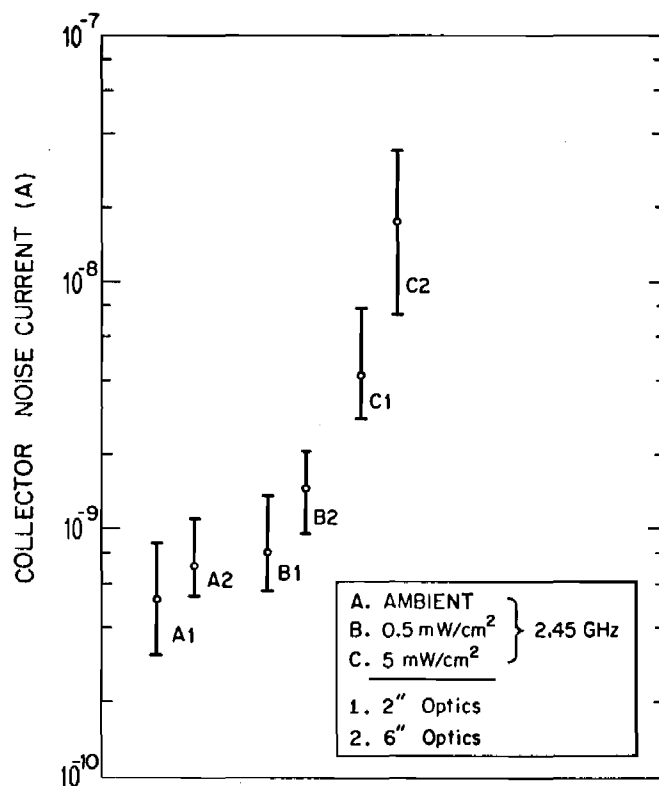


Figure 38. Photomultiplier Response Characteristics (10 dynode tube)

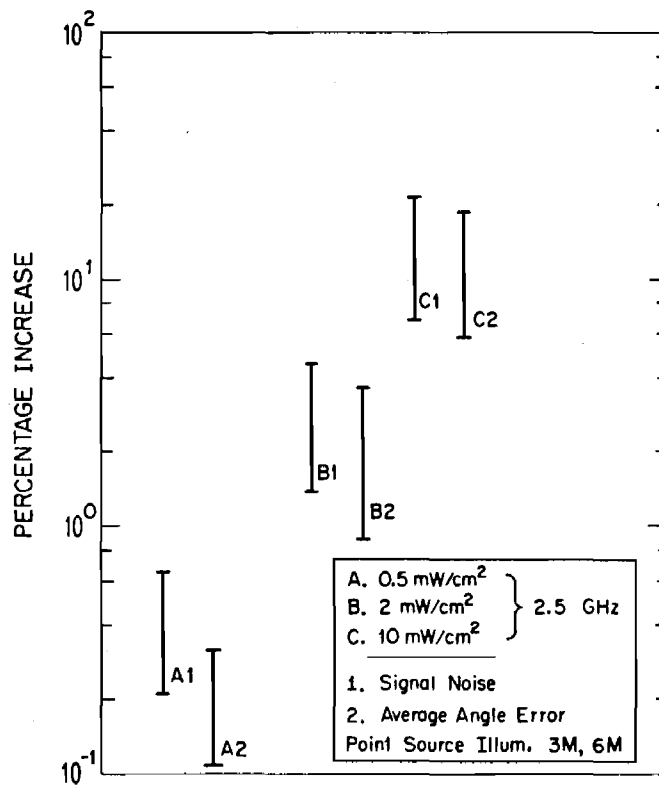


Figure 39. Image Dissector Sensitivity Characteristics

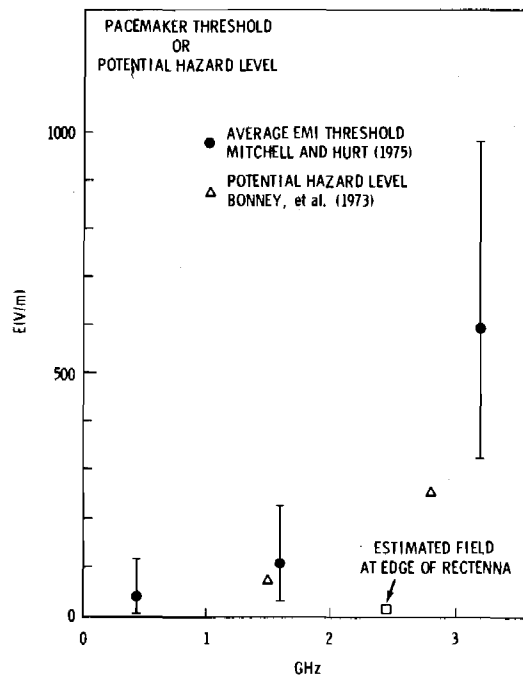


Figure 40. Observed Interference Levels for Cardiac Pacemakers as a Function of Frequency.

TABLE 9. Pacemaker EMC Test Parameters^a

FREQUENCY (MHz)	PULSE WIDTH (m sec)	MODULATION
450 (1),(2)	0.01 (1)	CW (2)
915 (2)	0.02 (1)	120 Hz Sine Wave (2)
1600 (1)	0.05 (2)	120 Hz Square Wave (2)
2810 (2)	0.50 (1)	TEST
3000 (3)	1.0 (1)	ENVIRONMENT
3050 (2)	1.5 (2)	Air (3)
	2.0 (1)	Implanted (2),(3)
PULSE REPETITION	5.0 (1),(2)	Simulated (1),(3)
FREQUENCY (PPS)	7.0 (2)	Simulated (1),(3)
2 (3)	10.0 (1)	Implant
10 (3)	20.0 (1)	
20 (3)		
120 (2)		
300 (2)		
	OBSERVERS	
	(1) Mitchell & Hurt (1975)	
	(2) Bonney et al. (1973)	
	(3) Denny et al. (1977)	

^aNo particular combination of test parameters should be inferred from this table.

The existence of EM effects on pacemakers has been well-known for several years. As a result researchers have identified interfering EM sources and manufacturers have worked to desensitize the devices against those sources of EMI that users might encounter. The success of these manufacturers' efforts is reflected in a study by Denny et al. (1977). This 5-year study, involving hundreds of pacemakers, showed that the average susceptibility threshold of pacemakers to a pulsed 450-MHz source increased from 35 V/m in 1973 to 144 V/m in 1976.

Workers in the pacemaker industry and researchers generally believe that continuous wave emitters are highly unlikely to produce EMC related failures but only limited testing with cw sources has been documented. Bonney et al. (1973) found a continuous wave source at 915 MHz to cause failures if the field intensity were 75 V/m or more. Since the vulnerability of pacemakers decreases at the higher frequencies, they are not likely to be affected in the 2.45-GHz field of 19 V/m or less expected outside SPS rectenna areas.

4.6.2 EMC Standards for Medical Electronic Devices

The general class of medical electronic devices contains many sensitive instruments likely to be susceptible to EMI. The electrocardiograph, for example, is vulnerable to 60-Hz line interference (Huhta and Webster, 1973). Medical devices are used most often in clinics and hospitals in large metropolitan areas. A wide variety of transmitters, appliances and medical electronic devices are likely to contribute to the electromagnetic environment in hospitals.

Diagnostic instrumentation such as electrocardiogram (EKG), electromyogram (EMG), and electroencephalogram (EEG) devices include high-gain (60-70 dB), dual-channel amplifiers, with a maximum bandwidth in the 20-Hz to 50-kHz region. Noise induced in ground paths and into each channel (uncorrelated) reduces the detail in the cardiographs and myographs. Input amplifiers are usually cascade FET circuits, which amplify input circuit and ground path noise, and with higher gain modes reduce the dynamic range of following amplifier stages because of rectification and bias shifts partially induced by intermodulation components. These devices use circuit shields and power-line filters to operate in the vicinity of electro-surgical and diathermy equipment.

The Bureau of Medical Devices at the Food and Drug Administration has supported a study of electronic devices and the ambient electromagnetic environment in several major hospitals. The results of this study establish guidelines for acceptable emissions from medical devices and safe susceptibility thresholds. These guidelines were published in the report "EMC Standard for Medical Devices," MDC-E 1609, (1976). The guideline for minimum radiated electric field susceptibility from the report is shown here as Figure 41. It covers frequencies from 100 kHz to 1 GHz. The existing guideline for electric field susceptibility at 1 GHz would permit the manufacture of devices with thresholds (~ 7 V/m) that are lower than the field intensities expected near the SPS receiving area (19 V/m). No data are indicated above 1 GHz, although a higher susceptibility threshold is expected since the susceptibility of electronic devices generally decreases with increasing frequency.

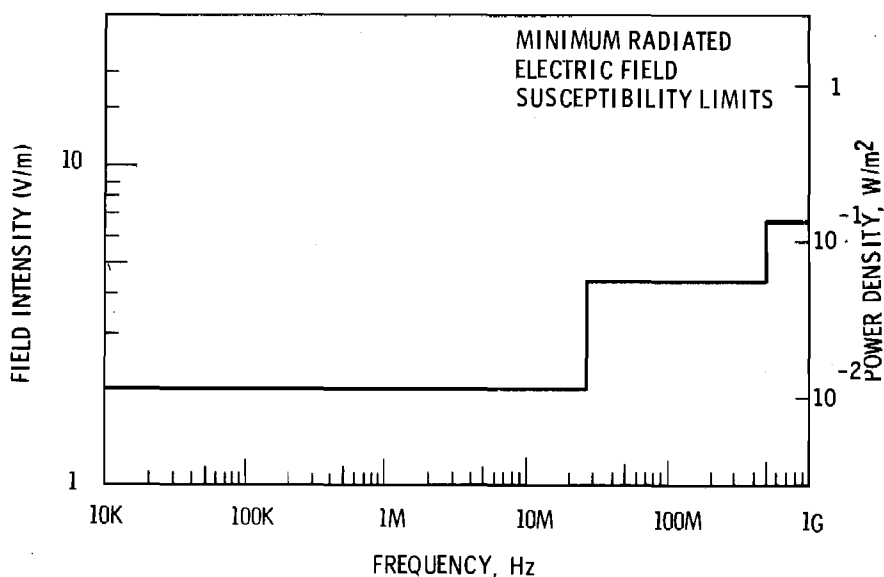


Figure 41. Permissible Interference Levels for Electronic Medical Devices (per MDC-E 1609).

4.6.3 Conclusions

Demand pacemakers' susceptibility thresholds are rapidly increasing because of design improvements, and at ultra-high frequencies the average threshold can be in the range of hundreds of V/m. It thus seems unlikely that pacemakers should fail as a result of the weak SPS-cw power beam outside the receiving areas. The existing guidelines for electric field susceptibility for medical devices recommends a susceptibility threshold of not less than 7 V/m for frequencies between 0.5 and 1.0 GHz. No limits are given, however, for frequencies above 1 GHz. This value is lower than the approximately 19 V/m field intensities expected near an SPS receiving site. The susceptibility of implanted electronic devices generally decreases with increasing frequency; therefore no adverse effect should occur outside a range of 10-15 km from a rectenna. Clinical instrumentation can also operate in the same range with facility shielding similar to that employed for the ordinary radio frequency screen room.

5.0 SYSTEM INVESTMENT SUMMARY

The electronic systems exposed to SPS microwave power represent a major investment by industries and government agencies. One task of the EMC Assessment was to collect data on the current investment in categories of communications and electronic equipment and systems identified as potentially susceptible to SPS interference, and collect budget information on planned enhancements or facility expansion in these services during the next 5-10 year period. System categories include public service communications, transportation radars and communications, commercial service communications, and military support instrumentation and communications systems.

The EMC guidelines developed in the EMC Assessment indicate both the techniques for the design of communications and electronic systems to operate in the SPS environment and the verification testing methods to ensure compatibility. Any costs associated with the future utilization of these techniques for future system development could be included in the life-cycle costs of these systems. The mitigation and investment costs for the various system categories and geographic regions also influence rectenna siting, albeit with less weight than other economic factors (e.g., land availability, distribution access, transportation access, etc.).

Data listed for current investments were obtained from federal and nonfederal government, industrial, and commercial operations organizations. Military operational equipment is not included in this summary.

Major source areas are listed.

1. Military test and evaluation ranges.
2. U. S. Department of Transportation.
3. U. S. Department of Interior.
4. National Science Foundation.

5. Radio and optical astronomy facilities.
6. U. S. operating railroads.
7. Communication common carrier companies.
8. State and County government communications departments.
9. Utility and pipeline companies.
10. NASA and Air Force satellite system project offices.

These data and projections are included in a topical report on investment and mitigation costs. In the case of satellite communications, these data recognize the anticipated transition to the 12/14 GHz and 20/30 GHz regions, and the incorporation of signal processing and switching operations into the orbit vehicle. Mitigation costs are based on circuit, antenna, and shielding modifications to accommodate the SPS environment.

Investment Data for Affected Categories of Electronic Systems

<u>System Category</u>	<u>Investment</u> (\$ x 10 ⁶)-1980 dollars
General Service Communications	\$1,700
Terrestrial communications networks	
Satellite terminals	
Dedicated Service Communications	\$1,200
State backbone networks	
County microwave systems	
Railroad microwave networks	
Utility/pipeline command/control & telemetry networks	
Air traffic control networks	
Radar Systems	\$500
Air traffic control	
Railroad hump control	
Military T&E	
Sensors	\$30
Railroad hot base detectors	
Railroad car identification	
Military T&E	
Resource monitors-terrestrial, aircraft, satellite	
Control-Processing Computers	\$300
Remote radar-communications control	
Utility-pipeline remote control and data processing	
Resource monitor/control - watershed monitor and water storage, meteorological stations, pollution monitoring	
Research Support Systems	\$80
Deep space tracking station	
Radio astronomy facilities	
Optical telescope guidance	
Astronomy instrumentation	
Satellite Vehicles	\$400
Monitor and control instrumentation transponder	
Total Current Investment Estimate	\$4210

6.0 MITIGATION SUMMARIES

Techniques to mitigate SPS microwave field effects on electronic equipment were described in Section 4. Test results for simulated SPS illumination both of systems in their original condition and as modified to reduce interference susceptibility were given for a number of systems. This section summarizes the nature and scope of mitigation measures, either equipment modification or geographic separation, that would be required in achieving electromagnetic compatibility between SPS and electronic systems.

6.1 COMMUNICATIONS RECEIVERS

Techniques to remove SPS interference from communications receivers include removal of the interferor from the signal channel, and the other inadvertant coupling modes to circuitry and through ground bus components (reference Figure 18). The methods listed are designed to ensure a 30-40 dB discrimination,

which will allow receiver operation with SPS power densities equal to that expected at the edge of a rectenna.

1. Notch filter at the antenna terminals.
 - a. Rejection bandwidth: 5 to 20 MHz.
 - b. Attenuation: 70 to 80 dB.
 - c. Insertion loss: < 1 dB.
 - d. Ripple peaks: 1 to 2 dB.
2. Shielding and grounding.
 - a. All nonmetallic openings or gaps in the enclosures < 1 cm in the largest dimensions.
 - b. Dual shielded signal and control cables for rf and signal processing modules.
 - c. Single point grounds $R < 0.1 \Omega$
 - d. Shield cover for transient protector devices; bypass capacitors ($C \sim 50 \text{ pf} - 200 \text{ pf}$) across the protector device.
3. Software controlled squint for a phased-array antenna system.
 - a. Interference rejection - 60 to 80 dB, assuming one principal reflection multipath component in addition to the direct beam. The tracking bandwidth must be $\sim 20 \text{ Hz}$ to accommodate troposphere-induced, small-angle variations in the direction(s) of arrival of the interferor components.

With the exception of the array application, these techniques were tested with FDMA and TDMA receivers. The rejection achieved allowed restoration of a 95% to 99% performance level in relation to receiver signal-noise ratio, data error rate, and signal acquisition characteristics.

Consumer electronic equipment such as television and other VHF microwave receivers often have only plastic enclosures. If these equipments are operated within 10 to 15 km of a rectenna site, conductive foil or paints could be added to the interior surfaces of the enclosures to reduce interference.

6.2 MINICOMPUTERS AND MICROPROCESSORS

The mitigation techniques listed will allow full performance restoration for centralized or distributed processors when operated at field intensities expected at the edge of the rectenna.

1. Enclosure shielding with nonmetallic openings < 1 cm in the largest dimension.
2. Louvers for temperature control should have a wire mesh (< 1 cm openings) covering the open area.
3. Dual shielded message and control cabling.
4. Single-point grounding ($R < 0.1 \Omega$).
5. Shielding of transient protectors with capacitor bypass ($C \sim 50 \text{ pf} - 200 \text{ pf}$).

6.3 OPTICAL SENSORS

The techniques recommended for optical sensors are listed.

1. Dual shielded cabling for video and control cabling.
2. Single-point grounding ($R < 0.1 \Omega$).
3. Shielding and bypass of transient protector devices.
4. Shielded enclosures with nonmetallic openings < 1 cm in the largest dimension.
5. For visual range sensors with focused optics, a thin wire mesh (38-42 guage copper wire diagonal < 1 cm) positioned at a defocused point with mesh connected to electrical ground.

6.4 RADAR RECEIVERS

Radar receiver mitigation techniques are functionally identical to those indicated for communications receivers.

One test was completed for the software driven squint technique using a military phased array tactical radar. With a minor modification of the array-control signal filtering software, a null in the range of 30-40 dB could be achieved with the media-induced angle-of-arrival modulation in the 1-10 Hz range on the interferor. This software mitigation method represents a viable and cost-effective method for phased array systems having adaptive capabilities in array control, signal bandwidth, and modulation format.

The methods listed below provide effective mitigation for SPS frequency interference to a level of 20 mW/cm² for the radar systems tested.

1. Input notch filter - (between antenna and first mixer).
 - a. Rejection bandwidth: 5 to 20 MHz.
 - b. Attenuation: 70 to 80 dB.
 - c. Insertion loss: < 1 dB.
 - d. Ripple peaks: 0.5 to 1 dB.
2. Shielding and grounding.
 - a. All nonmetallic openings or enclosure gaps < 1 cm largest dimension.
 - b. Dual shielded signal and control cables for rf and signal processing modules
 - c. Single-point grounds $R < 0.1\Omega$
 - d. Shield cover for all transient protector devices.
 - e. Low pass filter between transient protectors and external rf coupling aperture(s).
3. Array beam squint - phased array/computer controlled radar.
 - a. Software controlled squint for SPS interference - effective attenuation 40-60 dB, depending on array characteristics.
 - b. Rejection notch filter (only for airborne or satellite systems exposed to SPS main beam).

6.5 GEOGRAPHIC SEPARATION

Although most equipment can be modified to operate in the microwave fields expected from SPS, systems having critical relationships to public safety or national security should be protected by separation from rectenna sites. Typical operations for which separation is recommended include air transportation control, military operations evaluation areas, sensitive power generation and nuclear fuel processing facilities, and research facilities requiring the most sensitive radio frequency receivers or electro-optical detectors. The list below shows recommended separation distances between SPS rectenna sites and sensitive facilities. These separation constraints have been included in rectenna siting studies.

Recommended Geographic Separation between SPS Rectenna Sites and Sensitive Facilities

<u>Separation</u>	<u>Facility</u>
50 km	Nuclear Power Plant Nuclear Fuel Processing Nuclear Research Optical Astronomy Observatory
60 km	Military Development Test and Evaluation Air Traffic Control Radar
100 km	Air Defense Ballistic Missile Defense Deep Space Communication
150 km	Radio Astronomy Observatory Military Operation Test and Evaluation

The facilities in the 50 km separation category would utilize EMC shielding and protection procedures recommended as a result of this program for modules and systems. The indicated nuclear facilities include complex instrumentation systems that are serviced and calibrated frequently, and have a high sensitivity to public safety and performance criteria. Separation from an SPS rectenna site will eliminate the possibility of illumination levels sufficient to cause instrument actions contributing to intolerable safety risks and unstable operation. Optical astronomy facilities located at a minimum distance from a rectenna site will have no possibility of degraded operations for data collection instruments (photometers, spectrometers) and telescope guidance sensors if the mitigation recommendations are followed for sensors and circuitry.

The separation distances for military facilities and deep space communications equipment (60 km, 100 km, 150 km) are based on system susceptibilities to SPS fundamental and harmonic components. Mitigation techniques are not recommended for military facilities because unacceptable performance might result in operation in real military scenarios.

Radio astronomy receivers present major uncertainties in practical SPS interference mitigation. Sensitivity and bandwidth parameters present serious constraints for using in-channel rejection filters. Signal nulling techniques appear to offer promise since no device would be required directly in the signal channel. These considerations require that radio astronomy receivers be located at a distance to assure minimum coupling, and minimum separations of about 150 km. The identified mitigation requirements are: a rejection capability of 60-80 dB, a dynamic range of at least 30 dB, and a nulling error of less than 10^{-6} regardless of separation distances.

7.0 ALTERNATE FREQUENCY ANALYSIS

The Industrial Scientific and Medical (ISM) band at 2.40 to 2.50 GHz has been chosen in the Reference System design for the power transmission frequency. This is a logical choice but is not the only possibility. The major considerations on the frequency choice are:

1. Efficiency of power transfer through the atmosphere.
2. Interaction with the ionosphere.
3. Technological feasibility, i.e., the ability to efficiently convert DC to the frequency and recover it at the rectenna.
4. Electromagnetic interference to other systems, and
5. Size of required transmitting and receiving antennas.

Interaction of the power beam with the ionosphere has been the primary topic of Task 4 of the SPS CDEP Environmental Assessment. We will only note here that the power beam can both be influenced by the ionosphere and modify the ionosphere by transferring energy to it. The latter effect in particular is of major concern because it may determine the upper limit on microwave power density in the beam and thus the size of the rectenna array required to receive a given amount of power. The power beam cannot be allowed to modify the ionosphere to the extent that communications using the ionosphere, or the power beam itself, are disrupted. Transfer of power from a microwave beam to the ionosphere is highly frequency-dependent, decreasing with the square of frequency. If the ionosphere were the only concern, the desire to increase power density and thus minimize rectenna area would suggest the use of higher frequencies.

The use of higher frequencies would also allow a smaller satellite transmitting antenna to produce the same power density at the earth or allow higher power densities, and thus smaller rectennas, for a given transmitting antenna size. In general, the antenna sizes required are inversely proportional to the frequency used.

The higher microwave frequencies, from roughly 10 GHz upward, are also now less extensively used than lower frequencies. An MPTS operating above 15 GHz would thus be less likely to interfere with communication and other services as its spurious emissions, particularly harmonics, would occur at less used frequencies. Greater use of higher frequencies is expected however as technological advances make them more accessible and as the need for more channels continues to grow.

Interaction of microwave power from the system with other electronic equipment would also generally be expected to be somewhat reduced, although the size of apertures in shielding would have to be reduced, proportional to wavelength, to block the higher frequencies effectively.

The major constraint on the use of higher frequencies for the MPTS is the microwave propagation characteristics of the earth's atmosphere. There are three propagation effects of concern: clear air absorption, scatter by solids- notably rain or hail, and refractive anomalies. Clear air absorption is caused by molecules in the atmosphere, principally water and oxygen. Absorption in the 15- to 30-GHz range is due largely to water vapor and is thus dependent on altitude and humidity. For a typical rectenna site in a temperate climate, with an elevation angle of 30° to the SPS structure, clear air attenuation would cause about 1.6% loss of power at 2.45 GHz but 4% to 10% at 20 GHz, depending on humidity. Above about 50 GHz, absorption by atmospheric oxygen becomes severe, producing 25% or greater absorption for the same geometry. (For more information, see CCIR Report 719.)

Rain, hail, and other particles such as sand or dust in the atmosphere can absorb and scatter microwave energy from the SPS power beam. A study of power loss from the microwave beam as a function of rectenna site and frequency has been made by Ott and James (1980). Calculated values of this loss or attenuation for four rectenna sites are shown in Figure 42 for frequencies from 2.45 to 50 GHz. The rain-rate data on which the calculations are based are given below.

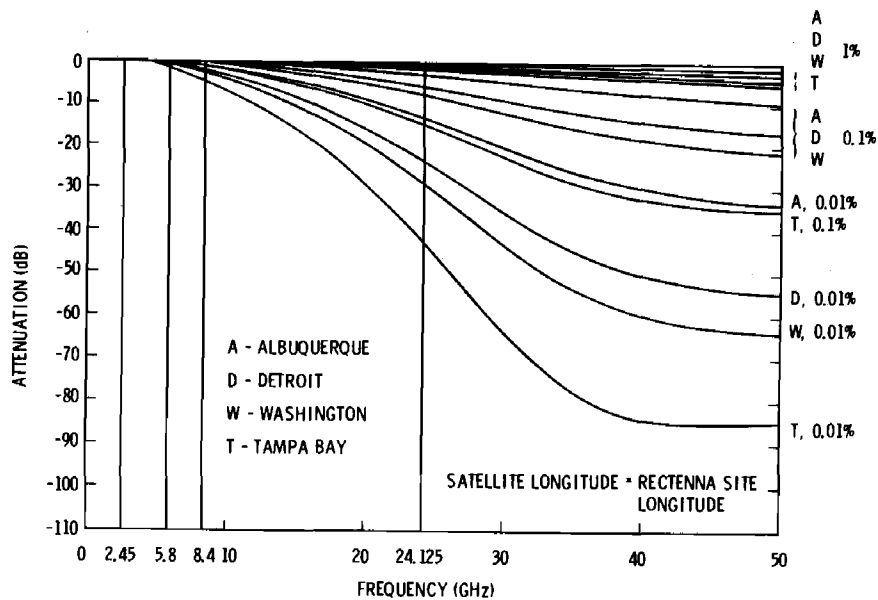


Figure 42. Predicted Atmospheric Attenuation as a Function of Frequency for Four Rectenna Sites. Attenuation would be expected to exceed the values shown for no more than the percent of a year indicated for each set of curves.

Rain Rate Distribution (mm/hr) Versus
Percent of Year Rain Rate is Exceeded

	0.01%	0.1%	1.0%
Albuquerque, NM	23	5	0.8
Detroit, MI	37	11	2.2
Washington, DC	49	15	3.0
Tampa Bay, FL	98	35	4.0

Note that the vertical scale of Figure 42 is logarithmic—10 dB attenuation corresponds to a 90% loss of power, 20 dB to 99% loss. The vertical bars mark higher frequency ISM bands which are potentially favorable candidates for MPTS frequency assignments.

A calculation of the attenuation expected due to a dust or sandstorm was performed by ITS using the theoretical scatter and absorption of small spherical particles and the known dielectric constants of sand and clay. The results show very little effect on power transmission to the rectenna.

It is important to realize that rain or other particles remove power from the microwave beam predominantly by scattering, i.e., dispersing it over a wider area. This would aggravate EMC problems within 100 km of rectenna sites by increasing the microwave field strengths in these areas.

The index of refraction of the lower atmosphere at microwave wavelengths is a function of atmospheric density, which is directly related to temperature and water vapor content. Gradients in refractive index are observed on a wide range of temporal and spatial scales: from hours and miles for storms or weather fronts to minutes or seconds and meters for radar "angels". Deflection or scattering from the microwave power beam due to refractive anomalies is not expected to contribute directly either to EMC problems or significant power losses. There is concern, however, that their presence could adversely affect the power beam control system and thus degrade beam forming or pointing, which would have the same effects as rain scatter. Higher microwave frequencies would be more sensitive to rapid, small-scale anomalies and thus might present a more complex control problem.

In summary, ionospheric effects, scaling of antennas and, to some extent, interference considerations suggest the use of higher frequencies but microwave propagation effects in the lower atmosphere present some serious problems above about 5 GHz.

8.0 MOJAVE SITE ANALYSIS

Early in the SPS CDEP a site in the Mojave Desert was identified by NASA Marshall Space Flight Center as a hypothetical rectenna location for study purposes. An initial exercise in the EMC Assessment addressed this site in order to demonstrate the importance of EMC considerations in site selection.

Figure 43 shows the Mojave site and the surrounding area that would be affected by SPS emissions outside the rectenna exclusion area. The inner ellipse corresponds roughly to the foot print of the main beam. The outer ellipse is roughly 78 km east-west by 100 km north-south and corresponds roughly to the smoothed pattern of Figure 44. Figure 44 shows a smoothed estimation of the EM energy from boresite to 50 km for the SPS main beam using the 10 dB taper. (To convert V/m to mW/cm² use: $\text{mW/cm}^2 = (\text{V/m})^2 / 3770$). For a perspective on the amount of energy beyond the rectenna site due to side lobe structure, note that field intensities measured at an antenna are given in microvolts per meter ($\mu\text{V/m}$) for communications systems. For high-power televisions or AM or FM broadcast stations, the field intensity beyond a mile, but within a few tens of miles, may be measured in millivolts per meter. The field intensity measured at the home antenna for the average TV owner would be in the microvolt per meter range. Many communication system receivers also have V sensitivities. Thus SPS represents a large input to communication systems operating within 100 km of the rectenna site. In addition to the field due to sidelobe structure, microwave power will be scattered from the main beam by propagation effects.

8.1 APPROACH

The potential effects of SPS illumination on the performance of electromagnetic and electronic systems operated within 150 km of the hypothetical Mojave rectenna site were evaluated. A retrieval from the NTIA Spectrum Allocation and Assignment files and from FCC commercial license records were used to identify electromagnetic systems in operation in the vicinity of the Mojave site. Other electronic systems (sensors, computers) were identified through contact with transportation, utility, and pipeline organizations and operators in the California Mojave area, southwestern Nevada, northwestern Arizona, California Communications Department, and the City and County of Los Angeles Telecommunications Agency. Information retrieved from the federal files included systems within a 145 km x 145 km boundary around the Mojave rectenna site, and with operating frequencies between 15 MHz and 5 GHz. A total of 813 government systems and 685 civilian authorizations were identified within these boundaries.

The equipment and systems identified in the file retrieval are categorized as follows:

1. Military Development and Operational Test and Evaluation
 - a. Instrumentation radars--conical scan and monopulse modes
 - b. Traffic monitor/control radars
 - c. Radar transponders
 - d. Radar signal and functional replicators
 - e. Wideband monitor receivers with recognition/decision software scan and instantaneous frequency modes
 - f. Television cameras for target position track
 - g. Electromagnetic system operational monitors--multiple wideband receivers with processing software
 - h. Range command/control communications nets
 - i. Range telemetry communications networks
2. Industrial Communications
 - a. Utility network command/control and telemetry
 - b. Pipeline network command/control and telemetry
 - c. Water resource telemetry
 - d. Multiplexed carrier networks--two major service systems
3. Transportation Support Systems
 - a. Railroad mobile equipments--yards and enroute complex
 - b. Air traffic control network
 - c. Emergency services--mobile, base station, and relay equipments--medical and general emergency applications
 - d. Railroad "car condition" monitors

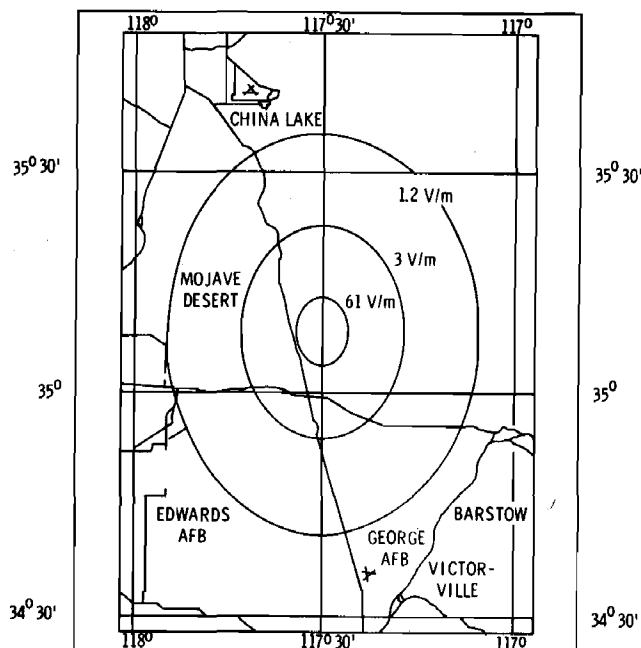


Figure 43. SPS Microwave Field Intensities near Proposed Mojave Rectenna Site.

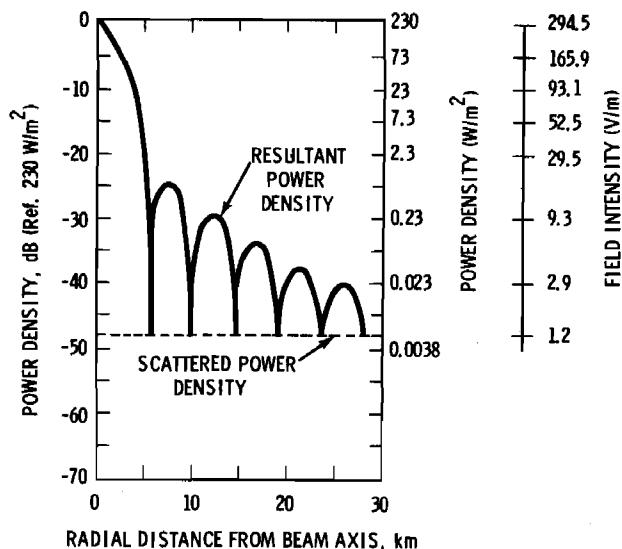


Figure 44. SPS Microwave Field Strengths near Rectenna Sites.

4. Public Service Communications

- a. State of California backbone network (law enforcement, resource management, emergency communications)
- b. Law enforcement systems--state, county, city--mobile, relay, and base station equipment
- c. Forest service units
- d. Fire and government emergency systems--county and city operations
- e. Common carrier networks--telephone, data, television services--remote area voice links

5. Specialized Services

- a. Space tracking and monitoring facilities (Goldstone area)
- b. Railroad hump radars

The China Lake and Edwards AFB test ranges include various radar, command/control and telemetry, and optical tracker scanner systems. For specific applications, IR trackers may be employed for moving surface vehicles and airborne vehicles having low radar cross section and not accommodating a transponder.

Range instrumentation will soon be expanded to include distributed mini-computer and microprocessors for event command and functional control, and various data verification and formatting and network control requirements. Remote computer control capabilities will be required for complex interactive system operations (e.g., multispectral recognition and assessment, and computer managed mission profiles), as well as more effective data processing and range instrumentation. Data security improvements in the control and data networks will also be achieved through the distributed processors.

The types of instrumentation and communications equipment deployed at the military test ranges are:

1. Radars--

FPS-16	MSG-3A
FPS-105	MPS-19
TPQ-39	NIKE AJAX
M-33	NIKE HERCULES

2. Television Cameras--

Plumbicon units mounted on radar antennas for tracking aid, and mounted on high terrain pedestals for multiple camera target tracking.

3. Command/Control and Telemetry--

UHF FM multiplexed analog, L and S band FM multiplexed. All receivers use monopole or low gain antennas.

Enhanced radar capabilities anticipated within 5 to 10 years include on-axis track modes (including digital prediction filter for range gate and pedestal angle control), phased array units for simultaneous multi-target track and integrated event control and telemetry, and simultaneous multiple frequency track modes to minimize multipath errors. Tests involving complex electronic warfare scenarios will require increased use of time- and event-sequenced multiple frequency modes to assure instrumentation compatibility with equipment and procedures being evaluated. Compatibility and short-period accuracy considerations will increase SHF applications.

Evolution of communications systems is expected to include increased microwave operations because of expanded data channel requirements. With the use of distributed processors for instrumentation control, preliminary data processing and formatting will be done at remote nodes before transmission to a central facility. Ultimately, frequency division multiplex (FDM) will be replaced by time-division, multiple-access (TDMA) to accommodate high data rates and for most efficient spectrum utilization. When operating communication systems in high interference environments with severe accuracy and data rate requirements, atmospheric and fiber optical links will be utilized.

Scanning or staring optical sensors are expected to be used increasingly for spatial tracking for high-accuracy requirements, particularly in complex electromagnetic environments. Passive tracking of vehicles (skin or exhaust plumes) with modulated sources will use scanning (vidicon, orthicon, plumbicon) and staring sensors (cooled semiconductor, charge coupled devices) for visual or IR band detection.

Distributed mini-computer and microprocessors will be used for communications and sensor control (data acquisition, verification, formatting, network control, sensor orientation and lock cycling) and various levels of data processing. Modular elements will be interconnected by dedicated cables or through microwave channels.

8.2 RECEIVERS

Range safety and mission operating area uncertainties (aircraft flight paths, missile trajectories, etc.) require that instrumentation radar and communication receivers operate without restriction over the entire upper hemisphere. A tracking antenna could therefore have its main beam or principal side lobes pointed at the SPS source. For distances between the Mojave rectenna site and the China Lake and Edwards AFB and the intervening terrain, the SPS interference is principally from the direct illumination at the fundamental SPS frequency. The direct second harmonic is estimated to be lower by 70 to 80 dB. The fundamental power density contours around the rectenna site are plotted in Figure 11. These are based on only the transmitted pattern, and do not include any scatter or refractive distortion of the power beam.

SPS interference effects include channel noise and, at higher SPS amplitudes, intermodulation products introduced into the input amplifier and/or first mixer. Scoring criteria for radar and communications receivers are listed below. Communications criteria are identified for both analog and digital modes.

RADAR

- a. Target detection range: skin and cooperative target modes
- b. Radar lock delay
- c. Target track error
- d. Loss of track probability

COMMUNICATIONS

- a. Signal acquisition delays
- b. Signal errors -- Analog mode
 - DMUX cross coupling
 - Data errors-- Digital mode
 - BER sync noise and loss
 - address error
 - data error

For radar testing purposes the S/N ratio measured at the radar signal detector inputs was varied from a level corresponding to minimum radar target cross section (smallest target that can be detected when skin tracking) or transponder power from lowest detectable signal to mid-range amplitudes (when tracking target with an active on-board transponder). When testing communication systems, the desired signal was varied from minimum usable signal at the receiver to average communication link signal amplitudes. An interfering signal in the 2.45 GHz frequency range was then introduced to the radar and communication systems under test. Noise and intermodulation spectral densities were measured and tabulated for various S/I combinations. Commercial and industrial communication receivers tested showed nearly identical responses for S/I ratios in the 10 to 20 dB range. The principal prediction response involved induced noise with an amplitude 0 to 3 dB higher than for comparable military FDM equipment. This difference is attributed to shielding and electrical grounding design because of the more stringent requirements of military specifications. At lower S/I ratios (1 to 6 dB), the level at which intermodulation products were first detectable was about 2 dB lower with commercial equipment.

Commercial communications, in the 2 GHz and 6 GHz bands, include systems operated by the Union Pacific and Santa Fe Railroads, and the State of California backbone network. These systems operate 200 and 400 channel FDM analog equipment. Other networks using 50-200 channel configurations serve utility and pipeline control and utility operations. The commercial equipment uses parabolic and high gain yagi antennas, since they do not require the flexibility of military test range operations. Commercial microwave systems are generally signal frequency fixed path configurations where military microwave systems require moving antennas and multiple frequency use.

8.3 MILITARY SIGNAL MONITORS

This class of equipment includes the various configurations of tactical receivers used for signal search, classification and identification, posture assessment, and electronic counter measures (ECM) management. The system can include 2 or 4 antennas, a frequency scanning receiver, analog or digital modulation component separation equipment, and a computer for signal files, comparison logic, alarm and display operation, and ECM control. The susceptibility scoring criteria were:

RECEIVER

- a. Intermodulation related signal density
- b. Extraction of signal modulation components
- c. Signal direction of arrival errors

COMPUTER

- a. Signal density saturation
- b. False alarm--control action probabilities
- c. Signal identification errors
- d. Signal processing delays

This receiver system (typical of a threat warning system) is generally employed with military operational test and evaluation exercises, and is therefore important to the capabilities of range facilities located near the China Lake range. The evaluation of this equipment demonstrated the level of degradation to be experienced by such operations. During war games that are designed to simulate various real tactical situations for design of battle field strategy, erroneous information or wrong procedural specification could result if systems were modified for SPS mitigation purposes biasing the interaction between this type of receiver and the signal environment. These operational ranges include control and monitoring facilities that require functional authenticity and would be very sensitive to the electromagnetic environment. Simulation of tactical situations in parts of the world where no SPS exists could not be achievable.

8.4 SENSOR EVALUATION

Scanning sensors such as TV cameras were tested by subjecting them to simulated SPS field intensities that would be encountered outside a rectenna exclusion area. The sensors were checked under these conditions for increased video noise and scan jitter and decreased spatial resolution and dynamic range. These parameters are related to requirements for security monitors and target tracking. The scoring criteria have different weighting for these two applications; software feature extraction employed for security systems exploits spatial image characteristics and movement (frame to frame comparison detection).

Sensor testing for the Mojave site analysis included 525 and 1000 line video cameras, forward looking infrared (FLIR) detectors, and small mosaic staring visual and IR sensors. Bar targets were used for the visual scanners, the maximum resolution being 2000 lines/inch. The IR bar targets used from 2 to 6 μ consisted of reflectance elements with a 1000 lines/inch resolution. Differential temperature bar targets with approximately 800 lines/inch resolution were used for the thermal sensors (8 to 13 μ).

Microwave radiation coupling was by means of a horn radiator illuminating the sensor and control systems directly into the optical aperture, $\pm 30^\circ$ off the optical axis, at the sides of the camera and electronic control units, and directly into nonmetallic and cable entry areas of the outer casing. The most sensitive areas by a 2- to 10-dB range were the nonmetallic casing (openings > 10 cm in one dimension) and the optical aperture. Generally, semiconductor detectors exhibit a susceptibility 1- to 3-dB greater than vidicon or plumbicon tubes. Large-aperture photomultiplier tubes exhibited approximately the same noise increase.

The scoring criteria for the two sensor categories are listed below:

SCANNING SENSORS

- a. Video noise amplitude
- b. Video dynamic range
- c. Image resolution
- d. Scan jitter

STARING SENSORS

- a. Signal channel noise amplitude
- b. Minimum detectable target
- c. Dynamic range

8.5 COMPUTER AND PROCESSOR EVALUATION

The susceptibility testing for mini- and microcomputers included direct radiation of modules and noise conductivity tests for signal and power ground connections. Distributed processors and integrated systems were tested for the following parameters.

INTEGRATED PROCESSOR

- a. I/O channel noise
- b. I/O register noise and transfer errors
- c. Control and clock bus noise

DISTRIBUTED PROCESSOR

- a. Module I/O channel noise
- b. Module control and clock bus noise, pulse jitter
- c. Module- module transfer errors
- d. Arithmetic module errors

Tests were conducted on 4-, 16-, and 32-bit processors, as used and proposed for the following applications: central/distributed computation and file manipulation, mobile terminal, and data logging. Military processors included weapon data computation, sensor control, and file processing functions. Commercial and military modules varied significantly in shielding integrity and grounding practice. These areas are major contributors to the susceptibility of these systems to interference problems.

8.6 RANGE INSTRUMENTATION

This category of equipment includes the numerous radars and associated TV camera equipment employed for spatial position and orientation tracking at China Lake, Edwards AFB, and Echo Range. These radars track airborne vehicles that test equipment effectiveness, including simulated engagement with surface defense units. The radars, identified in the previous section, include units that are "slaved" through command/control networks for target acquisition and "hand-over" to cover large-area flight operations. Data telemetry from these radars includes rectangular spatial position coordinates, rectangular coordinate velocity data, and signal characteristics employed for diagnostics. These instrumentation radars must satisfy an accuracy requirement of 1.5 to 5 meters in position for elevation angles above 15° , and 5 to 15 meters for the lower elevation angle tracking modes. Where increased accuracy in lower angles is required, the video records can be employed with the radar range and coordinate data to improve resolution.

The primary effects of the SPS power densities predicted for China Lake, Edwards AFB, and Echo Range are: 1) increased noise in the predetection components of the receivers, 2) reductions in target acquisition range, and 3) increased data errors in tracking. Considering the deployment of radars at these facilities, reduced detection range would increase the gap in coverage. These comments also apply to the TV cameras at Edwards AFB.

This tracking instrumentation must operate over an entire hemisphere to support effectively the operational exercises at these facilities. The SPS effect would be reduced if elevation were limited to approximately 50° , but this represents an impossible compromise for the military exercises.

The primary effects, as noted in the previous section, for the data networks at these facilities involve signal acquisition and data error rates. These effects translate into operational problems in greatly increased activity through the data network because of synchronization and error effects. A combination of errors and an increase in the net activity at the various test ranges would reduce the capability to support simultaneous missions. This capability is particularly important in engagement evaluation where numerous remote-controlled facilities may be involved and where delays in communication would represent an unacceptable experimental bias. Since such engagements generally involve event-related activities, for example, aircraft evasive maneuvers or electronic countermeasure initiations in the response to identification of a specific received signal node or the onset of a transmission on a

particular signal frequency, the validity of most multiple vehicle experiments would be unacceptable. These comments are qualitatively correct on the basis of the deployment of command/control and instrumentation equipment, the magnitude of the SPS interference, and previous histories at other test ranges where an EMC problem caused similar compromises in instrumentation and network performance.

8.7 OPERATIONAL SYSTEMS

The China Lake ranges are generally used to evaluate weapons systems performance and limited operational engagements. The latter includes, for example, delivery of ordnance and the collection of surveillance data in a simulated hostile environment. These tests are thus highly dependent on the electromagnetic support systems such as radars, command/control, and sensors. Considering the frequency range of military operational equipment employed for tactical aircraft, and the aperture of electro-optical devices supporting tactical missions, the SPS power densities would eliminate effective testing except for very short ranges of deployment. Modifications to tactical equipment to accommodate the SPS are not possible because they could compromise and bias the realism of event sequences and reduce the correlation between operational and functional events such as the interaction between electronic instrumentation and combat and support equipment operations.

The primary function of operational test facilities in the area is to evaluate proposed electromagnetic penetration support equipment and procedures, and provide operational training and doctrine testing for tactical Air Force penetration against hostile air defense systems. Environments are replicated that interact with penetrating electronic warfare systems, control maneuvers, and equipment operation for testing and training purposes. Critical events for electromagnetic systems include signal detection, signal source recognition and mode analysis, and counteractive interaction events. The capability to detect, identify, and classify specific signal characteristics, and to locate emitters is fundamental to the self-protection or standoff support for aircraft penetrating protected zones. These include air-air and air-ground electromagnetic system interactions.

The facility includes operational monitoring capabilities to evaluate all events relating to the survivability of surface elements and aircraft. The SPS power densities would reduce capabilities in range of coverage and event recognition, thus presenting bias and error in doctrinal and procedural decisions and improper event histories for training exercises.

8.8 EFFECTS AND IMPACTS

The functional degradation of radars, telecommunications systems, sensors, mini- and microcomputers, and the threat warning receiver has been evaluated for various conditions (Table 10). Ranges of effects are indicated because of variations in operational modes and different SPS power densities for equipment deployed at a number of sites (e.g., range radars, command/control and telemetry, railroad and California state microwave systems). The elements of performance degradation cited represent an average over all operating modes and geographic ranges. For example, instrumentation radar detection and tracking performance includes operation over a full hemisphere and the range of cross sections for military target vehicles (e.g., tactical fighter and reconnaissance aircraft, target drones, and transponder variations) during a tracking period. Variations include low elevation angle modes, where the accuracy degradation and loss of lock probabilities due to interference are greater because of propagation factors. On-axis radar configurations are also represented since this mode will probably be increasingly used at test ranges. The track error scores include normal smoothing, prediction filtering, and coordinate computations both in real time and with postmission processing software.

The communications system degradations cited in Table 10 include single channel and frequency and time multiplexed units operated by the military test ranges, the State of California, local county and municipal governments, and resource control and service industries.

The performance changes cited must be translated into effects on a supported operation or service to assess an impact on public service or safety. These operational impacts are described in decision trees relating functional characteristics to action events and resulting service capabilities or safety risks. These relationships are particularly evident in relating radar and associated communications system performance to the air space monitoring mission and transportation safety through the air traffic control process.

There are a number of fixed microwave multi-user communication systems which traverse the Mojave area. These include the State of California backbone network which handles communications involving law enforcement, forest fires, natural resource management, natural disasters (flood, earthquake, etc.) and other state administrative information and data; national communication trunks providing common carrier services such as Bell Telephone, GTE, and MCI microwave links; railroad microwave systems which carry train information and data. For these systems a direct relationship to safety is evident only during local emergencies, i.e., forest fire, train wreck, high winds, etc. Even in such cases, the situation is not immediately managed through these systems but through local police, fire departments, emergency

TABLE 10. SPS Effects on Systems in the Mojave Area

Function	Characteristic Effects	
Instrumentation Radar (Military Test Ranges)	a. Cooperative target acquisition range:	-(8-20%)
	b. Skin target acquisition range:	-(13-28%)
	c. Cooperative target track error:	+(15-40%)
	d. Skin target track error:	+(22-65%)
	e. Loss of track loop lock (skin mode) probability increase:	+(10-40%)
Command/Control and Telemetry Communications (Military Test Ranges)	a. Signal acquisition threshold:	+(5-20%)
	b. Data error:	+(5-28%)
	c. Sync loss probability:	+(3-25%)
Tactical Signal Identifi- cation - Analysis System	a. False alarm probability outside mission zone:	+(3-25%)
	b. False alarm probability within mission zone:	+(18-60%)
	c. Receiver noise threshold:	+(5-40%)
	d. Signal processing time:	+(45-115%)
	e. Software overload probability increase:	+(2-26%)
IR Scanner (Tactical System)	a. Video noise threshold:	+(2-26%)
	b. Target detection/identification error probability:	-(5-33%)
Utility and Pipeline Command/Control/Telemetry	a. Signal acquisition threshold:	-(5-15%)
	b. Data error:	+(10-30%)
	c. Link noise:	+(5-20%)
Image Intensifiers	a. Video noise level:	+(10-45%)
	b. Standard target detection/identifi- cation range:	-(5-30%)
	c. Multiple target spatial resolution:	-(2-60%)

disaster teams, etc., closest to the problem area. Any potential functional degradation caused by SPS in these types of fixed position microwave systems can be mitigated by fairly straightforward techniques. A detailed analysis of operational impacts of SPS illumination on military systems surrounding this particular Mojave site is not warranted. Functional modifications of operational equipment at these test and evaluation facilities represent an unacceptable risk in the training and doctrinal study missions. These considerations led to the decision that this particular hypothetical Mojave site would not be acceptable.

8.9 CONCLUSIONS AND RECOMMENDATIONS

This preliminary assessment of SPS microwave emissions on "victim" systems demonstrates the operational degradation that would occur to electronic systems in the SPS generated environment within approximately 100 km of the hypothetical site. This Mojave site evaluation reveals a wide range of performance degradation particularly in military systems. The basic functional and operational impacts of SPS are of such magnitude that in many instances they represent unacceptable compromises and biases to sensitive test and evaluation exercises.

The evaluation of this Mojave site provided impact data to NASA, contributed to site selection and evaluation criteria, and allowed a limited exercise of the data retrieval and analysis procedures that would be required for the EMC analysis of candidate rectenna sites. This Mojave site allowed reasonable rectenna siting because of its isolation from areas of even modest population density. Most of the interference problems concerned military operations, the degraded systems being integral components of complex development and operational test and evaluation programs. These military programs require the degree of isolation afforded by the Mojave region.

Based on the degradation of operational systems near the Mojave site and the inability to establish mitigating strategies without unacceptable operational compromise, a second hypothetical site north and east of the original site was reviewed. A cursory look at the "victim" systems surrounding the

new site indicates different classes which lend themselves to mitigating strategies. There were only 400 operational systems, mainly civilian and FAA links. Most of these systems could be modified to be compatible with the SPS generated environment.

The functional degradation of military, nondefense government, and commercial systems in the Mojave area is basically characteristic of the effects that will be encountered in other CONUS areas as far as the generic systems of Table 10 are concerned. Operational impacts, and therefore the associated economic impact, will vary by area because of differing uses, configurations, and priorities of affected systems.

The Mojave area lends itself well to resiting because of the large expanse of open, flat terrain. The development of new sites in most geographic areas would be more difficult, if not impossible, because of population density, terrain features, "victim" system density, etc.

As given by FCC and NTIA printouts of EM systems operating in northern and eastern CONUS regions, generally there would be a smaller concentration of military equipment in proximity to rectenna sites in these regions. These regions, however, include major transportation and commercial communications facilities and relatively large populations of susceptible computers, sensors, and control complexes associated with power generation and distribution, mass transportation, and industrial control facilities. Because of the higher population and business densities compared to the Mojave desert area, the total number of affected systems could be larger. This may mean more systems may need mitigation within a given area, but more complex techniques may not be necessary.

An EMC analysis and impact evaluation of rectenna sites has been demonstrated and shown to be fundamental in supporting site selections, helping to determine impacts on system performance, and helping to develop mitigating strategies for "victim" systems.

9.0 SATELLITE SYSTEMS

The compatibility of SPS and other satellite systems is a major concern because of the widespread use of satellites both within the United States and internationally. A premium currently exists for geostationary orbit slots, and any potential change in the number of these slots due to SPS or otherwise needs to be carefully evaluated. Satellite receivers typically operate in extremely weak fields and can be affected by other comparably weak fields. The following discussion addresses some of the satellite issues. However, the reader is cautioned that many unknowns exist in this field. For example, no measurements currently exist for satellite receivers in high level interfering microwave fields such as those expected from SPS. Thus the causes of interference and the coupling mechanisms are not understood in detail. However estimates have been made based on the best engineering judgement.

9.1 EARTH TERMINALS

Although it is difficult to generalize the allowable interference levels for satellite systems, approximate calculations can be made. The actual received signal levels that will cause interference in practice depend on a number of factors such as the victim antenna size, interference characteristics, receiver sensitivity, and modulation characteristics.

A general guide for estimating interference to satellite systems is contained in CCIR Report 713. This report shows that the maximum acceptable interference power flux density incident on the victim antenna is given by,

$$pfd = 10 \log (k t_s b_r) + 10 \log (n_1/n_s) - G_e - 10 \log \frac{\lambda^2}{4\pi} \quad (9)$$

where

- k = Boltzman's constant
- t_s = effective system noise temperature
- b_r = reference bandwidth
- n_1/n_s = ratio of allowable interference noise power relative to normal system noise
- G_e = effective victim antenna gain in dB
- λ = victim wavelength

However, since the effective aperture, a_e , of the victim's antenna is

$$10 \log a_e = G_e + 10 \log \frac{\lambda^2}{4\pi} \quad (10)$$

equation (9) can be rewritten as

$$pfd = 10 \log (k t_s b_r) + 10 \log (n_1/n_s) - 10 \log a_e \quad (11)$$

The reference bandwidth, b_r , in these equations is defined as the "bandwidth of concern to the interfered-with system, over which interference power can be averaged." The reference bandwidth for narrow-band, single channel per carrier systems is generally assumed to be 4 kHz. Protection requirements for conventional FM-FDM (frequency modulation with frequency division multiplex) are also generally specified in a 4-kHz bandwidth. The reference bandwidth for wideband digital systems, however, is usually taken to be 1 MHz. Both the 4-kHz and 1-MHz reference bandwidths will be used as appropriate to the system being studied. The ratio of system noise due to interference relative to the normal system noise (n_i/n_s) is typically assumed to be of the order of 0.1 or 0.01. These values are explained in CCIR Report 713. If one assumes an effective system noise temperature at $t_s = 60^\circ \text{K}$, then pfd can be plotted as a function of a_e as shown in Figures 45 and 46.

In Figure 45, one can see that the interference power flux density would have to be between -185 and -195 dB(W/m²·4kHz) to prevent interference to systems with reference bandwidth of 4 kHz and antenna apertures of 1 to 10 square meters. Figure 46, on the other hand, shows that a protection of -161 to -171 dB(W/m²·1 MHz) is needed to prevent interference to these systems with 1 MHz reference bandwidths and antenna apertures of 1 to 10 square meters. The extreme value of -221 dB(W/m²·4 kHz) is required to protect a large antenna INTELSAT system. However, one should note that this extreme protection is needed only if the interfering source is within the main beam of the INTELSAT antenna. Since these antennas have a beam width of approximately 0.3 degrees, it is likely that the SPS will be off-axis, which means that the protection criteria can be relaxed.

The satellite bands primarily affected by adjacent channel noise from SPS are three direct broadcast bands assigned within the frequencies of 2500 to 2690 MHz. The satellite band most susceptible to harmonic interference is the 7300- to 7450-MHz band assigned to government, fixed satellite, space-to-earth communications.

9.1.1 GPS Navigation Terminal

The Global Position Satellite System (GPS) is a network of satellites that, when completed, would transmit navigation signals. Current plans for GPS envision a constellation of 18 satellites that provide accurate three-dimensional position and velocity information to users anywhere in the world (Milliken 1978 and Lassiter 1977). The navigation signal is transmitted at two rf frequencies of $f_1 = 1575.42 \text{ MHz}$ and $f_2 = 1227.6 \text{ MHz}$. The f_1 signal is modulated with a secure pseudorandom code (P code) for military navigational uses, as well as a clear access (C/A) code for general civilian navigation. The f_2 frequency contains only the P code. Both codes use spread spectrum signaling techniques with the P code occupying an rf bandwidth of approximately 10 MHz while the C/A code occupies a 1-MHz bandwidth. The C/A code is a "clear access" code available to the general public while the P code is restricted to military users. The data rate of the navigation signal that is carried by the codes is 50 bps. Representative parameters for this type of system are:

Power flux density, 1575.42 MHz C/A signal at surface of earth	-155 dB W/m ²
Power flux density, 1575.42 MHz P signal at surface of earth	-165 dB W/m ²
Approximate rf bandwidth of C/A signal	1 MHz
Approximate rf bandwidth of P signal	10 MHz
Power flux density per 4 kHz, 1575.42 MHz C/A signal at surface of earth	-178 dB W/m ² ·4 kHz
Power flux density per 4 kHz, 1575.42 MHz P signal at surface of earth	-199 dB W/m ² ·4 kHz
Satellite Earth Terminal noise temperature T	60° K
Satellite Earth Terminal noise power density per 4 kHz (kTB with B = 4 kHz)	-210.8 dB W/4 kHz

GPS has been specifically designed to be useful in a hostile jamming environment, and the navigation signals are inherently interference resistant. In fact, as shown below, this system can operate even though the interference is stronger than the signal.

The increase in receiver output noise of a GPS satellite receiver, or any spread spectrum receiver, is given by

$$D = 10 \log \left(1 + \frac{1}{s} \cdot \frac{s}{n_o} \cdot \frac{1}{b_{RF}} \right) \text{ dB} \quad (12)$$

where

$$\frac{1}{s} = \text{interference to signal ratio,}$$

$$\frac{s}{n_o} = \text{receiver signal to noise power density ratio in the absence of interference,}$$

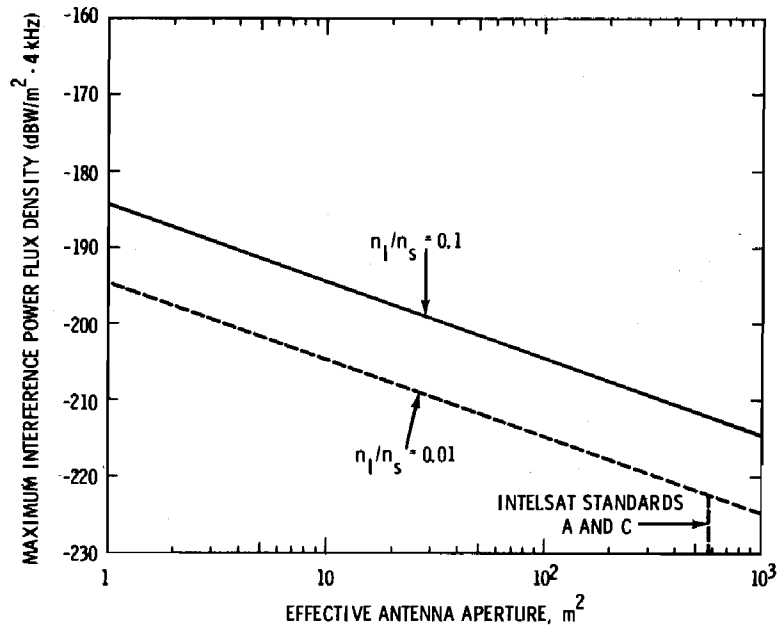


Figure 45. Maximum Interference Power Flux Density in a 4-kHz Reference Bandwidth Versus Effective Victim Antenna Aperture.

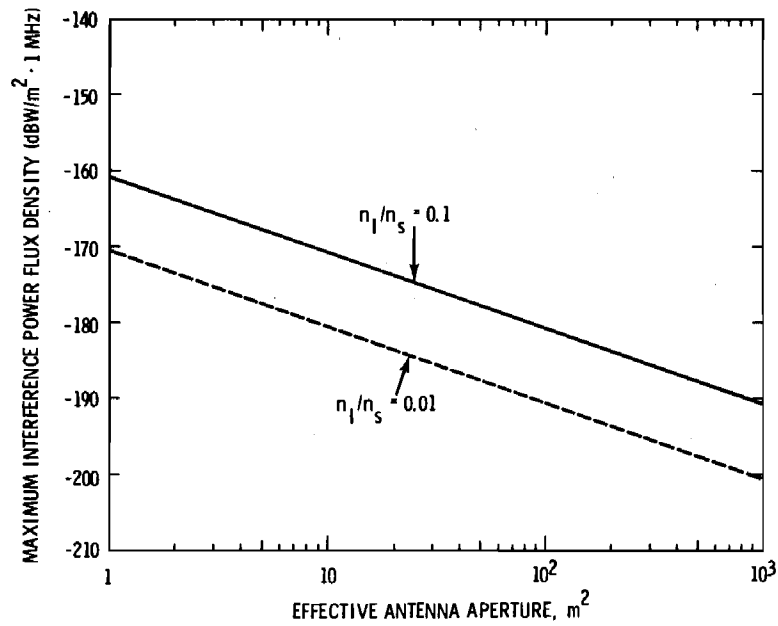


Figure 46. Maximum Interference Power Flux Density in a 1 MHz Reference Bandwidth Versus Effective Victim Antenna Aperture.

and

b_{RF} = receiver rf bandwidth.

Equation (12) is plotted in Figure 47. Since these receivers can typically withstand a degradation of 3 or more dB without serious consequences, we see that the GPS can function in an interference environment of $I/S = 20$ to 30 dB without significant performance degradation.

At this point, we are forced to ask what constitutes interference. Consider the hypothetical example of an interferer with $I/S = 5$ dB. Strictly speaking, this does not significantly affect the GPS receivers navigational capabilities. However, it does affect the receiver in other ways since it increases the normal system background noise. This affects the signal acquisition capabilities as well as the ability to reject additional interferers or jammers. Thus, to determine if SPS interferes with GPS, we looked for any significant increase in receiver background noise.

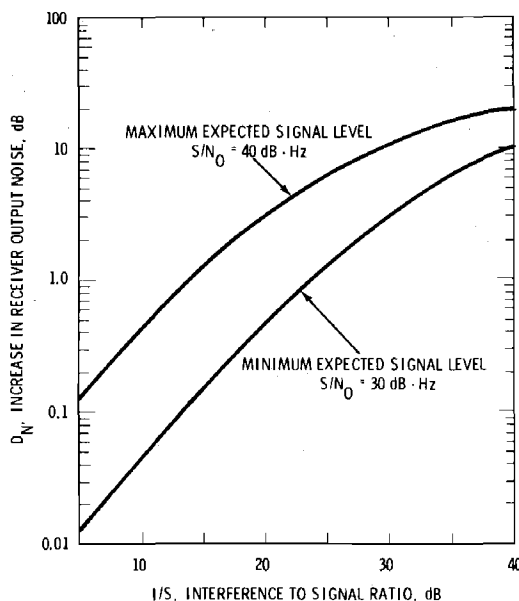


Figure 47. Expected Increase in GPS Spread Spectrum Receiver as a Function of Interference to Signal Strength Ratio.

Calculations of the SPS signal levels coupled into a GPS receiver are relatively straightforward as shown in Table 11. A value of 130 dB has been chosen for the amount of receiver filtering expected for the interfering SPS signal because of the large frequency separation between victim and interferer (1575 MHz and 2450 MHz, respectively). Leakage from connectors and chassis components, generally limits the maximum filtering of modern receivers to values in this range. After filtering, the expected interference-to-noise ratio (I/N) is 9 dB in a -10 dB W/m^2 field and -21 dB in a -40 dB W/m^2 field. Ideally, the I/N ratio would be less than 0 dB to ensure no interference. Although the I/N ratio is greater than 0 dB in a -10 dB W/m^2 field, it is significantly less than 0 in the -40 dB W/m^2 field. Neither of these fields would be expected to alter significantly the receiver's tracking accuracy.

9.1.2 MARISAT Ship Terminals

The MARISAT is a satellite system that provides maritime communications for both Navy and civil users. Two satellites located at 15° W and 176.5° E longitude provide coverage over the Atlantic and Pacific oceans. A general block diagram of the system is shown in Figure 48 (Gould 1975). The closest MARISAT frequency to SPS is the 1540-MHz satellite-to-ship link.

TABLE 11. Estimate of SPS Signal Levels in a 1575.42-MHz GPS Navigation Receiver

SPS power density	-10 dBW/m ²	-40 dBW/m ²
GPS reference bandwidth	1 MHz	1 MHz
GPS noise power in reference bandwidth (t = 60 K)	-151 dBW/MHz	-151 dBW/MHz
Effective GPS antenna aperture at SPS frequency (1.0 m diameter, 80% efficiency)	-2.0 dB·m ²	-2.0 dB·m ²
SPS power received on GPS antenna	-12 dBW	-42 dBW
I/N prior to receiver filtering	139 dB	109 dB
Estimate of receiver filtering attenuation (1575 MHz to 2450 MHz)	130 dB	130 dB
I/N after receiver filtering	9 dB	-21 dB

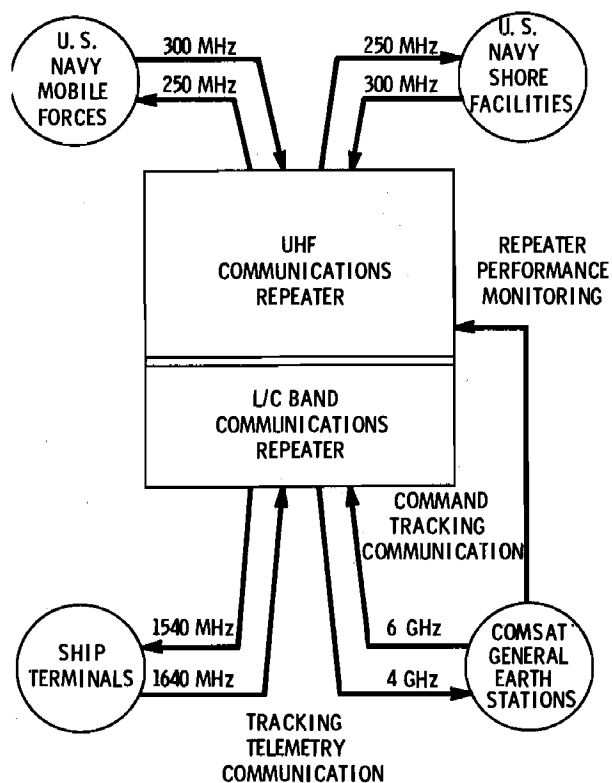


Figure 48. MARISAT Communication Links.

The 1540-MHz satellite-to-ship link transmits voice via a single-channel-per-carrier frequency modulated signal. Some of the typical technical characteristics for this link are:

EIRP at satellite	26 dBW	FM signal bandwidth	25 kHz
Power flux density at surface of earth	-137 dBW/m ²	Power flux density at surface of earth per 4 kHz bandwidth	-145 dBW/m ² · 4 kHz

Although the interference calculations for this system are similar to those described for GPS, MARISAT does not use spread-spectrum techniques and therefore cannot operate with the positive I/S ratios shown for GPS.

The SPS signal levels that can be expected in a MARISAT shipboard receiver were calculated (Table 12). These calculations indicate that interference is a potential problem in fields of -10 dBW/m^2 and that interference should not be expected in a -40 dBW/m^2 field.

TABLE 12. Estimate of SPS Signal Levels in a
1540-MHz MARISAT Ship Terminal

SPS power density	-10 dBW/m^2	-40 dBW/m^2
MARISAT reference bandwidth	4 kHz	4 kHz
MARISAT noise power in reference bandwidth ($t = 60 \text{ K}$)	-175 dBW/4 kHz	-175 dBW/4 kHz
Effective MARISAT antenna aperture (1.3 m diameter, 80% efficiency)	$0.3 \text{ dB}\cdot\text{m}^2$	$0.3 \text{ dB}\cdot\text{m}^2$
SPS power received on MARISAT antenna	-9.7 dBW	-39.7 dBW
I/N prior to receiver filtering	165.3 dB	135.3 dB
Estimate of receiver filtering, 1540 MHz to 2450 MHz	130 dB	130 dB
I/N after receiver filtering	35.3 dB	5.3 dB

In summary, one should note that in a -40 dBW/m^2 SPS field the estimated I/N ratio after receiver filtering was -21 dB for GPS and 5.3 dB for MARISAT. Ideally both of these figures should be significantly less than zero to insure that no interference exists. However, neither estimate necessarily shows significant potential for interference considering the unknowns involved. On the other hand, the I/N ratios increase to 9 dB and 35.3 dB , respectively, in a -10 dBW/m^2 field. Thus, one can see that the potential for interference significantly increases in a -10 dBW/m^2 field for earth terminals such as MARISAT with reference bandwidths of 4 kHz .

9.2 GEOSTATIONARY SATELLITES

Since SPS can radiate substantial amounts of power in directions other than the antenna boresite, one must also consider the possibility of interference to other satellites in geosynchronous orbit. This section examines the potential for interference to geostationary satellites spaced within a few degrees of SPS as well as geostationary satellites at approximately antipodal orbit locations. Geostationary satellites within a few degrees of SPS will be subjected to microwave energy radiated 90 degrees off boresite while satellites located antipodal to an SPS will be subjected to microwave energy radiated within a few degrees of SPS boresite.

As in the previous examples, many unknowns exist. The radiation pattern for the SPS at 90 degrees off of boresite is unknown. The microwave energy radiated 90 degrees off of boresite is likely to be caused by a number of phenomena, such as scattering from surface irregularities and structural components, diffraction from surface discontinuities, as well as leakage from chassis, connectors, etc. Given these assumptions one can visualize various conditions that would apply to the energy radiated 90 degrees off of boresight. For example, one line of thought is that the energy will appear to be radiating from numerous independent sources spaced throughout the surface of the SPS antenna with little phase coherence of the radiated energy over any significant distance. Thus, locations a few hundred km and 90 degrees off of boresite from an SPS antenna will be in the antenna's far field. However, other arguments are that there will be a significant degree of phase coherence in this energy and therefore one cannot assume that such locations will be in the far field. Energy coupling between two antennas is significantly more complex if one of the antennas is in the near field of the other.

An analysis of the power transfer from a large antenna to a small antenna when the small antenna is within the near field of the large antenna is discussed by Jacobs (1963). This analysis shows that the power transferred between the two antennas is

$$\frac{P_r}{P_t} = \frac{g_t a_s}{4\pi r^2} \quad (13)$$

where

p_r = power received,
 p_t = power transmitted,
 g_t = gain of the larger antenna at a distance r from the large antenna,
 a_s = aperture of small antenna, and
 r = separation between the two antennas.

The above formula is applicable as long as r is greater than the near field distance of the small antenna as given by

$$r > \frac{2d_s^2}{\lambda}$$

where d_s is the largest dimension of the small antenna and λ is the wavelength. Note that g_t is the gain of the larger antenna at the distance r . Estimating g_t when r is within the near field is a complex problem that is beyond the scope of this limited analysis. However, the near field gain of an antenna is always less than or equal to the far field gain.

The power flux density at the smaller receiving antenna is given by

$$f_d = \frac{p_r}{a_s} = \frac{p_t g_t}{4\pi r^2} \quad (14)$$

When r is in the direction of the geostationary orbit, it is useful to express r in terms of degrees of orbital arc ϕ where

$$r = \frac{d\phi}{57.3} \quad (15)$$

and d is the distance from the center of the earth to the geostationary orbit.

Substituting (15) into (14) results in

$$f_d = \frac{261.3 p_t g_t}{d^2 \phi^2} \quad (16)$$

Figure 49 shows a plot of the power density that can be expected for

$$\begin{aligned}
 p_t &= 6.85 \times 10^9 \text{ Watts} \\
 d &= 4.22 \times 10^7 \text{ m}
 \end{aligned}$$

and three values of g_t . Accurate estimates for g_t at 90° off of boresight (gain in the direction of the geostationary orbit) are not yet available. Quantities such as aperture phase distortion, manufacturing and assembly tolerances, and other considerations can significantly affect the radiation pattern 90° off of boresight. The current technology in satellite antennas results in g_t values as large as -10 dBi (dB relative to an isotropic radiator) (CCIR Report 558-1).

However the -10 dBi gain is applicable at the normal victim operating frequency which for MARISAT is 1640 MHz. A -10 dBi antenna gain at 1640 MHz is equivalent to an effective antenna aperture of -35.7 dBm². The following will assume that the effective victim antenna aperture 90 degrees off boresite is the same at 2450 MHz as it is at 1640 MHz.

Given these assumptions, the power coupled into a victim receiver can be calculated as shown in Table 13. The calculations shown in Table 13 are made for separation between SPS and victim of 0.1° and 1.0° and reference bandwidths of 4 kHz and 1 MHz. Note that the I/N ratio for the 4 kHz reference bandwidth system after filtering is 22.1 dB with 0.1° separation and 2.1 dB with 1.0° separation. Again these figures should be less than zero to minimize the potential for interference. These calculations show that a potential for interference exists to satellites separated from 0.1 to 1.0 degrees from an SPS.

9.2.1 INTELSAT Satellite

An example of possible interference from SPS to geostationary satellites approximately 180° away is INTELSAT IV or IVA in orbit over the Indian Ocean at about 61.4° East longitude (Figure 50). This satellite receives signals in the 5900-6400 MHz satellite bands and transmits on frequencies in the 3700-4200 MHz band. The SPS and INTELSAT orbit locations are 101.3° West and 61.4° East longitude, respectively. The SPS aim point is 34° North latitude and 101.3° East longitude which corresponds to a point near Lubbock, Texas. The geometry and power flux density involved in this case have been

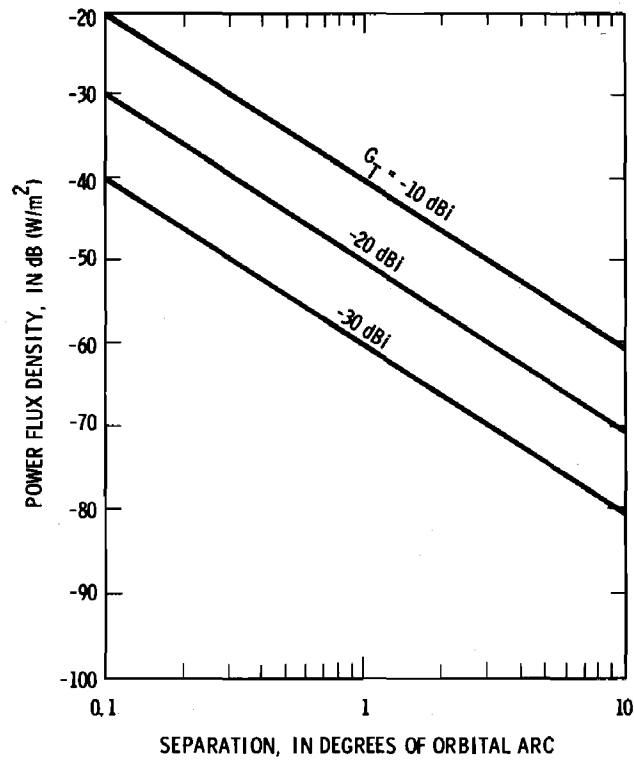


Figure 49. Power Flux Density Along GEO Orbital Arc from a Single SPS Satellite for Different Values of Transmitting Antenna Gain, G_T , at 90° to Boresight.

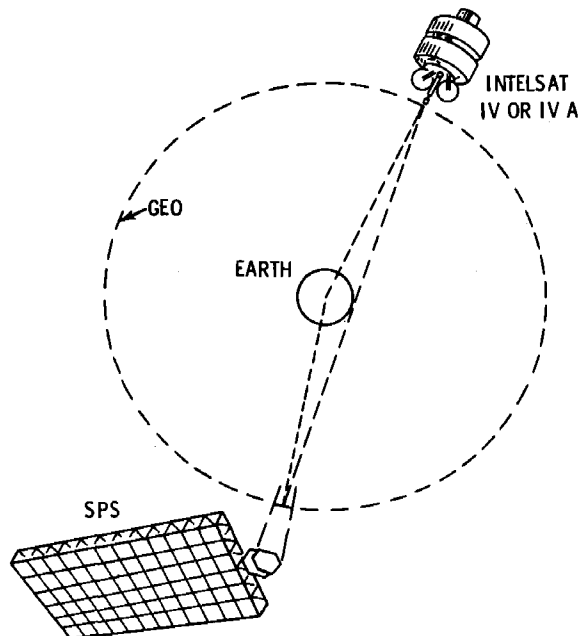


Figure 50. Geometry for Coupling of SPS to INTELSAT at approximately 180° Separation.

TABLE 13. Estimates of the Power Coupled into a 1640-MHz Satellite Transponder Separated 0.1° and 1.0° from SPS

	4-kHz Reference Bandwidth	1-MHz Reference Bandwidth
<u>Separation 0.1°</u>		
SPS power density at victim ($g_t = -10$ dBi)	-20 dBW/m ²	-20 dBW/m ²
Victim antenna gain in direction of SPS at 1640 MHz	-10 dBi	-10 dBi
Effective victim antenna aperture at 1640 MHz	-35.7 dB·m ²	-35.7 dB·m ²
Effective victim antenna aperture at 2450 MHz (Assumed)	-35.7 dB·m ²	-35.7 dB·m ²
SPS power received on victim antenna	-55.7 dBW	-55.7 dBW
Victim noise power in reference bandwidth ($t = 3000$ K)	-157.8 dBW	-133.8 dBW
I/N prior to transponder filtering	102.1 dB	78.1 dB
Estimate of transponder filtering 1640 MHz to 2450 MHz	80 dB	80 dB
I/N after filtering	22.1 dB	-1.9 dB
<u>Separation 1.0°</u>		
SPS power density at victim ($g_t = -10$ dBi)	-40 dBW/m ²	-40 dBW/m ²
Victim antenna gain in direction of SPS at 1640 MHz	-10 dBi	-10 dBi
Effective victim antenna aperture at 1640 MHz	-35.7 dB·m ²	-35.7 dB·m ²
Effective victim antenna aperture at 2450 MHz (assumed)	-35.7 dB·m ²	-35.7 dB·m ²
SPS power received on victim antenna	-75.7 dBW	-75.7 dBW
Victim noise power in reference bandwidth ($t = 3000$ K)	-157.8 dBW	-133.8 dBW
I/N prior to transponder filtering	82.1 dB	58.1 dB
Estimate of transponder filtering 1640 MHz to 2450 MHz	80 dB	80 dB
I/N after filtering	2.1 dB	-21.9 dB

examined by Ott et al. (a report entitled "Antenna patterns for the solar power satellite" has been prepared for limited distribution as a National Telecommunications and Information Agency Technical Memorandum). This satellite receives on frequencies in the 5900-6400 MHz satellite band and transmits on frequencies in the 3700-4200 MHz band. These calculations estimate the SPS transmit antenna gain to be -20 dBi for these conditions. Using the -20 dBi estimation the power flux density at INTELSAT can be computed using (14) with

$$\begin{aligned}
 g_t &= -20 \text{ dBi} \\
 p_t &= 6.85 \times 10^9 \text{ Watts} \\
 r &= 84.3 \times 10^3 \text{ km}
 \end{aligned}$$

which results in a power flux density of -91.2 dBW/m².

A signal level of -91.2 dBW/m^2 is significantly less than the saturation power flux densities of an INTELSAT transponder which is approximately -67 dBW/m^2 (Bargellini, 1972). This means that the interference prior to filtering is 29.2 dB weaker than the victim signal at the surface of the antenna. Estimates of the interfering SPS signal levels that would be received by the INTELSAT are listed in Table 14. Many factors are unknown in these calculations, such as the response of the circularly polarized, global beam INTELSAT antenna to the linear polarized, off boresight, SPS harmonics. The response of an antenna to frequencies other than those normally used is seldom known. The assumption used here is that the INTELSAT antenna aperture is $1.1 \times 10^{-3} \text{ m}^2$ which corresponds to approximately 0 dB gain at 2450 MHz and 10 dB at 7350 MHz.

TABLE 14. Estimate of SPS Signal Levels at an INTELSAT Satellite Spaced 180° in Geosynchronous Orbit from SPS

	SPS Fundamental 2450 MHz	SPS 3d Harmonic 7350 MHz
SPS power density at INTELSAT	-91 dBW/m^2	-169 dBW/m^2
INTELSAT reference bandwidth	4 kHz	4 kHz
INTELSAT noise power in reference bandwidth (N)	-158 dBW/4kHz	-158 dBW/4kHz
Estimate of INTELSAT antenna aperture to SPS signal (10.25° off INTELSAT boresite)	$1.1 \times 10^{-3} \text{ m}^2 = -29 \text{ dB} \cdot \text{m}^2$	$1.1 \times 10^{-3} \text{ m}^2 = -29 \text{ dB} \cdot \text{m}^2$
SPS received signal level (I)	-120 dBW	-198 dBW
I/N prior to filtering	38 dB	-40 dB

The 7350 MHz 3d harmonic from SPS is the signal closest in frequency to the 5900-6400 MHz INTELSAT receive frequencies. However, the I/N ratio prior to filtering is only -40 dB which would not cause significant interference. Thus, this signal is not expected to be a significant interferer. The same can be said for the fundamental. The magnitude of the I/N ratio for the fundamental is 38 dB prior to filtering. This ratio is not considered to be significant because of the large frequency difference between the interference and the victim receive frequencies. Additional filtering in the transponder and attenuation due to waveguides, etc., should reduce this ratio to a value well below zero.

9.2.2 TDRSS Satellite

Another example of potential interference along the geosynchronous orbit is that between SPS and the Tracking and Data Relay Satellite System (TDRSS) (Poza, 1977). This system of relay satellites and earth terminals supplies communications support for various space research missions. One of the functions of TDRSS, and the subject of the following analysis, is to supply communications relays for space shuttle missions (Batson, 1977).

The relay satellites can support both wideband and narrowband communications at S and K band frequencies. The TDRSS communications frequencies closest to SPS is the S band link with uplink frequencies of 2287.5 and 2217.5 MHz. Downlink assignments from TDRSS are at 2042 and 2106 MHz, and use spread spectrum signaling techniques, with a 11.232 Mc/s signaling rate, to prevent interference to ground-based terminals. The uplink to TDRSS, however, does not require spread spectrum signaling. It is this narrowband mode that is the subject of discussion here.

A typical transmission rate in the low data rate mode is 96 Kbps. This information stream is encoded with a 1/3 rate, constraint length 7, convolutional code. The resulting 288 Kbps coded waveform is transmitted with phase shift keying of the carrier. Typical signal levels for a TDRSS-to-space shuttle communication relay are given in Table 15 along with estimates of SPS interference levels that would exist with 1° separation between SPS and TDRSS. The reference bandwidth for TDRSS has been assumed to be 228 kHz. The interference to system noise ratio after filtering is estimated to be $I/N = -12.1 \text{ dB}$. Although an I/N ratio less than -10 dB normally does not indicate interference, the margin indicated is minimal considering the unknowns involved.

TABLE 15. Interference Estimates for a TDRSS-to-Space Shuttle Relay

<u>Victim</u>	
Space Shuttle EIRP	15.2 dBW
Path loss, shuttle to TDRSS (R=22786 nmi, f=2287.5 MHz)	-192.1 dB
Pointing and polarization losses	-1.0 dB
TDRSS receive antenna gain	36.0 dB
Receive signal level	-141.9 dBW
TDRSS noise temp	27.7 dBK
Boltzman's constant	-228.6 dBW/K·Hz
TDRSS noise density	-200.9 dBW/Hz
Information bandwidth, 96 Kbps mode	49.8 dB·Hz
rf bandwidth, 228 Kbps PSK mode	53.5 dB·Hz
TDRSS noise power in rf bandwidth	-147 dBW
<u>Interference</u>	
SPS transmit power, 6.5 GW	98 dBW
SPS antenna gain 90° off boresight	-10 dB1
Path loss, SPS to TDRSS, (700 KM, 1° separation, 2450 MHz)	-157.1 dB
TDRSS antenna gain to SPS signal 90° off boresight	-10 dB1
SPS interference power at input to TDRSS receiver	-79.1 dBW
Receiver diplexer filtering attenuation to SPS signal	-80 dB
SPS interference power after filtering	-159.1 dBW
<u>Summary</u>	
Signal to interference ratio at input to receiver diplexer prior to filtering (-141.9+79.1)	-62.8 dB
Signal to interference ratio after filtering in TDRSS receiver (-141.9+159.1)	17.2 dB
Interference to system noise ratio prior to filtering (-79.1+147)	67.9 dB
Interference to system noise ratio after filtering in TDRSS diplexer (-159.1+147)	-12.1 dB

9.3 SATELLITES IN LOW EARTH ORBIT

Another major concern of the EMC program was the effect on satellites in low earth orbit which might pass through an SPS power beam. The large powers involved represent illumination levels as high as 319 volts per meter for satellites such as the proposed space telescope at an orbit altitude of 10,900 miles. Operational effects for LEO satellites depend on orbits, equipment complement, equipment usage, and vehicle physical configuration. Existing and planned LEO systems include remote sensing, navigation and position fixing, and communications functions. On-board sensors sensitive to SPS interference include electro-optical devices, active and passive microwave systems, and particle detectors.

The susceptibility of various operational and planned LEO satellites has been examined during the course of the SPS EMC evaluation program. Functional degradation for the electronic systems on LANDSAT, GPS, and the SPACE TELESCOPE have been studied in relation to the amplitude of the SPS illumination components. Analysis and tests include the modes of coupling to on-board devices and subsystems, and performance effects in relation to satellite missions.

The susceptibility evaluations for LANDSAT, GPS, and SPACE TELESCOPE indicate the character of functional degradation for data sensors, communications, attitude/stabilization, and processing or control systems for power beam encountered periods. Penetration through antenna and physical apertures, and modes of coupling to internal devices and modules are examined to support sensor and circuit module tests for degradation measurement and mitigation technique specification.

9.3.1 LANDSAT Satellite

The LANDSAT satellite program is intended to develop and demonstrate a capability for global monitoring support to Earth Resources Management. Launch of LANDSAT-D is scheduled in the third quarter of 1981. A subsequent launching is anticipated during 1982-83 by the Space Transportation System. An advanced system, LANDSAT-H, is also being planned.

The LANDSAT-D (Figure 51) will provide imagery from a sun synchronous circular orbit altitude of 705.3 km with a 98.2° inclination. Imagery is derived from a Multispectral Scanner (MSS) and Thermal Mapper (TM) on the satellite. Scanner and mapper image data and system status are transmitted to CONUS and foreign control stations directly and through TDRSS (Figure 52).

A power density-time plot for the case of orbit coincidence with the SPS main beam is presented in Figure 53. This situation will occur frequently because of the 6 to 8 orbit tracks/day over CONUS.

SPS energy coupling into LANDSAT systems might affect the communications, sensor, power bus, and attitude control functions. Coupling would occur through the communications antennas, attitude sensor optical apertures and the optical apertures and thermal louvers of the MSS and TM (Figure 54). Energy coupling through the solar panels to the power busses is not a problem because of the filtering and regulation provided. Exposed area and scanner locations on the satellite indicate that the optical aperture is the principal coupling mode for these sensors.

The LANDSAT star tracker provides error data to the attitude control software. Star tracker noise and angle error ranges in relation to microwave illumination levels are indicated in Figure 55. Attitude error would accumulate over a period of about 4 to 5 seconds within the SPS beam.

Because of the locations of the TM and MSS on the satellite, the sensor responses will be sensitive to SPS orbit position. Sensor performance was evaluated for the peak and average SPS power density magnitudes indicated in Figure 53. The satellite will be subjected to microwave field intensities greater than 100 V/m for about 1 second, intensities greater than 10 V/m for 3.2 seconds, and intensities greater than 1 V/m for about 13 seconds at LANDSAT velocity. Coupling of this energy into the TM and MSS systems may occur through the thermal control louvers or directly through the optical aperture.

The TM was tested using normal test procedures with no simulated SPS illumination. Bar targets were scanned, and recorded impulse response to a 0.2°C resolution was measured. This gave the normal imaging performance of the system. Identical tests were then conducted using the bar targets, recording impulse response, with the addition of a microwave signal illuminating the optical aperture. The microwave signal level was varied in steps from 1 mW/cm² until complete malfunction occurred at 16 mW/cm². The microwave illumination was then aimed directly into the thermal control louvers with the louvers open to the position which gave maximum coupling. The bar target tests were conducted again at various levels of illumination. A preliminary data set indicates an increase in video channel noise of 8%, and a decrease in modulation transfer function of 18% to 20%, which affects the spatial imaging capability by approximately 20%.

The satellite-earth station uplinks use an S band channel (direct and through TDRSS at 2106.4 MHz with wideband modulation modes through the TDRSS). Other satellite receiver channels include a 1377.5-MHz track signal from TDRSS, and the 1227.6-MHz and 1575.4-MHz transmissions from GPS. For the direct earth-station to satellite S band link (2 Kbps - NRZ/PM), a bit error rate (BER) increase of 70% to 85% would occur for SPS main-beam exposure period (approximately 16 seconds). For the wideband TDRSS channel, the BER would increase 20% to 40%, the higher range caused by nonlinear responses in the first conversion and amplifier stages of the receiver during exposure to SPS power densities of ≥ 8 mW/cm².

For perhaps one to three SPS satellites maximally separated over CONUS, the LANDSAT mission profile could be modified to eliminate command/control transmission during the specific orbit time slots corresponding to SPS illumination. This is obviously not a satisfactory mode of operation, but could be a temporary solution for an operational satellite while functional modifications are incorporated into future vehicles. These modifications should eliminate the BER effects for the narrowband and wideband transmissions to the satellite, thus removing all mission dependencies between LANDSAT and SPS operations.

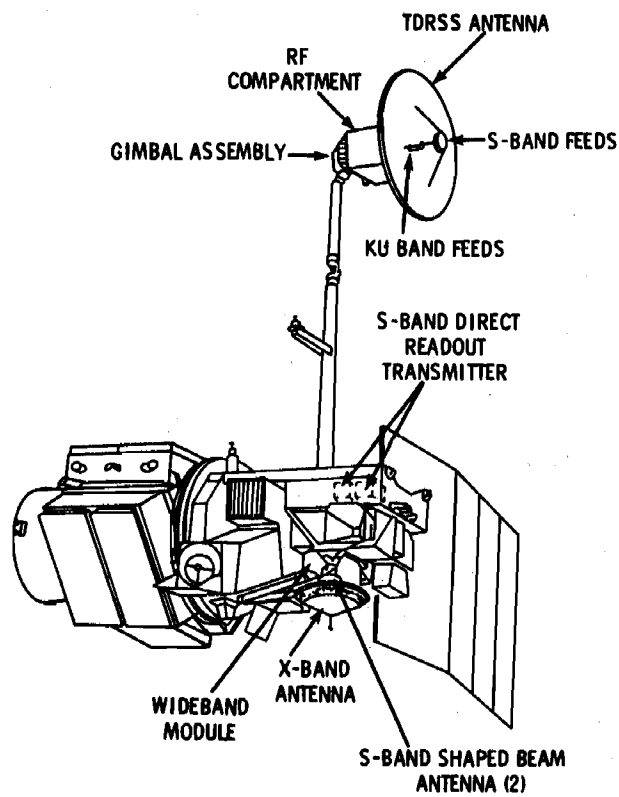


Figure 51. LANDSAT-D Configuration.

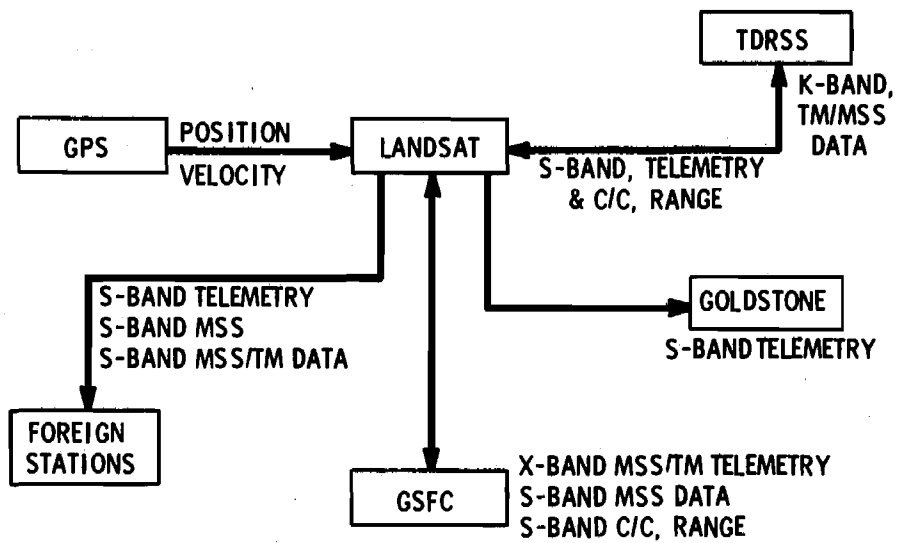


Figure 52. LANDSAT Communication Links.

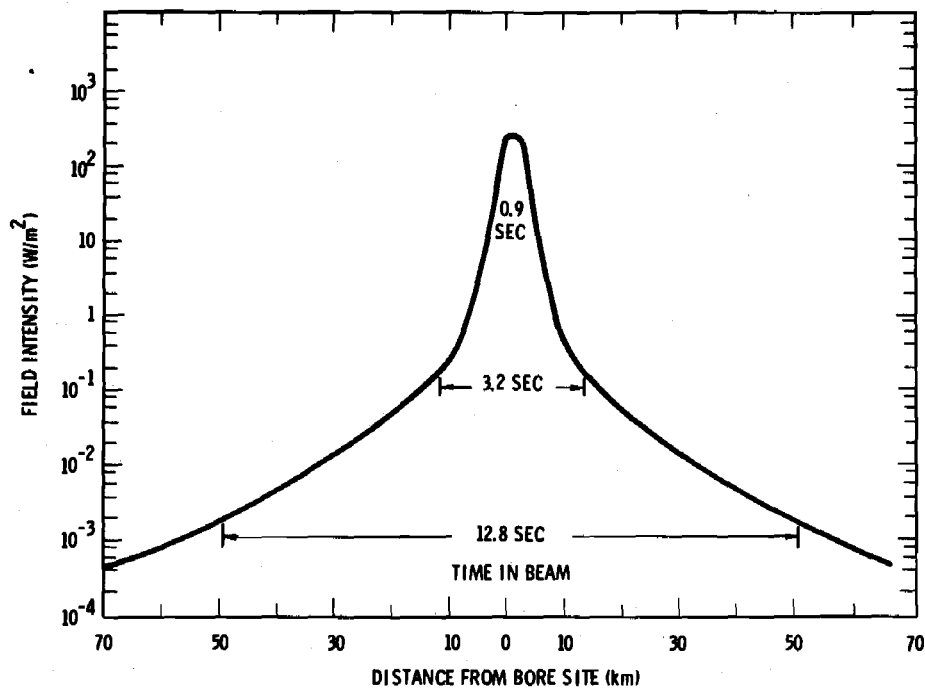


Figure 53. Microwave Field Intensity Encountered by LANDSAT during Transit of SPS Power Beam.

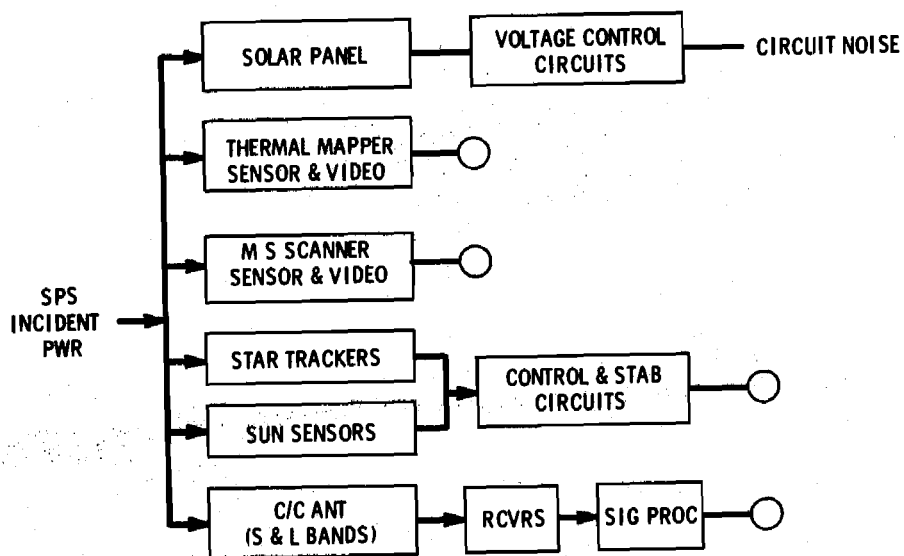


Figure 54. Block Diagram for Evaluation of SPS EMC Effects on LANDSAT. Circles identify evaluation points.

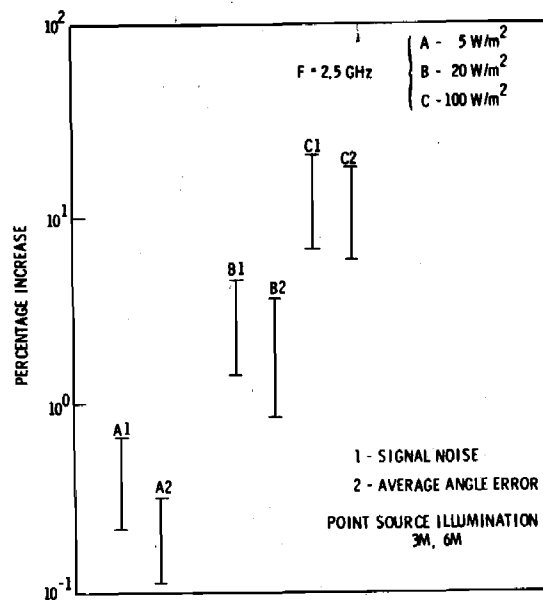


Figure 55. Effects of Microwave Illumination on a Star Tracker System Viewing Point Sources Simulating 3rd and 6th Magnitude Stars.

Mitigation techniques of possible use for receivers include rejection filters and antenna modifications. The former are preferred because of the relative simplicity, and the elimination of antenna control command and steering software additions. This filter should have a bandwidth of about 10 MHz, and an out-of-band insertion loss of less than 2 dB.

Mitigation techniques for the MSS and TM include circuit filters, noise extraction (spectral density-correlation models) in the data analysis process, and extended shielding for the detectors and collocated video amplifiers. Additional shielding for the video channel and scan control circuitry is recommended to eliminate jitter in the line scans, if the coupling is proven to be directly into these circuits and not through internal common connections. For the star tracker, circuit shielding and optical aperture wire mesh shielding are recommended. The latter is applicable here since focusing optical components are used in front of the photomultiplier tube. Effects of the sun sensor are insignificant; approximately 2% increase in noise, primarily because of SPS harmonics. This noise should cause less than 2° to 5° orientation change of the solar panels over a period of 1 to 1.3 seconds of maximum SPS beam exposure, and be corrected within 2 to 5 seconds after LANDSAT leaves the SPS beam. The error magnitude is limited by the solar panel control bandwidth and the small aperture of the sun sensors. Where sun acquisition by the sun sensors is occurring during SPS main beam exposure, the solar panel transient time would be extended by approximately 3 to 5 seconds because of the signal channel noise and related angular uncertainties.

9.3.2 GPS Satellite

The GPS is a navigation and position fixing system being implemented by the Department of Defense (DOD) to support worldwide strategic and tactical combat operations. The DOD is expected to decide within 1 to 2 years to allow nondefense uses of GPS. The orbiting complement will include 18 satellites by 1982. The satellites will have a 10,900-mile circular orbit, with a 12-hour orbit time.

This system provides a passive operational mode for users (receive only). The satellites provide two frequency transmissions at 1227.6 GHz and 1575.4 GHz in a QPSK format. Signals include time correlation, ephemeris, identification, and data to compute propagation errors. Users include satellites, aircraft, surface vehicles, and individuals through man pack receiver and display units. A position measurement accuracy of ± 10 to ± 30 meters is expected for the system; the variance depends on the severity of local multipath conditions and signal thresholds, and receiver velocity in the case of low altitude military aircraft.

Earth-to-satellite communications provide ephemeris update orbiting clock corrections and command/control data to the satellite computer from a CONUS station, directly and through TDRSS relay. The uplink communications use S band. Conical spiral receiver antennas are located on the space and earth pointing surfaces of the satellite.

The GPS power density variations for SPS beam intersection are plotted in Figure 56. Power coupling modes into the GPS satellite (Figure 57) are similar to those for LANDSAT. The GPS vehicle has the additional mode of direct entry through the thermal control louvers that control the temperature of the principal electronic functions -- clock, computer, and command/control receiver and decoder components. This direct penetration energy would primarily couple to electronic functions through cables and interface circuits (impedances Z_1 through Z_4).

Maximum and average SPS power levels reflected into the satellite electronics are 25 W and 2.8 W, respectively, considering power densities about 1 W/m^2 and louver openings of 10° , 30° , and 45° . Induced jitter in the internal clock and message decoder logic is estimated to be in the 10% to 65% range for SPS power in the 10-W to 25-W range. These initial estimates would need to be validated in future tests of modular logic components configured to represent GPS systems.

The S band communications receiver and associated processor would experience an increase in BER in the range of 50 to 1000 with the antennas exposed to SPS power densities of 100 W/m^2 to 1000 W/m^2 . The probability of losing signal because of mixer stage intermodulation products, in-channel noise, and gain compression lock is also important.

Mitigation techniques that would need to be validated for the GPS communications receivers are identical to those indicated for LANDSAT. Functional differences would result from the increased SPS maximum power density and the broad-band GPS signal mode.

Sun sensor control of solar panel orientation will be affected only in the same manner as discussed for LANDSAT. The short exposure times and the low control bandwidth limit the possible roll of the solar panels due to signal noise. The statement regarding sun acquisition when exposed to SPS illumination is also applicable to GPS.

The earth sensors on GPS are effectively shielded from SPS exposure by the satellite structure for all possible SPS - GPS geometric relationships over the western hemisphere. For geometries where GPS is over European or Asian areas but has a line-of-sight with an SPS side lobe, those power densities are at least 10^3 to 10^4 below the threshold for satellite pointing upset.

The GPS transmitters will not be affected by SPS penetration at the levels indicated. Power and driver amplifier circuitry, and the physical configuration, indicate no possibility of induced PM jitter on the transmitted signal attributable to coupling into transmitter circuitry. Transmitter antennas are shielded from direct SPS power exposure by the body of the GPS. The 50Ω power amplifier impedance, the wideband output tuned filters, and the output-input coupling of the power and driver stages indicate a net coupling of -40 to -65 dB for the SPS fundamental frequency, and values of -70 to -80 dB for the SPS second harmonic.

9.3.3 Space Telescope

In 1977, the space telescope project was approved by the United States Congress. The space telescope has major advantages over ground-based telescopes in three important areas. 1) The first and most significant is an order of magnitude improvement in angular resolution, 2) twenty-four hour per day observing time, and 3) the telescope being beyond the Earth atmosphere allows photometric data collection over a much wider wavelength range - ultraviolet, infrared, and submillimeter wavebands as well as the visual spectrum.

The Space Telescope orbit is circular at a 500 km altitude and 28.8° inclination. A cross-sectional view of the satellite observatory is shown in Figure 58. The telescope consists of the primary and secondary mirrors, the metering structure for maintaining the relative positions of the mirrors, the internal light baffling system and the fine guidance sensors. Communications with the satellite will be via the TDRSS. The scientific instruments on board are as follows:

Wide Field/Planetary Camera - the camera contains eight charge coupled device (CCD) detectors, each consisting of 800×800 elements.

Faint Object Spectrograph - uses digicon detectors, each of which consists of a linear array of 512 independent diode elements.

Faint Object Camera - the design uses a three-stage image intensifier with an intensified silicon target television camera tube.

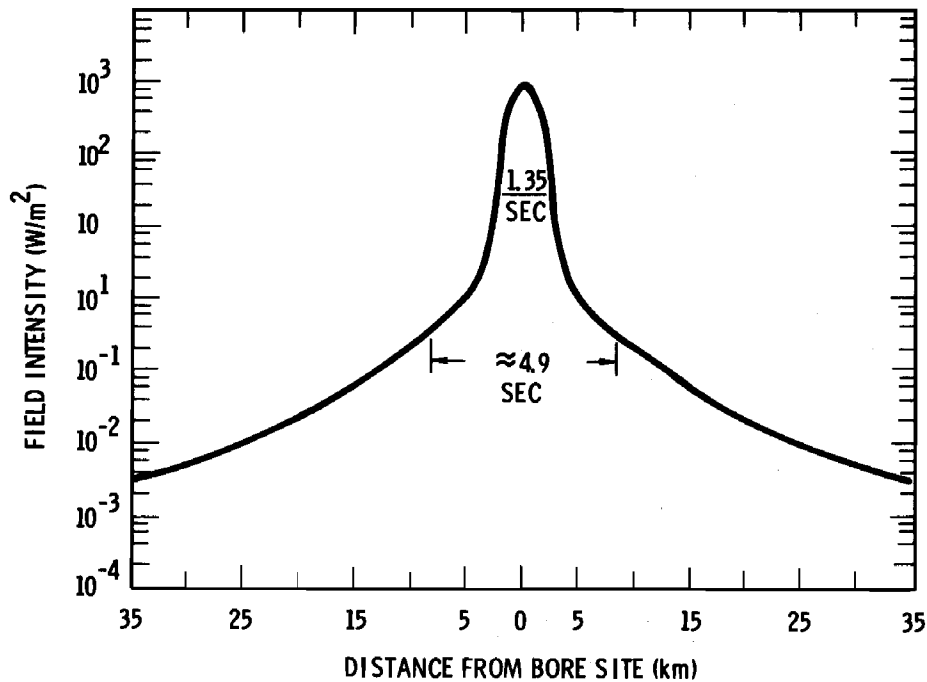


Figure 56. Microwave Field Intensity Encountered by GPS during Transit of SPS Power Beam.

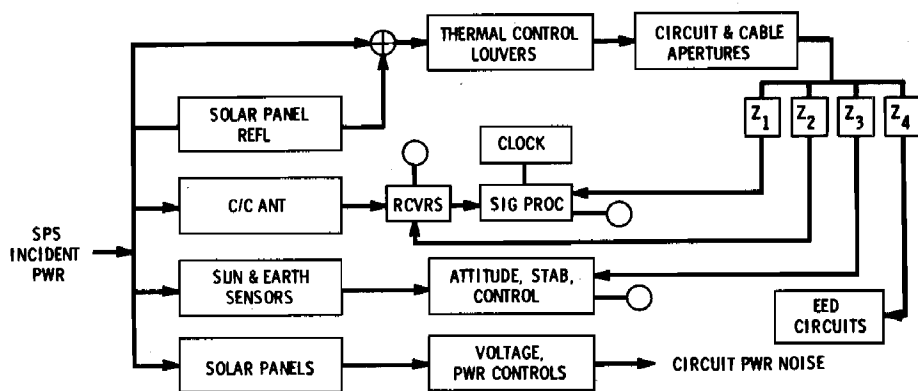


Figure 57. Block Diagram for Evaluation of SPS EMC Effects on GPS. Circles identify evaluation points.

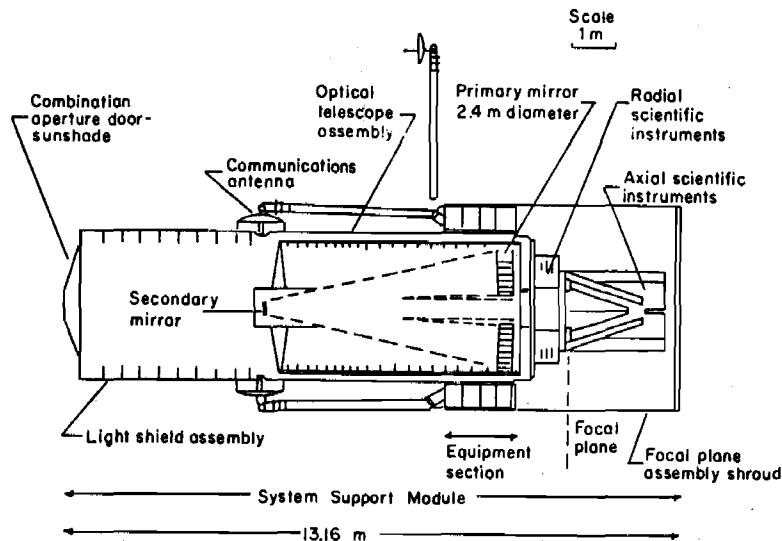


Figure 58. Cross-Sectional View of the Satellite Observatory

High Resolution Spectrograph - the detector is a digicon device consisting of a linear array of 512 diode elements.

High Speed Photometer/Polarimeter - the device consists of a number of image dissectors, their associated electronics and a focal plane aperture mask and filter plate.

Fine Guidance System - uses three independent sensors and detectors located in annular segments around the field of view in the focal plane. This system provides great astrometric potential. These three high-resolution sensors provide data for star field maps to support future stellar experiment planning. These sensors must acquire stars at $M=13$ with an accuracy of 7×10^3 arc seconds.

Coupling of electromagnetic energy into the satellite instrumentation will occur mainly through the telescope's 2.4 meter optical aperture. The SPS peak field intensity would be approximately 28 mW/cm^2 . This would be equivalent to about 1 kw of microwave power at the telescope aperture. About 40% of the energy would be coupled through the baffled area to the primary mirror. Some 20% of this energy would then be reflected through the mirror system into the detector area. There would be about 60% penetration into the detector areas which would be equivalent to 55 watts of 2.45 GHz energy directly into the instrumentation area.

The impact of SPS radiations on the scientific instruments would be to increase detector channel noise, reduce spatial resolution, and reduce dynamic range. For the satellite guidance system and astronomy missions there would be increased detector channel noise and reduced spatial resolution which would increase attitude instabilities for the few seconds the space telescope is in the SPS beam.

Figure 37 previously shown on page 36 shows a CCD array as used in the widefield camera being illuminated with a normal source signal and the associated resolution given in lines per minute. One line is the normal response of such an array. The other shows the degradation in resolution in the presence of a 2.5 GHz, 2 mW/cm^2 rf field. Here it can be seen that it takes a higher source illumination for a given resolution in the presence of the microwave field, particularly below 10^{-5} mW/cm^2 .

CCD matrices, digicon devices, image intensifiers, and image dissectors will experience degraded capabilities in the presence of SPS energy as the satellite observatory intersects the main power beam and major side lobes. The apertures in front of the detectors afford very limited protection since the axial length will be less than $\lambda/2$ for the SPS fundamental or primary harmonics.

Mitigation techniques would include wire mesh shielding for image dissectors, digicon devices, and CCD arrays, where focusing optics are employed. For submillimeter, infrared, or ultraviolet detectors, the wire mesh would cause unacceptable distortion and large data errors. Increasing the axial length of the apertures for the instrument detectors to 6 cm will provide 40-60 dB microwave attenuation. Uplink communications through TDRSS should not be accomplished during beam intersection. Crystal lenses in

the optical link would attenuate microwave energy to keep unacceptable interference from the fine guidance system or other on-board systems used in stabilization and tracking for the telescope. Upset in attitude stabilization would be corrected over a considerable portion of an orbit to stabilize the total system after passage through an SPS beam. A provision for "coasting" through the power beam should also be acceptable because of the short transit time. To maintain specification accuracy, a rate memory mode will be required in the attitude stabilization system.

9.3.4 Summary of LEO Effects and Mitigation

The SPS interaction with LEO satellites involves primarily periods of orbit intercept with the SPS power beam. Performance effects concern uplink communications, sensors for data collection and attitude control, and internal modules that are directly exposed to penetration apertures (e.g., thermal control louvers). Mitigation methods for these LEO satellite functions are listed.

1. Silence uplink receivers when encountering SPS power densities $> 0.2 \text{ mW/cm}^2$. This will involve an orbit period of from 0.5 s to 3 s depending on orbit altitude.
2. Add mesh shields to all thermal control apertures; mesh $< 2 \text{ cm}$ diagonal dimension.
3. Single-point grounding and complete metal shielding for all logic, computer, and clock components. All signal, control, and signal ground cabling must use coaxial cabling.
4. Attitude control sensors (star trackers) should be covered with a wire mesh ($d < 2 \text{ cm}$) if focusing optics are employed. Mesh is placed at defocused axial positions, and AWG 26 to 32 copper wire grounded to the satellite structure should be used.
5. Attitude sensors not using focusing optics should use crystal mirrors or a metal cylindrical collimator having an axial length $\geq 6.5 \text{ cm}$. These methods will provide $\sim 20\text{--}30 \text{ dB}$ suppression.
6. Earth sensors (visual and IR optical staring or scanning devices) should use a metal collimator with axial length $\geq 6.5 \text{ cm}$, and complete shielding around video amplifiers and control circuits coupling from the sensor elements.
7. Where the recommended data sensor shielding must be compromised in axial dimension, image enhancement software will be required in data reduction to remove periodic noise components and to restore higher spatial frequencies.

9.4 OTHER POTENTIAL INTERFERENCE CONSIDERATIONS FOR SATELLITE COMMUNICATIONS SYSTEMS

Co-channel interference levels below $-185 \text{ dB(W/m}^2 \cdot 4 \text{ kHz)}$ will be needed to protect earth terminals with antenna apertures of 1 square meter or more, see Figure 45. These figures apply to narrowband systems such as single channel voice systems and FM-FDM voice systems with a 4-kHz reference bandwidth. Wide-band satellite earth terminals with a 1-MHz reference bandwidth can withstand higher interference levels of up to $-161 \text{ dBW/m}^2 \cdot \text{MHz}$, see Figure 46. Earth terminals whose operating frequency is significantly separated from the SPS power transmission frequency can withstand interference levels substantially higher than those quoted above because of filtering in the receiver. Estimates of the maximum amount of filtering available in satellite receivers is -130 dB . Laboratory testing needs to be conducted to define more precisely the maximum filtering available in satellite receivers.

Calculations of the potential interference between SPS and NAVSTAR GPS navigation receivers showed that SPS does not represent an interference threat to the 1575.42-MHz navigation signal. The combined rf and IF filtering of the navigation receivers should be sufficient to prevent interference even in an SPS power flux density of -10 dBW/m^2 (0.01 mW/cm^2). A similar conclusion was also reached in a study of interference to MARISAT earth terminals in an SPS microwave field of -40 dBW/m^2 ($1 \times 10^{-5} \text{ mW/cm}^2$). However, a potential interference problem does exist with MARISAT terminals in a field of -10 dBW/m^2 .

Interference problems are also possible between SPS and other satellites closely spaced in geosynchronous orbit. This study estimates that a power flux density as high as -20 dBW/m^2 can be expected at victim satellites within 0.1° of separation from SPS. This figure is based on an SPS antenna gain in the direction of the geosynchronous orbit of -10 dBi . Signal levels of this magnitude can be sufficient to cause interference to satellite systems with reference bandwidths of 4 kHz. It is estimated that separations of more than 1.0° may be required to prevent interference to other satellites in geosynchronous orbit.

9.5 FUTURE SATELLITE SYSTEMS

A number of resource monitoring satellites are currently in the concept definition phase. These conceptual systems are:

1. Earth Watch
Orbit altitude approximately 6000 mi,
mapping and microwave monitor.
2. Microsat
Passive L band radiometer.
3. Radar Holographer
Bistatic radar (GEO illuminator with LEO collector).
4. GEOSAR
GEO synthetic aperture radar.
5. Ellipsometer
Bistatic radar for moisture measurement.
6. LANDSAT-H
MSS scanner and synthetic array radar.

Most satellites passing through an SPS beam will experience problems similar to those of LANDSAT and GPS. Satellites with optical apertures will probably experience more problems than those without that coupling mode. In-depth analysis of these satellites would be necessary if the SPS concept is pursued.

9.6 CONCLUSIONS AND RECOMMENDATIONS

The evaluation of the SPS operation effects on other GEO and LEO satellites indicates the character of EM functional interactions, including modes of penetration into satellite receivers, sensors, and circuits, and the resultant functional degradation in data collection and processing.

The GEO communications satellites should be separated from an SPS by about 1.0° at orbit altitude to assure acceptable uplink performance, where SPS interference effects include coupling of SPS fundamental and harmonics from spacetenna sidelobes, and reflective multipath from the SPS structure. This separation will allow an $S/I > 15$ dB for the adjacent communication links.

Future satellites using array antennas can employ nulling techniques for SPS harmonic components that are within communications bands. This method can provide about 20-30 dB suppression from unmodulated interferers.

Satellite-satellite communications modes with an SPS between communications satellites cannot be satisfactorily accomplished without a frequency translator-repeater operating on the SPS vehicle because of reflection multipath interference. Without the SPS repeater, fade depths might restrict link utility for digital or medium bandwidth analog data transmission.

Multiple use communications platforms and multiple spacetenna-SPS platform configurations represent a viable technical option for elimination of the orbit slot contention problems for a 60 SPS deployment.

10.0 EFFECTS ON ASTRONOMY AND RELATED RESEARCH

The SPS Reference System (DOE/ER-0023) was used to identify and evaluate significant potential effects on astronomy and related research areas. Some effects are due to specific and active properties of the system. Others arise from general and passive aspects of any system of large satellites. A fractionally small portion of the microwave power not collected by the rectenna would probably interfere with current observations in radio astronomy and could conceivably damage receiving apparatus. Thermal emissions at radio frequencies from the large warm satellites could also have an effect on radio astronomy. The diffuse reflection of sunlight from the large satellites in geosynchronous orbit would affect optical astronomy and aeronomy by increasing the brightness of the night sky. The brightness of the night sky may also be increased by operations in low earth orbit (LEO) and by specular reflection from the large satellites.

The assessment of the impact on astronomy has two natural divisions: optical effects and radio effects. This division is consistent with an astronomical tradition of dividing the profession according to the portion of the electromagnetic spectrum that is observed. From another viewpoint, the division expresses the separate effects of the passive and active properties of the satellite system. In particular, the major optical effects caused by SPS would be functions of the system's structures in orbit and would continue even if the system were turned off. Radio astronomy, however, would be particularly affected by the active portion of the system--the intended microwave transmission of energy from space to earth. Both optical and radio astronomy impacts are primarily a result of unintentional side effects. The optical effects would occur because the SPS solar blankets would reflect some of the light that strikes them. The radio effects would occur because a small portion of the transmitted energy would not be confined to the narrow beam from the orbiting antenna to the earth rectenna, or to the assigned portion of the radio spectrum.

This summary of effects is freely drawn from a workshop on the potential impact of the conceptual Satellite Power System on Astronomy (report: CONF-7950143) attended by recognized working scientists and held in May 1979.

10.1 RADIO ASTRONOMY AND DEEP SPACE RESEARCH

The SPS concept which proposes the transmission of power to earth via microwaves has a number of potentially damaging consequences for radio astronomy and space research. Production of harmonic radiation and generation of noiselike radiation throughout the spectrum could result in harmful interference. This interference might be produced by SPS satellites in normal operation and in potentially more damaging quantities by various failure modes.

The SPS is unique in the large quantities of radio frequency radiation that will be generated, especially at the fundamental frequency. Radio observatories have been carefully situated at remote sites to protect against such adjacent channel interference effects from earth-based transmitters, but location cannot protect against such effects from transmitters in synchronous orbits. The field strengths in grating side lobes are of particular concern, and for a large number of SPS ground-receiving stations, it is not clear that grating side lobes will miss active radio observatories, or that observatory operation within a side lobe will be practical.

Radio astronomy and space research are recognized radio services as defined in the Radio Regulations of the International Telecommunication Union, with recognized frequency bands that are protected by allocation in the treaty documents. Definitions of harmful interference to these services have been developed by the International Radio Consultative Committee (CCIR). CCIR Report 224-4 describes these criteria for radio astronomy, and CCIR Reports 365-3 and 685 give the criteria for the space research service. The harmful spectral flux densities, specified in $\text{dB(W/m}^2\text{-Hz)}$, have been established as reasonable and measurable quantities, and an SPS would have to conform to those specifications in order to avoid harmful interference to those services.

In addition to the specific bands allocated to the Radio Astronomy Service, passive radio astronomy research is conducted at many other frequencies throughout the spectrum. Many of the frequencies of interest are spectral lines (often Doppler shifted from their real frequencies). A list of such spectral lines is included in CCIR Report 223. To achieve reasonable interference protection at frequencies outside the bands allocated to radio astronomy, radio observatories have been located in remote areas where man-made interference levels are low. To formalize such protection, the FCC established in 1958 a National Radio Quiet Zone (NRQZ) surrounding the National Radio Astronomy Observatory in Green Bank, West Virginia, and the nearby Naval Radio Research Laboratory in Sugar Grove, West Virginia. Within this quiet zone, FCC licensing procedures are intended to allow only transmitters that produce power fluxes at the observatories of less than 10^{-17} W/m^2 . A few broadcasting stations remote from the NRQZ do exceed these limits, producing power fluxes at the observatories on the order of 10^{-12} W/m^2 . Other observatories and the Deep Space Network Station at Goldstone, California, have less formal arrangements to minimize local sources of interference, generally based on the requirement that spurious radiation in the protected bands not exceed the levels given in CCIR Report 224-4 (or CCIR Report 685 in the case of the Deep Space Network).

The strongest anticipated SPS harmonic, the second at 4.9 GHz, does not fall into a currently allocated band of these services, but does fall well within the principal operating band of the Very Large Array (VLA), a major national radio astronomy facility near Socorro, New Mexico, and at the shortest usable wavelengths of the Arecibo telescope, the worlds' largest radio/radar telescope. These facilities could be seriously compromised.

The potential for SPS interference with radio astronomy and deep space research depends crucially upon the noise and harmonic generation properties of all components of the system. At present, the properties of the klystrons in the Reference System must be estimated by extrapolation. If prototype SPS

transmitters and antennas are developed, laboratory tests could be made of radiated power in the range from approximately 1000 MHz up to the frequency where radiation in the SPS main beam is no more than the amount equivalent to the satellite's passive thermal radiation as seen from the surface of the earth. This test result would permit calculations of the impact of SPS on radio astronomy and deep space research.

The interference potential of the SPS Reference System would significantly increase if the off-axis signals were time-varying on the same time scales as are used for astronomical observations, as it can then mimic the expected behavior of the observations. As currently defined, the Reference System has such an intrinsic time-variability. In the Reference System, all 60 satellites transmit at 2450 MHz. However, it is not possible to phase lock the satellites in such a way that the off-axis radiation from different satellites will remain phase-constant for all ground-based observers. Each satellite pair, considered as a transmitting interferometer, will have an off-axis fringe pattern. Unavoidable station-keeping motion will cause this fringe pattern to sweep across the United States in a complex and partially unpredictable pattern.

One potential solution is to offset the frequencies of different satellites by small amounts, to introduce lobe rotation and thus reduce the averaging time needed to reduce the interference. A frequency assignment plan for the SPS satellites is required to assure no unacceptable intermodulation effects.

Generation of harmonics and intermodulation products in nonlinear elements in the SPS and its environment could produce spurious emissions in the radio frequency spectrum. Such effects occur frequently where many antennas transmitting on different frequencies are assembled in a small area. They are the result of the interaction of currents of different frequencies in rectifying junctions in metal structures, hence the name "rusty bolt effect." Normally, intermodulation products attenuate rapidly with distance.

The extremely high field strength in the main beam of the SPS, nearly 300 V/m at the earth's surface, makes it probable that nonlinear conduction will occur in any rectenna structure containing corroded joints or fasteners or other nonlinear elements. Even if it were possible to eliminate all electrically nonlinear joints in the vicinity of the rectenna, the diodes in the array would serve as modulators, producing the same effect unless adequate filtering were provided. Other signals of much lower strength, such as those from television or radar transmitters some distance away, can be expected to interact with the SPS fundamental frequency and its harmonics. It is conceivable that these modulation products may be of suitable frequencies and strengths to be transmitted over great distances by reflection from the ionosphere or from aircraft or spacecraft.

Illumination of other spacecraft or aircraft by the SPS beam may result in similar effects. These vehicles carry antennas connected to nonlinear receiving and transmitting circuits. Especially in the transmitting circuit, the SPS frequency and the other transmitting frequency, or their harmonics, may mix in ways to produce out-of-band radiation. Nonlinear effects from metal structures on the vehicle may also be expected.

The side lobe radiation flux from each power satellite could range as high as $2 \times 10^{-3} \text{ W/m}^2$ within a few hundred km of the rectenna, 10^{-1} W/m^2 at the grating lobes, and 10^{-5} W/m^2 at various peaks out to distances of 400 km from the rectenna (DOE/ER-0023, Figures 19 and 22). For comparison, the flux near radio and TV broadcast stations in metropolitan areas (e.g., in Los Angeles at a distance of 20 km from Mt. Wilson) might be of the order 10^{-5} W/m^2 . A system with 60 satellites serving the entire country would raise the power flux to this value (10^{-5} W/m^2) at side lobe peaks scattered over the whole country, since the mean spacing between rectenna sites would then be ~ 300 km. Thus, in a sense, construction of the SPS would make the radio environment of much of the continental United States as unsuitable for sensitive radio observations as the most densely populated areas are now.

In addition to the satellite signal, fundamental and harmonic power and wideband noise would be re-radiated by the rectennas. This radiation may be reflected by aircraft and by unusual meteorological conditions to distances of the order of 100 km from the rectenna site. The severity of the direct radiation problem will depend on local topography.

Observations made with arrays of receivers used as interferometers may, in some circumstances, be less sensitive to SPS interference than those made with a single receiver. Calculations have been made to estimate the effects of fringe-frequency averaging and decorrelation which reduce the sensitivity of the VLA to interference. The magnitude of the effects for other synthesis arrays depends on parameters of the particular array. The fringe-frequency averaging depends on the size of the synthesized field of view and hence on the configuration and observing frequency. The most compact VLA configuration, for which the interference reduction is least effective, will be used as an example in considering the tolerable interference levels. For this case the reduction is approximately 10 dB for the 18- to 21-cm band and 17 dB for 1.3 cm. These figures refer to declinations south of $+70^\circ$, and the fringe-frequency averaging becomes less effective toward the pole.

The decorrelation effect depends mainly on the antenna configuration and the bandwidth, and again the most compact configuration will be considered. The interference reduction is approximately 14 dB for a 25-MHz bandwidth and 17 dB for a 50-MHz bandwidth. These figures apply to a source of interference at the declination of the satellite, -5.5° , and for an observing declination north of $+20^\circ$. As the observing declination approaches that of the satellite, the interference reduction becomes much less effective.

Under certain circumstances the above effects should allow the VLA to operate with no decrease in performance in the presence of interference received in the far sidelobes of the antennas, for which the gain is equivalent to that of an isotropic radiator. With that condition, and for declinations from $+20^\circ$ to $+75^\circ$, levels of interference about 20 dB to 30 dB higher than the CCIR levels should be tolerable. However as the declination of the satellite is approached, this margin falls to about 13 dB.

Since the line of satellites is essentially constant in declination, at -5.5° as viewed from the VLA site, there will be a zone of declinations centered on -5.5° in which the array cannot operate without receiving interference above a tolerable level. To avoid such interference, the range of hour angle tracking would have to be reduced by something more than the 60° longitude range of the satellites, and satisfactory mapping of celestial objects in this zone would not be possible.

10.2 OPTICAL ASTRONOMY

The primary effect of the SPS on optical astronomy would be through the predicted increases in brightness of the night sky. The assessment of this effect focused on diffuse reflections from the satellites. Other concerns, such as the effects of specular reflections and possible impacts on infrared and space astronomy, are not treated in detail, primarily because of surface characteristic uncertainties, as in the case of airglow from the SPS-heated ionosphere. They can be completely characterized if specific SPS designs are developed. For example, specific effects of specular reflections from the antenna depend heavily on rectenna siting and antenna properties.

The actual method of conducting astronomical research is the root of any effect of the proposed SPS on astronomy, and on optical astronomy in particular. Optical astronomy is characterized by its preoccupation with the detection of photons. A photon of visible light represents about 4×10^{-12} ergs of energy, which means that if a 100-watt light bulb emitted 100 watts of visible photons, it would emit 10^{20} of them per second. Detectors used in optical astronomy are sensitive enough to detect single photons. In many cases, astronomical detectors are photon counters.

An important problem encountered in photon counting is that the answer arrived at includes an uncertainty corresponding to the square root of the total number of photons counted. Therefore, the fractional error in the number of photons detected is $1/\sqrt{N}$ where N is the total number of photons detected. If an astronomer counts 100 photons, the uncertainty is 10%, if 10,000, the uncertainty is 1%.

Unfortunately, the detection of photons from astronomical objects is complicated by the fact that the sky is a source of photons as well. In the case of an idealized astronomical observation, one can imagine looking at an astronomical object, with a typical optical detection system and trying to make an observation with 1% accuracy. Because the detector cannot avoid looking at both the sky and the object, it collects and counts the photons from both. However, when the object is very much brighter than the sky, the photons from the sky make a negligible contribution to the total signal, and we get 1% accuracy just as soon as we have detected 10,000 photons from the source. In such a case, the brightness of the source determines how long the observation will take. If, however, the number of photons received from the sky is comparable to or greater than the number from the object under study, then the brightness of a nearby portion of sky must be determined and subtracted from the observation of the object. However, sky photons can only be measured at best to an accuracy of $1/\sqrt{N}$ just as photons are from the object. For example, if the sky is nine times brighter than the object and our detector counts 10,000 photons from the sky and object together, which gave us 1% accuracy before, our accuracy for measurement of the object would only be 10%. In this case, the observation is said to be "sky limited"—in order to get a 1% measurement of our source, the detector must have detected 1,000,000 photons. This value represents 100,000 photons from the source or ten times as many as were required to get a 1% measurement without the sky. Therefore, even if the sources in our two examples were the same brightness, the addition of the bright sky would increase by a factor of ten the amount of observing time required for the same accuracy measurement.

Natural and man-made sources of sky brightness already have a significant impact on the conduct of optical astronomy. The largest natural contribution to the diffuse night sky brightness comes from the moon. The moon has such a profound effect on the sky that observatories routinely divide their observing schedule into "dark" (no moon) and "bright" (moon up) time. Dark time is in much greater demand than bright time on large telescopes.

At present, the primary man-made source of sky brightness is outdoor light from cities and towns. Astronomers have attempted to combat this light pollution in a number of ways—the most obvious, building

telescopes in remote locations well away from city lights. For example, the detailed site surveys that precede construction of a major observatory always include assessments of the sky brightness. In some cases, urban areas have grown up adjacent to observatories. At some of these observatories, observations are limited to the kinds of objects observed during "bright" observing time at darker sites as is the case at Mt. Wilson Observatory where the light pollution from Los Angeles and nearby cities makes the sky very bright. At other observatories, observatory staffs have attempted to convince local public officials that it is possible to control light pollution and minimize the effects of outdoor lighting on astronomy. Tucson, Arizona, and Richland, Washington, among others, have very strong light abatement ordinances specifically tailored to preserve dark skies.

Objects of astronomical observations fall into two categories: point sources and extended sources. For point sources, every attempt usually is made to make the amount of sky being observed as small as possible. Although this is limited by the turbulence of the atmosphere, a small aperture does represent a practical method of reducing the effect of sky brightness for objects that appear as point sources, such as stars.

However, this strategy is not usable for extended objects, such as galaxies. In order to reduce the amount of sky being observed, one must correspondingly reduce the amount of the object to be studied. The case of galaxies is an important one since the average surface brightness of a galaxy (the number of photons emitted per unit area) is considerably less than the average brightness of the dark night sky. Galaxies are brighter toward their nuclei; therefore, the net effect of increasing the sky brightness is to reduce the amount of a galaxy that can be observed. This effect is qualitatively illustrated in Figure 59. The consequences to research of not being able to observe the outer regions of galaxies are noted after the following section.

An observing program is the set of observations that astronomers will make in order to address a particular astronomical problem. The organization of typical observing programs is important. The increase in diffuse sky brightness as a result of SPS is a function of position on the sky, which implies that in particular regions of the sky it will not be possible to observe particular kinds of objects.

Observing programs consist of "surveys" and "type studies". Most observing programs include elements of both kinds of studies. A survey entails the measurement of a few parameters for a large number of objects. An example is the National Geographic-Palomar Sky Survey. This survey, conducted in the 1950s, consists of photographs taken through two different colored filters of almost the entire sky visible from Mt. Palomar. A type study is the detailed study of a single object that is either unique or thought to be representative of a class of objects. Generally, type examples are usually the nearest members of the class.

When planning the details of an astronomical observing program--specifically, what objects are to be observed--several other factors must be considered. The most important is the fact that the atmosphere is not completely transparent, so that the flux of photons from an object is attenuated as it passes through the atmosphere. The amount of attenuation is exponentially related to the amount of the atmosphere the radiation passes through, which is measured in airmasses. An airmass is the ratio of the amount of air toward the object to the amount of air toward the zenith, the point straight above the observer. In order to maximize the number of photons observed, observations must be planned to minimize the average airmass through which the object is observed. In practical terms, this usually means that an object will be observed during the time that the object is within 30° of the meridian, an imaginary line on the sky on which astronomical objects are at their minimum airmasses. Objects are in this band for four hours every day. Many astronomers have concluded that four hours is a practical upper limit for a single observation. Finally, because objects more than 60° from the zenith must be observed through more than two airmasses, objects that never come closer than 60° to the zenith are usually not included in an observing program.

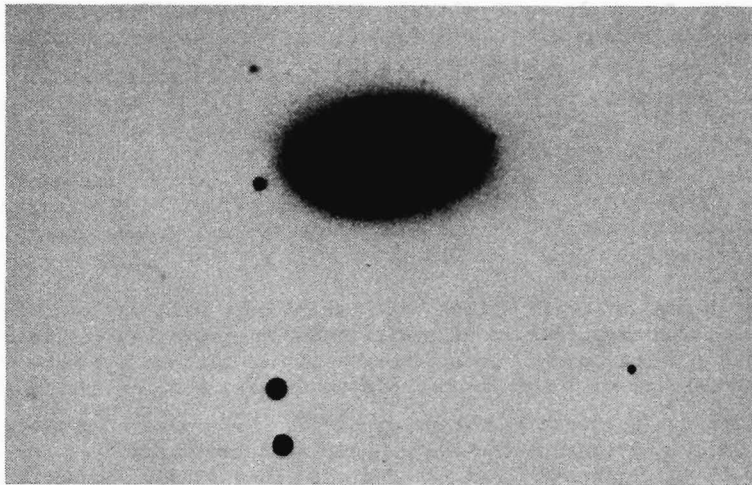
10.2.1 Major Research Areas

Current areas of active research that would be negatively affected by the SPS program are listed below. These are important research areas, but no effort at completeness is intended.

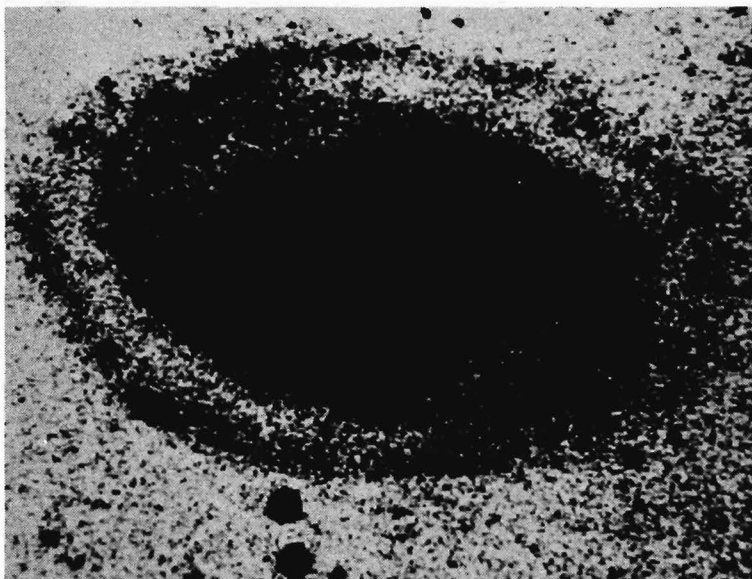
10.2.1.1 Cosmology and Extragalactic Astronomy (Studies of Objects Beyond the Milky Way)

Because distances to extragalactic objects are so great, most galaxies, although as luminous as several billion stars, are as difficult to discern and study as the faintest stars visible in our own galaxy.

- The Size of the Universe. Measurements of the size of the universe depend on our ability not only to observe the most distant (and faint) objects but also to develop techniques for distance measurement. The identification of distant objects is extremely marginal because of their faintness and is complicated by the presence of a bright sky background "against" which they must be viewed from the ground. Even small increases in sky brightness can render these objects undetectable.
- Curvature of the Universe.
- Formation Era of Galaxies.
- Open or Closed Universe.



A



B

FIGURE 59. Photograph taken at Prime-Focus of the Cerro Tololo Inter-American Observatory 4-m Telescope of the Galaxy NGC 1079 (40-min exposure IIIaj plate and GG385 filter). Photograph A shows conventional print contrast: B shows the contrast stretched to go between dark and light over a narrow brightness range just above sky background using the Interactive Picture Processing System of Kitt Peak National Observatory. The difference between the two pictures shows the loss of outer detail seen in B that would occur with a doubling of the background sky brightness.

- Active Galaxies and Quasars.
- Faint Regions of Nearby Galaxies.

10.2.1.2 The Milky Way

Our galaxy is one of the most interesting, yet enigmatic, of astronomical objects. We look to our solar neighborhood to understand how stars are born, live their lives, and die, and to understand how our galaxy is structured. The nuclei of many galaxies harbor unusual and, as yet, not understood energetic processes. What about our own? Do other stars have planets? To complicate observations, large clouds of dust hide 90% of the galaxy from view to observers using optical and ultraviolet techniques. The effective size of the visible galaxy would be severely diminished by even small increases in the night sky levels.

- Diffuse Galactic Light. "Hot tunnels" carved through the galaxy by supernova blast waves appear to permeate the galaxy. Many studies are underway to understand the physical conditions (e.g., temperatures of a million degrees) through optical and ultraviolet observations, but the light levels from these regions are very, very low (they were only recently discovered).
- Faint Nebulae.
- Stellar Winds and Mass Loss.
- Structure of the Galaxy.

10.2.1.3 Solar System

There are some interests in the solar system for which a bright background would severely impede ground-based research. For example, comets and their tails, asteroids, and other "minor" constituents of the solar system are generally faint. The plane of the ecliptic is fairly closely aligned with the equatorial plane of the earth and the satellites, and the faint objects found preferentially in the ecliptic plane, such as minor bodies, will be difficult to observe near the satellites. Although comets do not have ecliptic orbits, they and their tails are generally in their most favorable aspects as they near the ecliptic. Similarly, the zodiacal light is also confined to the ecliptic plane and, likewise, will be difficult to observe near the satellites.

10.2.2 Effects of SPS on Optical Observations

The single most important point to keep in mind when considering the effects of SPS on optical astronomy and aeronomy is that the major effect, the increase of sky brightness, stems from the passive properties of the system. As such, this effect is inherent in any space-based solar power collection scheme. For the Reference System, the solar blanket intercepts a large quantity of solar radiation. The most important portion of the collected energy which has an effect on astronomy is the light reflected from the front surface of the blanket. This reflected radiation constitutes approximately 7% to 15% of the visible radiation incident on the solar blanket and is made up of both diffuse and specular reflection, as described in the workshop report. The diffuse reflection is responsible for the most persistent and troublesome effects on astronomical and aeronomical observations. The magnitude of the effects is determined by the apparent brightness of the satellites and the properties of the atmosphere. In turn, the brightness of the satellites is determined by their size and reflectivity. The Reference System satellites would be exceeded in brightness by only the sun and the moon.

Even though the actual brightness distribution around an individual power satellite will depend strongly on physical conditions, several properties of the brightness distribution of the entire system are relatively independent of local physical conditions. The area of increased brightness is sharply peaked. In Figure 60, the predicted increase in the sky brightness along the meridian at midnight for Kitt Peak National Observatory has been plotted for a 60-satellite system. While the intensity scale shown in the figure is for a satellite brightness equal to that of Venus, the shape of the profile is independent of satellite brightness and variations in local meteorological conditions (the profile having two parts, the core and the wings). The sharply peaked core region represents the portion of the sky in which the scattered radiation from the one or two nearest satellites dominates the brightness distribution. In the wings, all of the satellites make a modest contribution to the sky brightness. The transition between core and wings is determined primarily by the separation between the satellites, which for the Reference System is 1° .

Figure 60 also shows the thresholds for a noticeable effect, hindrance and contamination as defined after the following section. The width of the affected zones is the region between the intersection of the brightness profile and the various thresholds. Both the effect of changing satellite brightness and the varying meteorological conditions can be thought of as moving the brightness distribution profile up or down with respect to the threshold values. For example, with either satellites brighter than assumed (4% albedo) or less favorable weather conditions, the profile is moved upward, thereby substantially increasing the amount of the sky in the different zones.

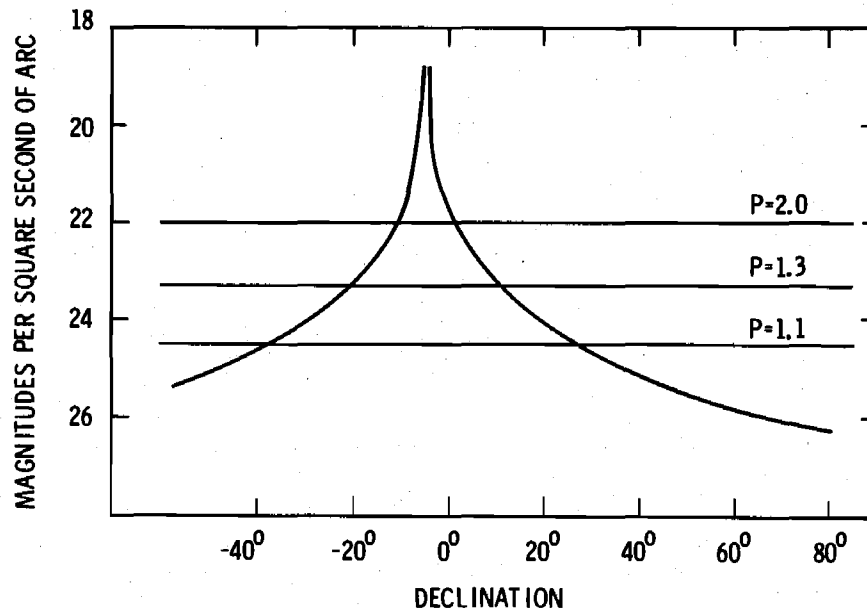


FIGURE 60. The SPS Brightness Profile. This figure shows the predicted brightness of the sky as a result of a 60-satellite SPS system along the meridian at local midnight for Kitt Peak National Observatory at the vernal equinox. The calculation of this profile is based on an assumed 4% diffuse albedo. The brightness levels, P , corresponding to the three impact thresholds described in the text, are also shown.

Unfortunately, the total area at the contaminated zone is not directly proportional to satellite brightness. Because the brightness profile is so sharply peaked, even relatively large reductions (by factors of 2 or 3) in the brightness of the individual satellites would not greatly reduce the size of the contaminated zone. Alternatively, the relatively broad wings of the intensity profile mean that corresponding increases in the apparent magnitudes of the satellites will result in quite large increases in the size of the contaminated zone.

Objects in low earth orbit (LEO), even though smaller than the large SPS structures to be placed in geostationary orbit (GEO), can have similar optical effects. An object with a surface area of 1 km in an 800-km-high orbit has the same apparent size as a 55-km² SPS solar blanket. Their relative brightness will then be determined by geometry and albedo. One difference is that the LEO object is only illuminated through the portion of its orbit that is not in the earth's shadow.

Another difference between GEO and LEO objects poses a particular problem for astronomical observations. Since the power satellites themselves are located in GEO, their position in the sky is fixed. As a result, if their apparent luminosity can be reduced, then the parallactic effect between the northern and southern hemisphere observatories would allow astronomical observations to be planned in a fashion that would minimize but not remove the effect of the SPS on observing programs.

An object in LEO is not geostationary, and it will appear to move across the sky as it travels in its orbit around the earth. Therefore, if the LEO structures are large and reflective, they would appear as bright planet-like objects moving relatively rapidly across the sky. Workshop attendees pointed out that observations made with the 48-in. Schmidt telescope located on Mt. Palomar are routinely affected by existing satellites. The photographs made with this telescope cover a relatively large area of the sky, about the size of the bowl of the Big Dipper (6° x 6°), and are usually made with exposure times of about one hour. Since there are a large number of objects now in orbit around the earth, it is not unusual for a picture taken with this telescope to show the trails of satellites. Because current satellites are small, they are not very bright and the trails are primarily a nuisance. As LEO satellites get larger and brighter, it will be necessary to schedule observations to avoid them.

Because there are natural sources of diffuse sky brightness (sunlight reflected by dust in the solar system and aurora and airglow in the earth's upper atmosphere), any effect of the SPS should be compared to those sources of radiation. The parameter p is the factor by which the flux of radiation from the night sky is increased over its natural value. In general, the workshop attendees felt uncomfortable associating particular values of p with specific effects on optical astronomy. However, in the following paragraphs we suggest that $p > 1.1$ results in a noticeable effect, that $1.3 < p < 2.0$ creates a serious hindrance to optical astronomy, and that regions of the sky with $p > 2$ are contaminated zones within which faint-object astronomy is no longer a reasonable endeavor.

The required observing time is directly proportional to our pollution factor p . When working on faint sources, increase in light pollution is equivalent to reducing the aperture of a telescope by a factor of $1/\sqrt{p}$. For the largest American telescope, the 200-in. telescope at Mt. Palomar, the effect of doubling the sky brightness would be to reduce the aperture of the telescope to 140 in.

The threshold values for effects on optical astronomy described above were arrived at in the following fashion:

- Noticeable effect ($p = 1.1 - 1.3$) - Although some members of the astronomical community would find any additional source of diffuse sky brightness unacceptable, we believe $p = 1.1$ as a result of SPS to be the threshold for a demonstrable impact on optical astronomy. This figure is the usual value quoted for the onset of "light pollution" for the purposes of light abatement ordinances with cities near observatories. The value represents a 10% increase in the night sky brightness and is equal to about 1/2 of the natural variation of the airglow over the 11-year solar cycle. As a further point of reference, at Kitt Peak National Observatory, the lights of Tucson, Arizona, result in $p = 1.07$ at the zenith.
- Severe hindrance ($p = 1.3 - 2.0$) - This level of light pollution will obviously have a demonstrable effect on optical astronomy. The lower range ($p = 1.3$) means that observations will take 30% longer to reach the same level of statistical accuracy; $p = 2.0$ corresponds to the doubling of observing time.
- Contamination ($p > 2.0$) - At this level of light pollution, compensating for increased sky brightness with increased observing time is no longer possible. Figure 59 illustrates the loss of information for observations of galaxies that would result from $p > 2.0$.

The relationships among SPS-induced increases in sky brightness, typical astronomical observing programs, and thresholds for specific impacts on optical astronomy are summarized in Figure 61. The diagrams in this figure show the outer contours of three light pollution zones described in the preceding section as they would appear at midnight from the Kitt Peak National Observatory. This observatory was chosen as representative of the observatories located on the major continental masses of the Western Hemisphere.

Diagram 61A shows the computer contours for 4% satellite albedo. Diagram 61B shows the contours if the apparent brightness of the individual satellites were increased by a factor of two. The vertical axis in each of these diagrams is declination, the astronomical equivalent of latitude. As the earth rotates, astronomical objects will appear to rise at the left of these diagrams and move to the right at constant declination. Because the power satellites are in geostationary orbit, the brightness contours will remain fixed in this coordinate system, and astronomical objects at the same declinations will appear to move through these zones of light pollution. These diagrams (Figure 61) illustrate how extremely sensitive the specific impacts on astronomy are to the detailed properties of the proposed system.

The primary effect of the SPS on optical astronomy is to contaminate a large region of the sky to the extent that the study of astronomical objects currently at the limit of detection would be impossible within that zone. The size of the region is extremely sensitive to the properties of the SPS and the meteorological conditions at specific observatories. The impact is greatest for those observatories at longitudes nearest the center of the satellite array. For the Reference System, the instruments most affected are those on the North and South American Continents. The kinds of observations most affected are those currently limited by sky background.

The practical consequences for research programs are as follows:

- For those programs involving the study of randomly distributed objects, such as intrinsically faint stars and, in some respects, faint galaxies, the number of objects that can be studied will be reduced by an amount proportional to the fraction of the sky covered by the contaminated zones, estimated between 3% and 10%. Further, these observations will be severely hindered in a region that may cover as much as a third of the sky.
- Surveys designed to ascertain the cosmic distribution of objects may become subject to systematic errors stemming from the inability to study the whole sky.
- Specific regions of the sky may be excluded from observation. Various parts of the sky provide a better opportunity to study particular classes of objects. The region most affected by the Reference System is the ecliptic plane. The galactic poles and the Virgo cluster of galaxies are at the edge of the zones most noticeably affected. These two areas of the sky are extremely important to extragalactic astronomy; and a substantial increase in SPS brightness above that assumed would render these areas unusable for many important kinds of observations.
- Several important kinds of observations of type examples of classes of objects could be lost to astronomy. These objects, as noted earlier, are usually the nearest members of the class and are generally the subject of extensive observation and extremely detailed analysis, which is essential to the identification of the physical processes that control the structure of the source. Examples

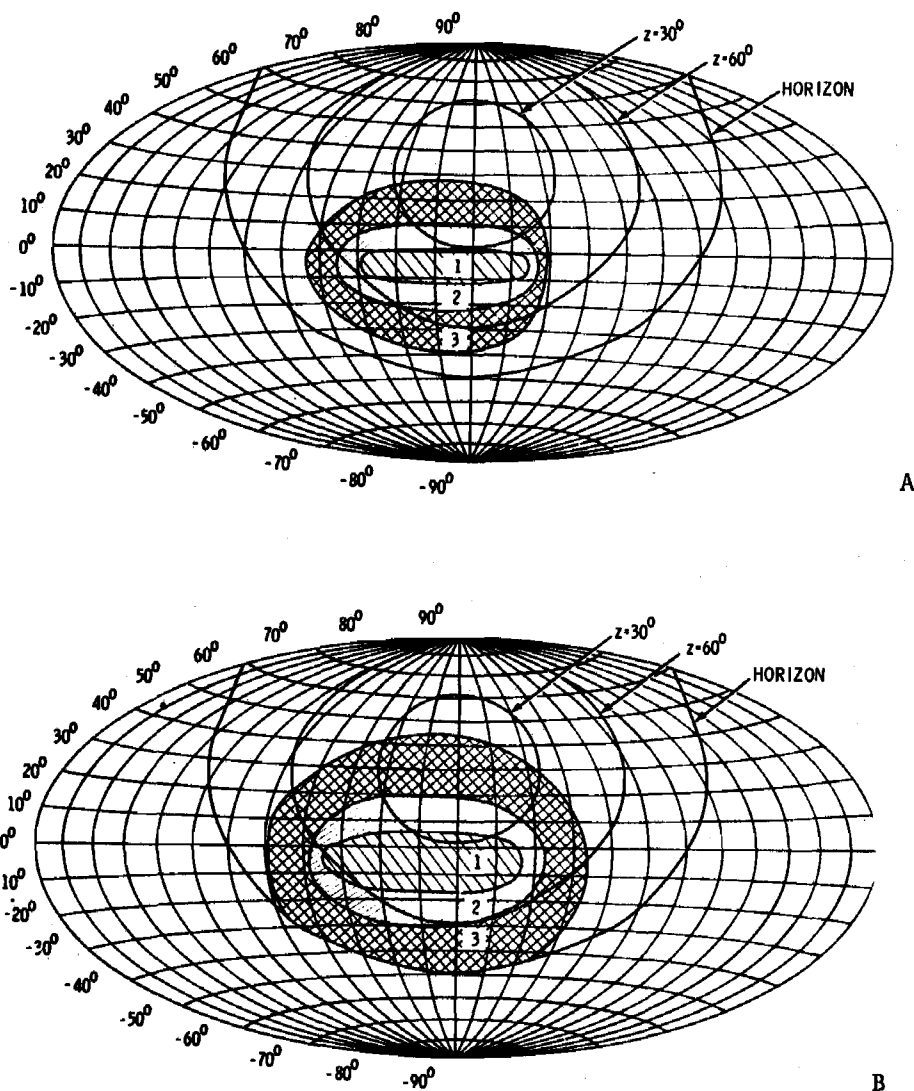


FIGURE 61. (A, B) Distribution of Predicted Increases in Diffuse Night Sky Brightness as a Result of a 60-Satellite System. A and B show the distribution of brightness as sun at midnight, the night of the vernal equinox, from Kitt Peak National Observatory. A shows the case for 4% albedo which led to an apparent visual magnitude of -4.3 (as bright as Venus) for the individual satellites. The brightness distributions in B are the result of increasing the brightness of the satellites by a factor of two. The map is an equal area projection and the area enclosed with the horizon line is all of the sky that is visible at a given time from the respective observatories. The separate regions correspond to the impact threshold zones described in the text: 1) contaminated zone; 2) severe hindrance; 3) noticeable effect. Contours showing the fraction of the sky more than 30° above the horizon ($z=60^\circ$) and 60° above the horizon ($z=30^\circ$) are also shown for reference.

of specific objects that will fall within the contaminated zone include a) the Orion Nebula, a major testbed for theories of star formation; b) 3C273 and 3C120, two of the brightest quasistellar radio sources (Quasars); and c) NGC 1068, one of the brightest and closest galaxies that has an active nucleus.

10.3 AERONOMY

The proposed SPS will have two effects on aeronomy. The first is analogous but not identical to the effect on optical astronomy; the illumination of the night sky by the diffuse reflection from the SPS solar arrays will interfere with aeronomical observations. The second effect creates an aeronomical phenomenon through the interaction of the microwave beam with the ionosphere. Significant increases of light are anticipated in this region of interaction. The region's vertical and lateral extent is limited by ionospheric electron concentration and by beamwidth. The range of its view from the ground is roughly only several hundred kilometers.

While it is conceivable that special studies of processes might take advantage of the uniquely localized parameters within the beam, the masking effect of the artificial excitation would vitiate most studies of the natural upper atmospheric environment using these standard emissions within a ground radius of 300 to 1000 km, depending on height and type of research.

A more pervasive consideration is the permanent and general illumination by a belt of sunlit satellites, whose finite reflectivity-produced light estimated as brighter than perhaps 0.1 of a full moon. This light is not only seen close to the sources via small angle scattering but also is distributed more or less over the sky seen from a ground station, depending on the prevalence of fine haze. In optical studies of the upper atmosphere itself, much research rests on ground-based spectrophotometric measurements of the faint light emissions, which yield information on the energy delivered within the sun's outer environment of particles, waves, and radiation. How the solar wind energizes the earth's magnetosphere is traced by the pattern of auroras formed by incident electrons, and the chemistry of upper atmospheric processes is shown by the airglow.

This science depends on measurement of faint-sky light, accurately discriminated as to wavelength, intensity, and variations with time and space. Intensities of auroras, which cover a wide range, often approach those of the airglow while maintaining much information content. Especially at midlatitudes, the subvisual stable auroral red arcs and the diffuse auroras require very sensitive spectral measurement and are unique indicators of the plasmapause region of the magnetosphere. Much future study will center on relatively weak emissions extending from the near-ultraviolet to the near-infrared. Many measurements press detection sensitivity to the limits of background light. High-resolution studies of Doppler shifts in thermospheric winds are at the limit of photon statistics. The airglow continuum is already compromised by natural backgrounds, and the artificial light would directly overwhelm it in any but the best conditions. Weak band emissions from minor atmospheric components would find obvious competition from scattering. Numerical estimates of the impact are difficult because of variable requirements of different experimental tasks, ranges of thin haze cover, and various contributions from aerosol and Rayleigh scattering. Effects would translate into reduced hours and poor intensity discrimination, and in some cases an end to many desired aeronomical studies.

10.4 MITIGATION

Mitigating strategies focus on potentially inexpensive modification in astronomy and aeronomy apparatus, SPS design features, and possible redeployment of affected observations. Due to the nature of astronomy apparatus and the broad way in which SPS may affect astronomy, the modification of existing astronomy equipment is not a promising mitigation technique. This is because of two fundamental conditions: astronomy observations are currently limited by interfering radiation and the satellites are located in geosynchronous orbit.

Larger telescopes should be considered for optical astronomy since increases in the brightness of the night sky are equivalent to a proportional decrease in the effective aperture of a telescope. However, a portion of the night sky would be lost even with new telescopes having twice the effective aperture because of the predicted increases in sky brightness. It is possible to design and build filters that will protect radio astronomy equipment from damage. Input filtering will reduce the sensitivity of the radiometers by introducing loss in the signal path and by the thermal radiation from the filter elements. Input filtering may also increase the system noise temperature by 25% or more, even if the filter is cooled to the physical temperature of a cooled parametric amplifier (20 K). Finally, the use of input filters, of course, cannot remove interference at the signal frequency.

Effects on astronomy and aeronomy depend on both broad properties of the SPS concept and unspecified details of the system's design. Important SPS design features for optical astronomy include a reduction in the albedo of the satellites and in the solid angle subtended by the satellites as seen from the earth. The most important parameter in determining the apparent brightness of the satellites is its albedo, which is the ratio of the radiation reflected from an object to the total incident radiation. Active baffling might be a way of lowering the albedo.

At the side lobe levels given in the Reference System Report (DOE/ER-0023), separation between rectennas and radio astronomy observatories will be important. Separation of several hundred km or more is probably required. Interference to radio astronomy observations is still probable and all the ways in which the SPS system could create radio frequency interference will not be known until SPS hardware has been designed and tested.

The redeployment of affected observations into space is the most promising area for the mitigation of impacts on astronomy. The major difficulty foreseen for space-based radio astronomy is expense. Once costing algorithms are available for space transportation and for supporting personnel in space, they should be used to estimate the cost of moving astronomy and maintaining it in space. The cost of moving all radio astronomy facilities into space will be an important worst-case value. The Workshop attendees believed that this cost would be prohibitively large.

Space telescopes have several advantages. At optical frequencies, space telescopes will produce a smaller image size and allow higher resolution studies of extended objects. In addition, the background light within a stellar image would be reduced several orders of magnitude compared to what can be obtained on the ground. Other advantages are that it can work in the ultraviolet and infrared where ground-based observations are currently limited by atmospheric emission and absorption.

Two points must be noted with regard to any proposal that space astronomy might serve as a substitute for lost capability of ground-based optical telescopes. First it is important to remember that astronomy is an observational science rather than an experimental science. It has not always been obvious what the critical observations are or what the best instrument to pursue them will be. As a result, the diversity of astronomical facilities has been an important source of vitality in research. While astronomy in space is important and desirable, creating a relatively small number of space facilities as a replacement of impaired ground-based facilities would not preserve this vitality. Second, ground-based observations have historically been used to complement studies made from space. A reduction in ground-based capabilities would compromise the overall scope of research.

For aeronomy, space-based observation may be unable to replace lost capability in current ground-based observations. The brightness of the earth's surface prohibits downward looking observations of faint but important atmospheric emissions.

11.0 CONCLUSIONS AND RECOMMENDATIONS

The EMC evaluation has addressed the range of performance effects on electronic equipment and systems, and tested techniques to modify most of these systems to allow operation in the appropriate SPS environments. This evaluation included communications, radar, computers, and sensor systems; applications including common carrier and industrial/transportation/military command/control communications, military and transportation radars, scanning and storing sensors used for a wide range of military and resource management operations, medical electronics, and special research support services. Terrestrial, aircraft, and satellite systems in the cited functional categories were evaluated.

Mitigation techniques were tested for most affected systems, with the goal to allow normal modes of operation within the SPS environment. For terrestrial, aircraft, and LEO space systems this involves SPS fundamental frequency illumination levels of 1-5 mw/cm², 23 mw/cm², and 20-100 mw/cm² respectively. The ranges for LEO systems concern the differences in orbit altitude (e.g., LANDSAT at ~120 miles and GPS at ~11000 miles altitudes). Successful mitigation methods have been identified for many electronic systems. Radio astronomy receivers represent the most severe constraints in separation distances from rectenna sites, and complexity of functional mitigation techniques.

11.1 Conclusions

The conclusions of this EMC program are summarized in the following listing.

1. Most communications, radar, sensor, and computer devices and systems would be unacceptably degraded in performance when located within 20-50 km of a rectenna site. Mitigation techniques, primarily shielding and signal channel filtering modifications, would allow normal performance for terrestrial system operation with SPS power densities expected at a rectenna exclusion boundary.
2. Separation constraints would be required between rectenna sites and facilities having critical safety criteria, or where mitigation of interference would compromise the performance and operational capability. Nuclear power and research facilities are examples of the former; military operations and test and evaluation facilities are in the latter category (reference Section 6).

3. Aircraft communications and navigation equipment would be degraded to an unacceptable performance level by exposure to SPS power densities, including beam center and edge power densities. Effective mitigation includes shielding and filtering, and minor antenna pattern modifications to reduce sensitivity to the vertical SPS power beam.
4. A monitor and control procedure is required for rectenna structure intermodulation emissions, to locate sources and effect repair so as not to cause interference in the HF-UHF spectral regions to terrestrial and aircraft systems.
5. Satellites in LEO can be exposed to power densities in the $20\text{--}100\text{ mw/cm}^2$ range depending on orbital altitude. No practical procedures can be identified to assure no LEO orbit will pass through an SPS beam particularly with a full SPS deployment. Shielding and filtering methods can remove effects on sensors and computer/control circuitry, thus eliminating attitude and system command/control impact. Uplink receivers will require desensitization when passing through an SPS power beam to prevent large transient data error blocks from being passed to on-board computers and controllers. This action can readily be provided by a separate receiver channel for 2.45 GHz.

Earth viewing sensors should be protected by additional telescope shields to prevent SPS power coupling by reflection from LEO satellite components (e.g., solar panels, parabola antennas).

6. Satellites in GEO, if sufficiently separated from the solar power satellite, would not be expected to be affected. This would be true even for satellites in a GEO position opposite (separated by 180°) the power satellite. The allowable spacing between a solar power satellite and other satellites in GEO would probably not be less than 1° , but this is based on approximate analyses that will require refinement as the SPS technology develops.
7. Scattered sunlight from SPS would, unless reduced substantially below levels expected from the Reference System (4% diffuse albedo), have a harmful effect on optical astronomy and other scientific observations requiring dark night skies.

Thermal microwave emissions from SPS photovoltaic arrays may have some effect on satellite communications, radio astronomy and deep space research. Extent of the impact depends on the level of such emissions and SPS location.

Radio astronomy receivers represent the most complex area for interference mitigation because of the sensitivity and wide spectrum of observations. These facilities probably could not operate within a distance of 150 km from a rectenna site. Signal channel filtering is not generally acceptable because of the increased receiver noise temperature.

11.2 RECOMMENDATIONS

If the SPS concept is to be pursued further, the following efforts are recommended either to provide data needed for a more complete and firmly based EMC Assessment or to examine ways to mitigate anticipated problems. As part of any future design program, obtain data and include interference analyses and mitigation evaluation of the SPS which are important to EMC concerns:

- a. Determine the levels of spurious emissions from the MPTS. This will require construction and testing of important representative components and subsystems such as spacetenna and rectenna modules, control components, and power amplifier systems.
- b. Evaluate the potential for electromagnetic emissions from other components of the SPS, e.g., generation of intermodulation components in rectenna and satellite structures or electronic systems, or radiation from control electronics.
- c. Refine estimates of reflected light, both diffuse and specular components, from all space components of the SPS including LEO construction facilities.
- d. Testing of susceptibility of electronic equipment to SPS microwave fields and of mitigation techniques.
- e. Test the effects of strong out-of-band signals on sensitive receiving systems as used in satellite communication and radio astronomy, and mitigation techniques.

- f. Include effects of the atmosphere on the SPS microwave power beam to assure electromagnetic compatibility.
- g. Any SPS design and development program should continue to emphasize minimization of emission characteristics for harmonics and spurious components, and optical reflections and thermal emissions.

ABBREVIATIONS

A/C	Aircraft
AGC	Automatic Gain Control
BER	Bit Error Rate
CCD	Charge Coupled Device
CCIR	International Radio Consultative Committee (provides technical support to the ITU)
CDEP	(Satellite Power System) Concept Development and Evaluation Program
CONUS	Continental United States
CPSK	Coherent Phase Shift Keying
CPU	Central Processing Unit
DMUX	Digital Multiplex
EMC	Electromagnetic Compatibility
EW	Electronic Warfare
FET	Field Effect Transistor
GEO	Geostationary Orbit
GPS	Global Positioning System (also called NAVSTAR)
FCC	Federal Communications Commission
FDM	Frequency Division Multiplex
FLIR	Forward Looking Infrared
FM-FDM	Frequency Modulation with Frequency Division Multiplex
I/N	Interference-to-Noise Ratio
I/O	Input or Output
IR	Infrared
I/S	Interference to Signal Ratio
ITS	Institute for Telecommunication Sciences of the National Telecommunications and Information Administration, Boulder, CO
ITU	International Telecommunication Union
LEO	Low Earth Orbit
LSI	Large Scale Integration
MPTS	(Satellite Power System) Microwave Power Transmission System
MSI	Medium Scale Integration
MSS	Multispectral Scanner (LANDSAT)
MTF	Modulation Transfer Function
NCFSK	Noncoherent Frequency Shift Keying
NRQZ	National Radio Quiet Zone (defined in FCC Rules and Regulations, Part 73.1030)
PNL	Pacific Northwest Laboratory, operated by Battelle for the U.S. Department of Energy
PRF	Pulse Repetition Frequencies
QPSK	Quadrature Phase Shift Keying
Rectenna	Rectifying Antenna (component of the SPS Microwave Power Transmission System)
RF	Radio Frequency (above 20 kHz)
RFI	Radio Frequency Interference
SHF	Super High Frequency (3 to 30 GHz)

S/I	Signal to Interference Ratio
S/N	Signal to Noise Ratio
SPS	Satellite Power System
TDMA	Time-division, Multiple-access
TDRSS	Tracking and Data Relay System Satellite (NASA)
TM	Thematic (or Thermal) Mapper (LANDSAT)

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ENVIRONMENTAL ASSESSMENT for the SATELLITE POWER SYSTEM - CONCEPT DEVELOPMENT and EVALUATION PROGRAM.

and five individual task reports:

ENVIRONMENTAL ASSESSMENT for the SATELLITE POWER SYSTEM - CONCEPT DEVELOPMENT and EVALUATION PROGRAM - MICROWAVE HEALTH and ECOLOGICAL EFFECTS.

ENVIRONMENTAL ASSESSMENT for the SATELLITE POWER SYSTEM - CONCEPT DEVELOPMENT and EVALUATION PROGRAM - NON MICROWAVE HEALTH and ECOLOGICAL EFFECTS .

ENVIRONMENTAL ASSESSMENT for the SATELLITE POWER SYSTEM - CONCEPT DEVELOPMENT and EVALUATION PROGRAM - ATMOSPHERIC EFFECTS.

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