NTIA-Report-81-64

Analysis of Interference Caused by the Solar Power Satellite to Satellite Earth Terminals

J.R. Juroshek

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

Dale N. Hatfield, Acting Assistant Secretary
for Communications and Information

February 1981

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ANALYSIS OF INTERFERENCE CAUSED BY THE SOLAR POWER SATELLITE TO SATELLITE EARTH TERMINALS

John R. Juroshek*

The solar power satellite (SPS) is a concept for generating electrical power from solar energy via a geosynchronous orbiting satellite. A facility, such as this, would be able to send approximately 5 to 10 gigawatts of power to earth on a highly focused 2450 MHz microwave beam. The electromagnetic compatibility problems cause by this amount of microwave power transmission are recognized as a critical fâctor in the implementation of such a system. This report examines the potential for interference between SPS and conventional satellite earth terminals.

The report begins with a general discussion of the different ways that interference between SPS and satellite systems can occur. Estimates are made of the levels of harmonics and out-of-band noise that are likely to be radiated by SPS. These levels are then compared to the interference threshold for various representative satellite scenarios. The report concludes that a potential for interference exists in the 2500 MHz to 2690 MHz direct broadcast satellite frequency assignments. Another potential problem is SPS radiation at the 7350 MHz 3d harmonic that falls within the 7300 MHz to 7400 MHz space-to-earth government satellite band.

Key words: interference, satellite; solar power satellite

1. INTRODUCTION

The solar power satellite (SPS) is a concept for generating electrical power from solar energy via a geosynchronous orbiting satellite. Such a facility would enable solar energy to be collected in space, converted to microwave energy, and beamed to earth on a highly focused microwave beam. Current estimates are that such a system would be able to generate from 5 to 10 gigawatts of usable power.

The electromagnetic compatibility (EMC) problems caused by this amount of microwave power transmission is recognized as a critical factor in the implementation of such a system. Electromagnetic systems well removed from the 2.45 GHz SPS operating frequency can potentially be affected by inband and out-of-band radiation from the satellite. Consequently, the following study has been undertaken to identify and analyze the potential impact on a variety of different electronic systems.

---

*The author is with U. S. Department of Commerce, Institute for Telecommunication Sciences, National Telecommunications and Information Administration, Boulder, Colorado 80303.

2. SPS REFERENCE SYSTEM

The SPS reference system, as currently defined, is primarily a product of system definition studies conducted by Boeing Aerospace Company under contract to Johnson Space Center and Rockwell International under contract to Marshall Space Flight Center. Results from these studies are summarized in a report entitled "Satellite Power System, Concept Development and Evaluation Program" (U.S. Department of Energy and National Aeronautics and Space Administration, 1978). This section will briefly describe some of the important aspects of the reference system that are pertinent to the EMC study.

The largest part of the orbiting satellite is the approximately 10.4 km by 5.2 km solar array. This array, which would be made with either gallium-aluminum-arsenide or silicon solar cells, would intercept approximately 70 gigawatts of solar energy. With an estimated conversion efficiency of 7%, this solar array would provide 5 gigawatts of dc power for conversion by klystrons to microwave energy. This power would then be beamed to earth via a 1.0 km diameter phased array microwave antenna. A special pilot beam would be transmitted from earth to the satellite for dynamic phasing of the transmit antenna. Some of the parameters of interest in the transmit system are shown in Table 1.

TABLE 1. Summary of SPS Satellite Parameters

Frequency	2.45 GHz
Output Power to Grid	Approx. 5 GW
Transmit Array Size	1 km Diameter
Microwave Transmission Efficiency	63%
Solar Conversion Efficiency	7%
Transmit Antenna Aperature Illumination	Truncated Gaussian with 10 dB edge taper (10 step)
Power Density Center of Transmit Antenna	22 kW/m^2
Power Density Edge of Transmit Antenna	2.4 kW/m^2
Transmit Radiating Elements	Slotted Waveguide
Klystron Size	70 kW

The ground receiving antenna (rectenna), on the other hand, is a 10 x 13 km array. This array would be built with panels of multiple half-wave dipole elements feeding diodes for direct conversion of rf energy to dc. Filters would be inserted between the dipole and diodes to suppress reradiation of harmonics generated in the rectification process and also for impedance matching. Expected power densities from SPS at the surface of the earth, expressed in milliwatts-per-square-centimeter and volts-per-meter, are given in Table 2.

TABLE 2. Approximated Power Density at the Surface of the Earth

Center of Rectenna	23 mw/cm^2	294 v/m
Edge of Rectenna (5 km from center)	1.0	61.4
Exclusion Fence (5.7 km from center)	0.1	19.4
First Side Lobe (9.0 km from center)	0.08	17.3
Second Side Lobe (13.0 km from center)	0.03	10.6
Third Side Lobe (17.0 km from center)	0.01	6.1
50 km from Center	.001	1.9
200 km from Center	.0002	.87
400 km from Center	.00005	.43
First Grating Lobe 450 km from Center	.01	6.1

The relationship between power density and field strength is given by

$$p_d(mw/cm^2) = \frac{[E(v/m)]^2}{120\pi} 10^{-1} , \tag{1}$$

where

$p_d(mw/cm^2)$ = power density in milliwatts per square centimeter,

$E(v/m)$ = field strength in volts per meter,

and

120π = resistance of free space in ohms.

3. INTERFERENCE MECHANISMS

There are basically four different ways for interference to electronic systems such as satellites to occur. The first three ways, as described below, assume that the victim is a communications system and that the interference enters through the victim's antenna system. The fourth way, however, assumes that the interference enters through other paths such as chassis openings and interconnecting wires.

The first interference mechanism, which is arbitrarily designated as Type 1, is pictorially described in Figure 1. Shown here is the frequency response (IF plus rf) of a victim receiver, as well as the spectrum of the interfering SPS signal offset in frequency relative to the victim. The cause of interference, in this instance, is the out-of-band energy from SPS that falls within the victim's normal operating frequencies. Thus, the only way to reduce the interference is to reduce the amount of out-of-band energy that falls within the victim's frequency band. Improving the victim's system by adding additional filtering will not significantly reduce the interference.

The second mechanism, designated as Type 2 interference, is shown in Figure 2. For this case, the interference is due to the inability of the victim receiver to reject SPS energy at 2.45 GHz. In contrast to the previous case, the interference is not dependent on the out-of-band SPS radiation characteristics and therefore the interference can be reduced by improving the filtering in the victim receiver.

The third type of interference, which is often called intermodulation interference, is described in Figure 3. Here both out-of-band SPS energy and the victim's receiver response would normally be sufficient to prevent interference. However, when the SPS signal passes through nonlinear elements, its energy can be translated into different frequencies that do cause interference. The problem is compounded by the fact that other rf signals unrelated to either the victim or SPS can enter into the process and affect the final result. This form of interference is probably one of the most difficult to predict and often one of the most difficult to cure. Improved rf filtering is often successful in combating this type of interference.

The fourth mechanism occurs when interference enters the victim by indirect means such as the coupling of rf energy through chassis openings and interconnecting wires. This type of interference, in contrast to the previous three, is not dependent on the victim antenna system. Interference of this nature is most likely to occur in high level rf field where power densities exceed 10^{-1} mw/cm^2. This type of interference is also likely to be the dominate cause of interference in non-communications related electronic equipment such as computers, tape drives, etc.

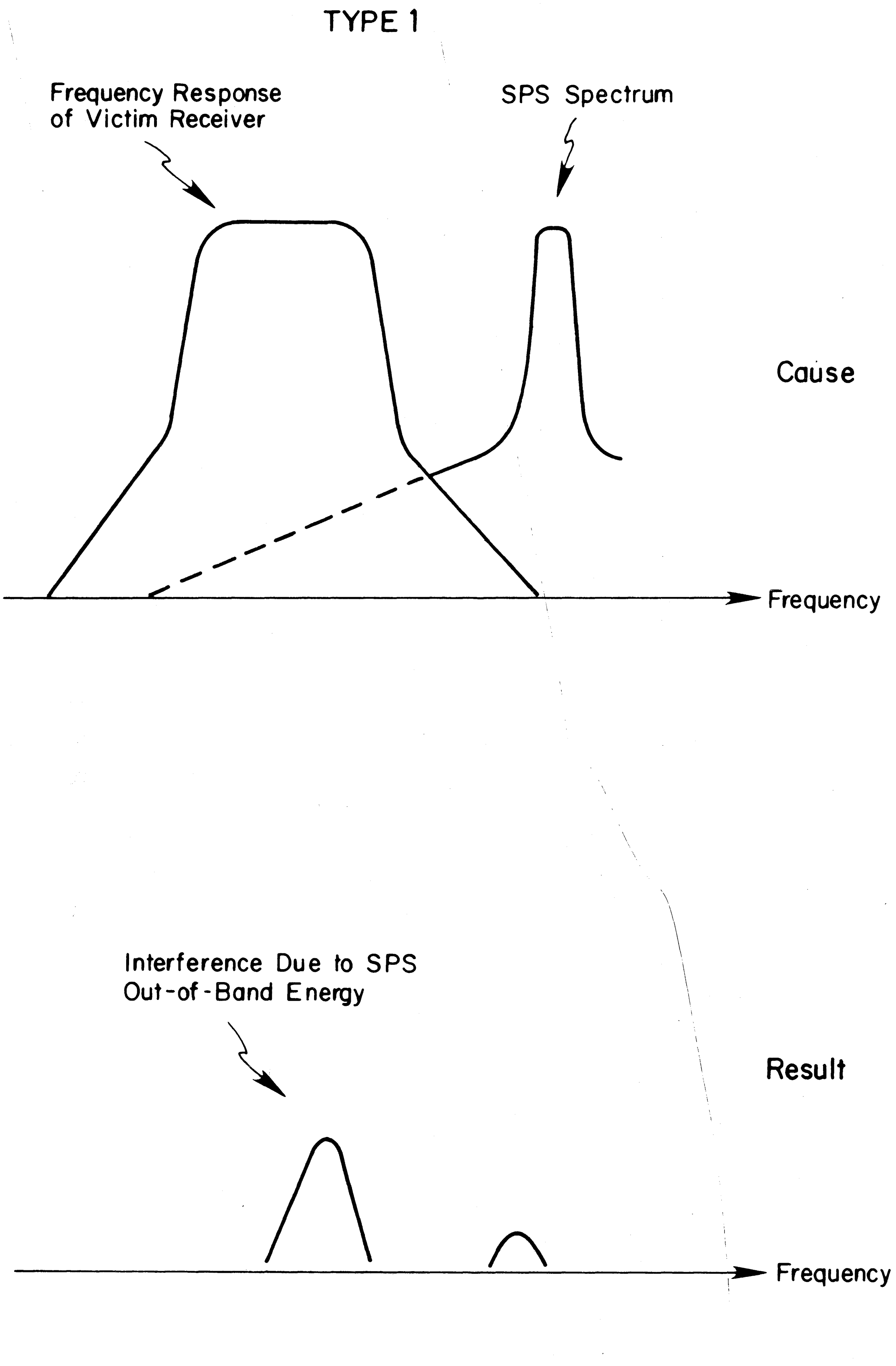

Figure 1. Description of type 1 interference.

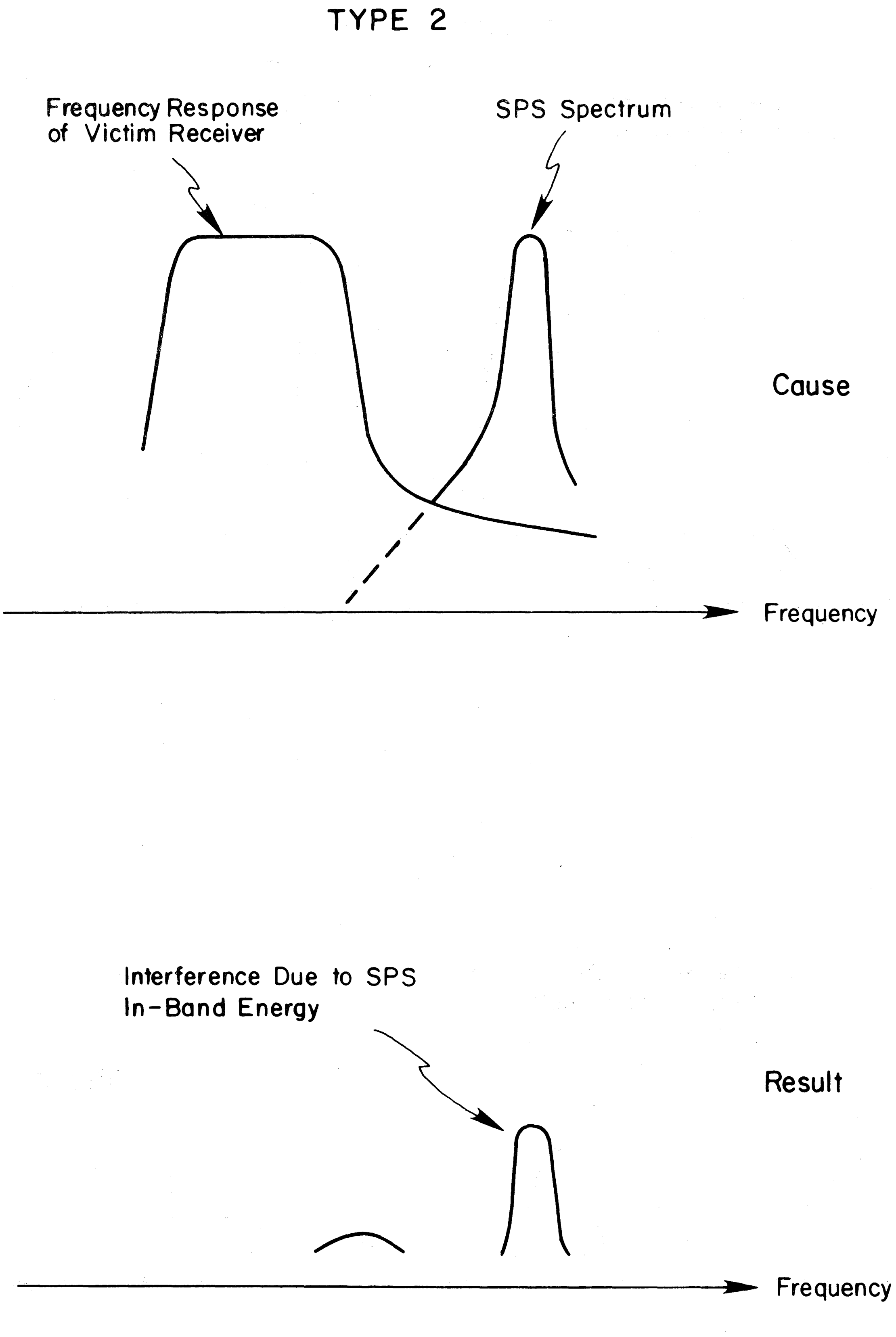

Figure 2. Description of type 2 interference.

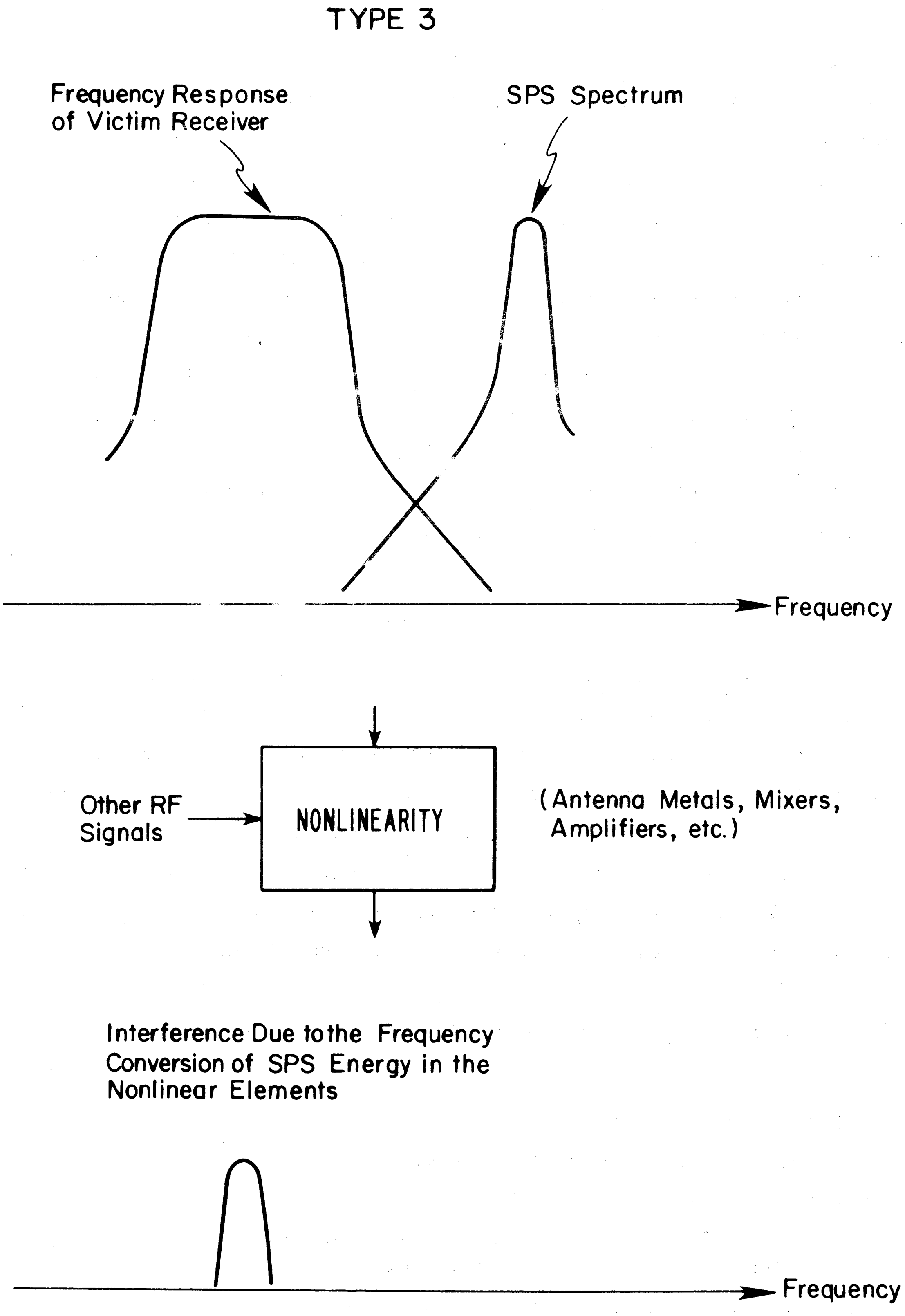

Figure 3. Description of type 3 interference.

4. SPS INTERFERENCE TO SATELLITE SYSTEMS

4.1 Background

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 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 will attempt to address 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 expected from SPS. Thus, the causes of interference and the coupling mechanisms are not undersood in detail. However, estimates have been made based on the best engineering judgment. A summary of the frequency bands below 30 GHz that are allocated to satellite use in the United States is shown in Table 3. This table does not include frequency bands allocated to space research.

4.2 General Discussion of Interference Levels

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

A general guide for estimating interference to satellite systems is contained in CCIR Report 713 (1978). This report shows that the maximum acceptable interference power flux density incident on the victim antenna is given by

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

where

k = Boltzmans constant,

t_s = effective system noise temperature,

b_r = reference bandwidth,

n_i/n_s = ratio of allowable interference noise power relative to normal system noise,

G_e = effective victim antenna gain in dB, and

λ = victim wavelength.

TABLE 3. Summary of Satellite Frequency Allocations Below 30 GHz in the U.S.

FREQ	USE	DIRECTION	FREQ	USE	DIRECTION
7000-7100 kHz	AS		7250-7300 MHz	FS	S-E
14000-14250	AS		7300-7450	FS	S-E
21000-21450	AS		7450-7550	FS-MES	S-E
28.00-29.70 MHz	AS		7550-7750	FS	S-E
137-138	MES		7900-7975	FS	E-S
149.9-150.05	RNS		7975-8025	FS	E-S
399.9-400.05	RNS		8025-8175	FS	E-S
400.05-400.15	SFS		8025-8175	EES	S-E
401-402	MES	E-S	8175-8215	EES	S-E
402-403	MES	E-S	8175-8215	FS & MES	E-S
406-406.1	MS	E-S	8215-8400	EES	S-E
420-450	AS		8215-8400	FS	E-S
460-470	MES	S-E	10.95-11.2 GHz	FS	S-E
1535-1542.5	MMS		11.45-11.7	FS	S-E
1542.5-1543.5	AMS & MMS		11.7-12.2	FS & BS	S-E
1543.5-1558.5	AMS		12.5-12.7	FS	E-S
1636.5-1644	MMS		12.7-12.75	FS	E-S
1644-1645	AMS & MMS		14.0-14.2	FS	E-S
1645-1660	AMS		14.2-14.3	FS	E-S
1670-1690	MES	S-E	14.3-14.4	RNS	
1690-1700	MES	S-E	14.3-14.4	FS	
1700-1710	MES	S-E	14.4-14.5	FS	E-S
2500-2535	BS		17.7-19.7	FS	S-E
2535-2655	BS		19.7-20.2	FS	S-E
2655-2690	BS		20.2-21.2	FS	S-E
3700-4200	FS	S-E	21.2-22	EES	S-E
5925-6425	FS	E-S	24-24.05	AS	
6625-6875	FS	S-E	27.5-29.5	FS	E-S
6875-7125	FS	S-E	29.5-30	FS	E-S

KEY:

AS - Amateur-Satellite
AMS - Aeronautical Mobile-Satellite
BS - Broadcasting-Satellite
EES - Earth Exploration-Satellite
FS - Fixed-Satellite
MES - Meteorological-Satellite
MMS - Maritime Mobile-Satellite
MS - Mobile-Satellite
RNS - Radio Navigation-Satellite
SFS - Standard Frequency-Satellite
S-E - Satellite-to-Earth
E-S - Earth-to-Satellite

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

$$10 \log a_e = G_e + 10 \log \frac{\lambda^2}{4\pi} , \tag{3}$$

equation (3) can be rewritten as

$$\mathrm{pfd} = 10 \log (k t_s b_r) + 10 \log (n_i/n_s) - 10 \log a_e . \tag{4}$$

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 narrowband, single channel per carrier systems, is generally assumed to be 4 kHz. Protection requirements for conventional FM-FDM (frequency modulation with frequency division multiplex) is also generally specified in a 4 kHz bandwidth. The reference bandwidth for wideband digital systems, however, is usually assumed to be 1 MHz. This report will use both 4 kHz and 1 MHz reference bandwidth 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 assumed to be of the order of 0.1 or 0.01. A justification for these values is given by the International Radio Consultative Committee (CCIR) in Report 713 (CCIR, 1978a). If one assumes an effective system noise temperature at t_s = 60°K, then graphs of pfd versus a_e can be prepared as shown in Figures 4 and 5. Note that a protection criteria of pfd = -221 dB(W/m^2·4 kHz) is required for the large INTELSAT antennas (ibid).

These results are summarized in Figures 6 and 7. In Figure 6, one can see that the interference power flux density would have to be between -185 to -195 dB(W/m^2·4 kHz) to prevent interference to systems with reference bandwidths of 4 kHz and antenna apertures of 1 to 10 square meters. Figure 7, on the other hand, shows that a protection of -161 to -171 dB(W/m^2.1 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/m^2·4 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 beamwidth of the order of 0.3 degrees, it is likely that the SPS will be off-axis which means that the protection criteria can be correspondingly relaxed.

4.3 CCIR Estimates of SPS Out-of-Band Noise

Estimates of the out-of-band noise that can be expected from SPS within the frequency range of 2.35 GHz to 2.55 GHz are described by the CCIR in Report 679 (CCIR, 1978b) as summarized in Figure 8. It is important to understand the CCIR estimates since they affect the interference analysis.

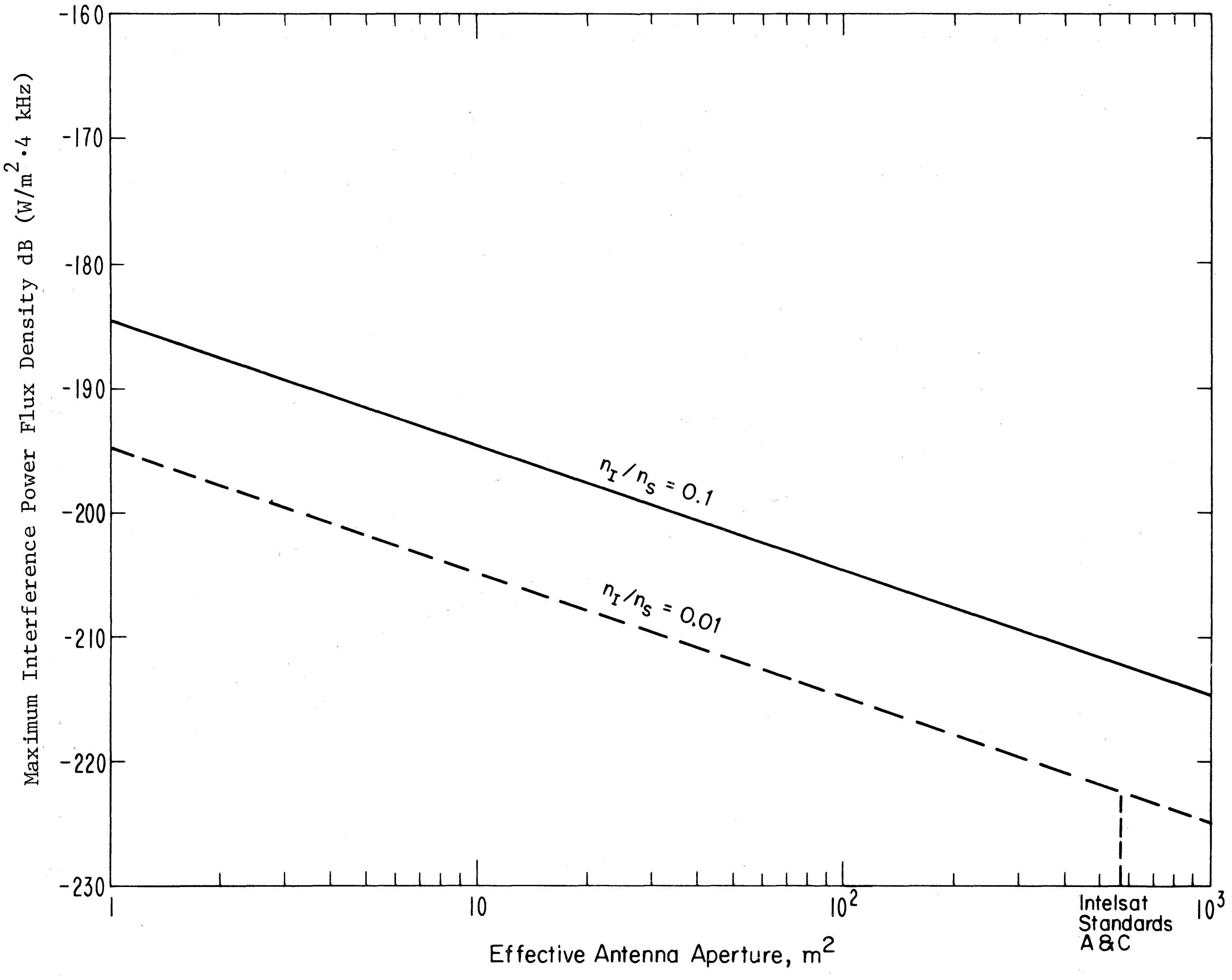

Figure 4. Maximum interference power flux density in a 4 kHz reference bandwidth versus effective victim antenna aperture.

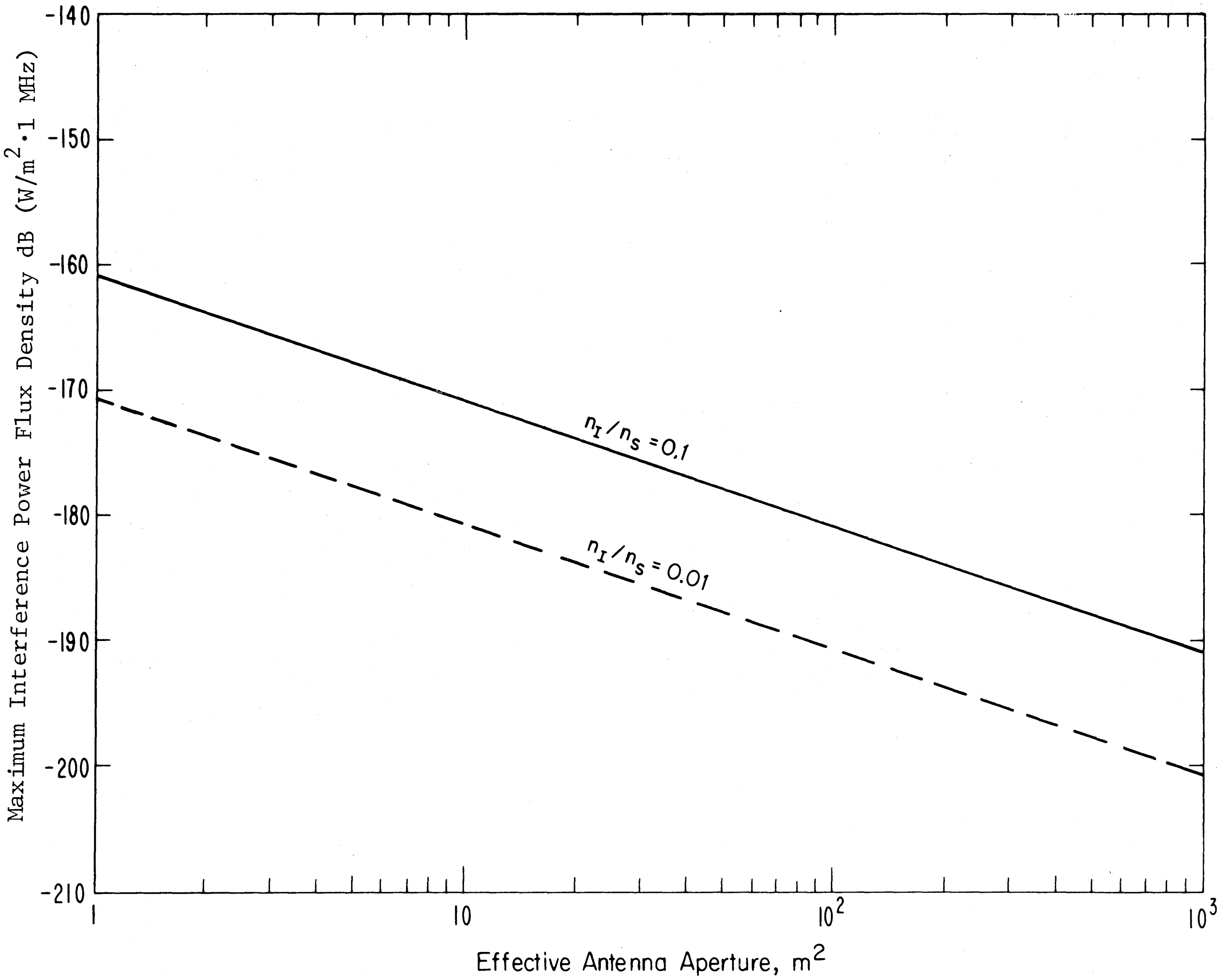

Figure 5. Maximum interference power flux density in a 1 MHz reference bandwidth versus effective victim antenna aperture.

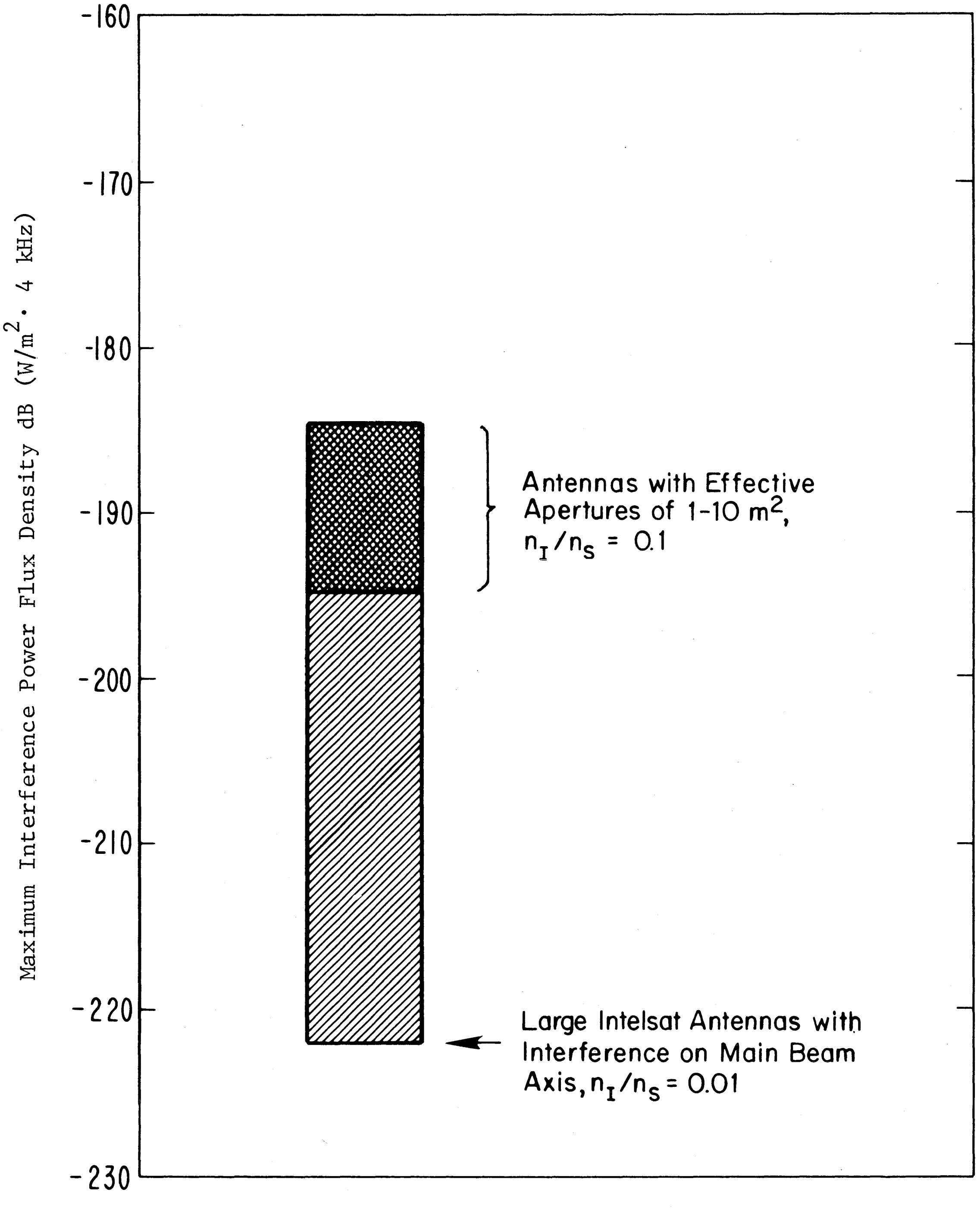

Figure 6. Summary of maximum allowable power flux density in a 4 kHz reference bandwidth.

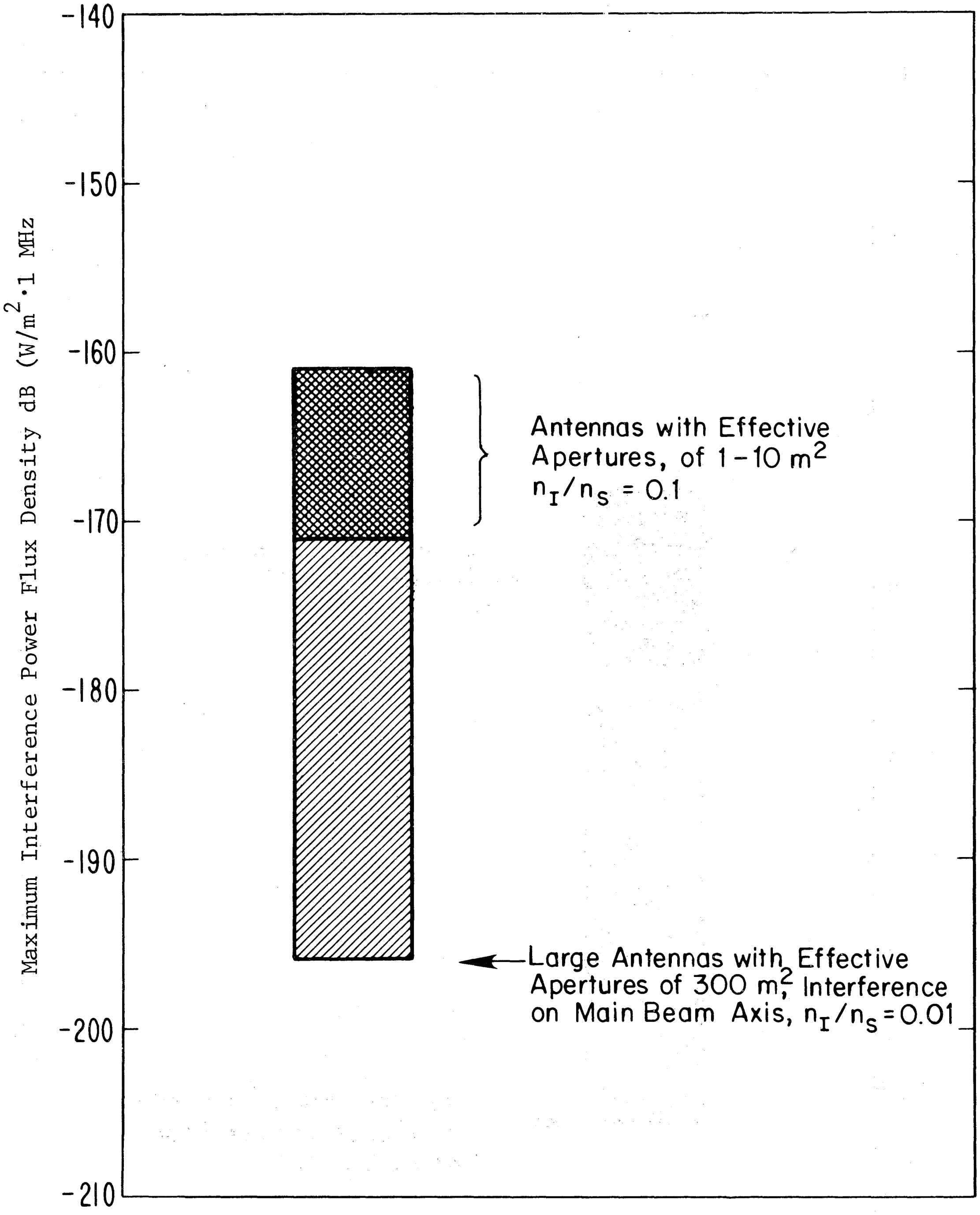

Figure 7. Summary of maximum allowable power flux density in a 1 MHz reference bandwidth.

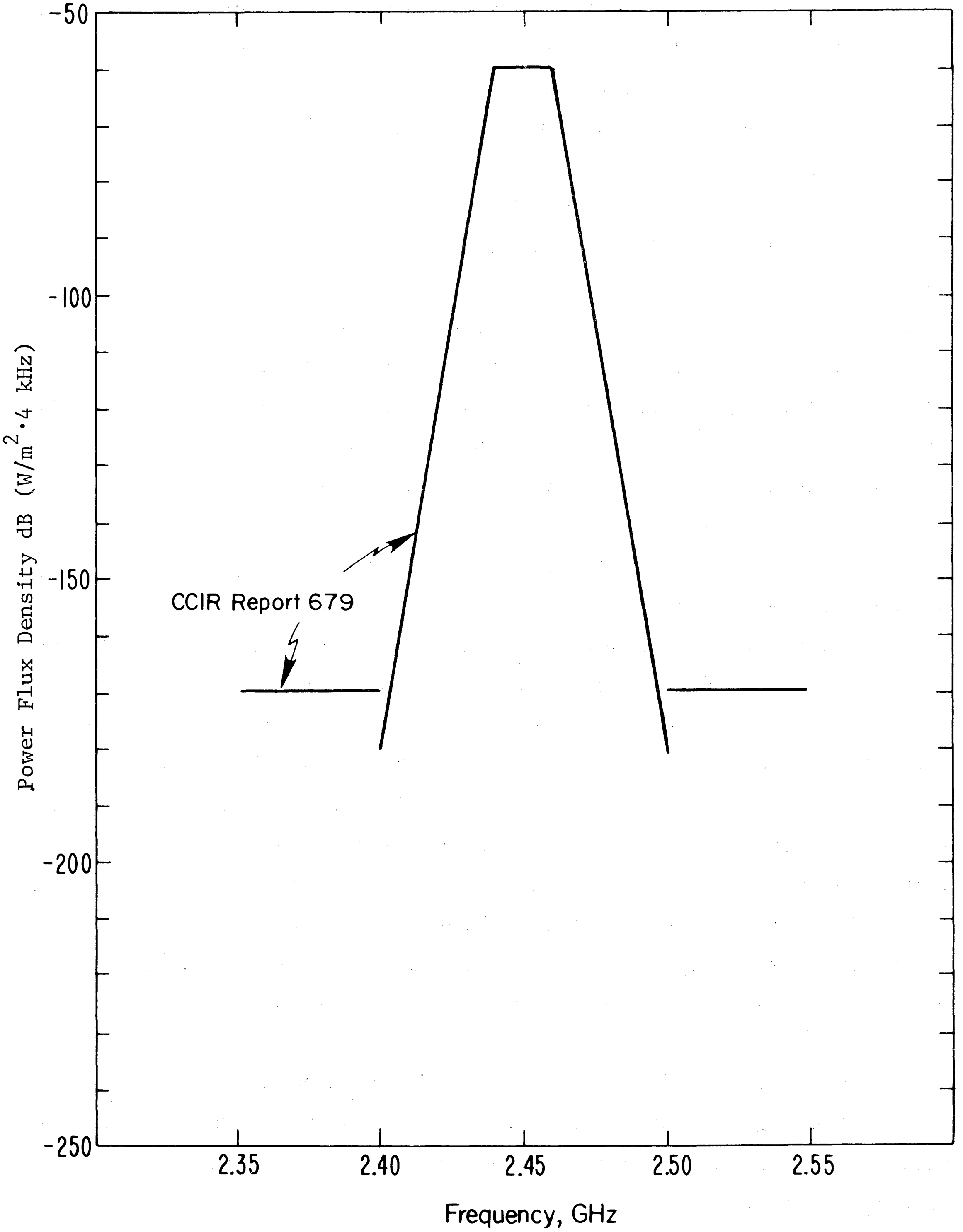

Figure 8. CCIR estimate of out-of-band power density for SPS.

The CCIR estimates begin by assuming a transmitter output power of 6.5 GW or 98.1 dBW. The power flux density at the surface of the earth, at 10 km from the center of the rectenna, is computed to be -13 dB (W/m^2). Next, it is assumed that the transmitter energy is uniformly spread over a ± 10 MHz band about the 2.45 GHz center frequency. Frequency spreading reduces the power flux density in a 4 kHz band to -50 $dB(W/m^2 \cdot 4\ kHz)$, which corresponds to a net reduction of 37 dB.

The design for the SPS power sources envisions a 5 cavity klystron with a 120 dB attenuation of out-of-band noise. The CCIR report thus assumes a band edge power flux density of

$$\text{pfd} = -50 - 120 = -170\ \text{dB}(\text{W/m}^2 \cdot 4\ \text{kHz}). \tag{5}$$

There are a number of assumptions in the CCIR report that need to be discussed. Obviously, the power flux density within the ± 10 MHz band can be reduced by frequency spreading, however, Report 679, as shown in equation 8, assumes that the out-of-band energy receives the same benefits from frequency spreading as the in-band energy. Reasons why this might not be true are given in the following example.

Figure 9 shows a hypothetical example of k klystrons uniformly spaced in frequency across some arbitrary bandwidth B. The power density of each klystron within the narrower klystron bandwidth, B_i, is assumed to be P_d, while the power density outside of this bandwidth is P_d -120 dB. As can be seen from the figure, the power density at the edge of the ± 10 MHz bandwidth is the sum of noise contributions from all klystrons. Its value is dependent on the out-of-band power density versus frequency characteristics of each klystron. Unfortunately, microwave sources can have a fairly constant out-of-band noise power density even at frequency separation of 5 MHz from the device center frequency (Schuneman, 1972; Johnson, 1969). A typical klystron noise spectrum is shown in Figure 10. Thus, the noise contribution from adjacent klystrons is significant which means that frequency spreading does not necessarily reduce in-band and out-of-band power flux density by the same amount.

Figure 9 also shows the effects of frequency spreading on the harmonics. As can be seen from the figure, the Nth harmonic is spread in frequency over a bandwidth N·B. Estimates of the signal levels for these cases are discussed in more detail in the following section.

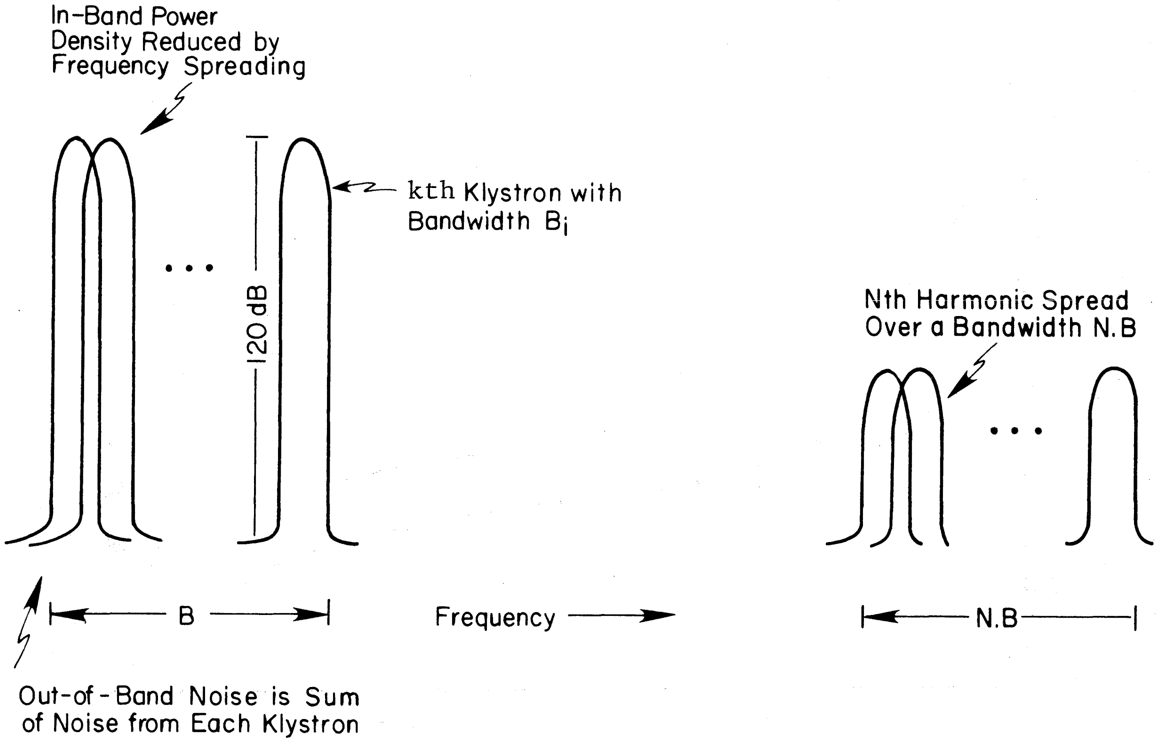

Figure 9. Example showing affects of frequency spreading of SPS microwave beam.

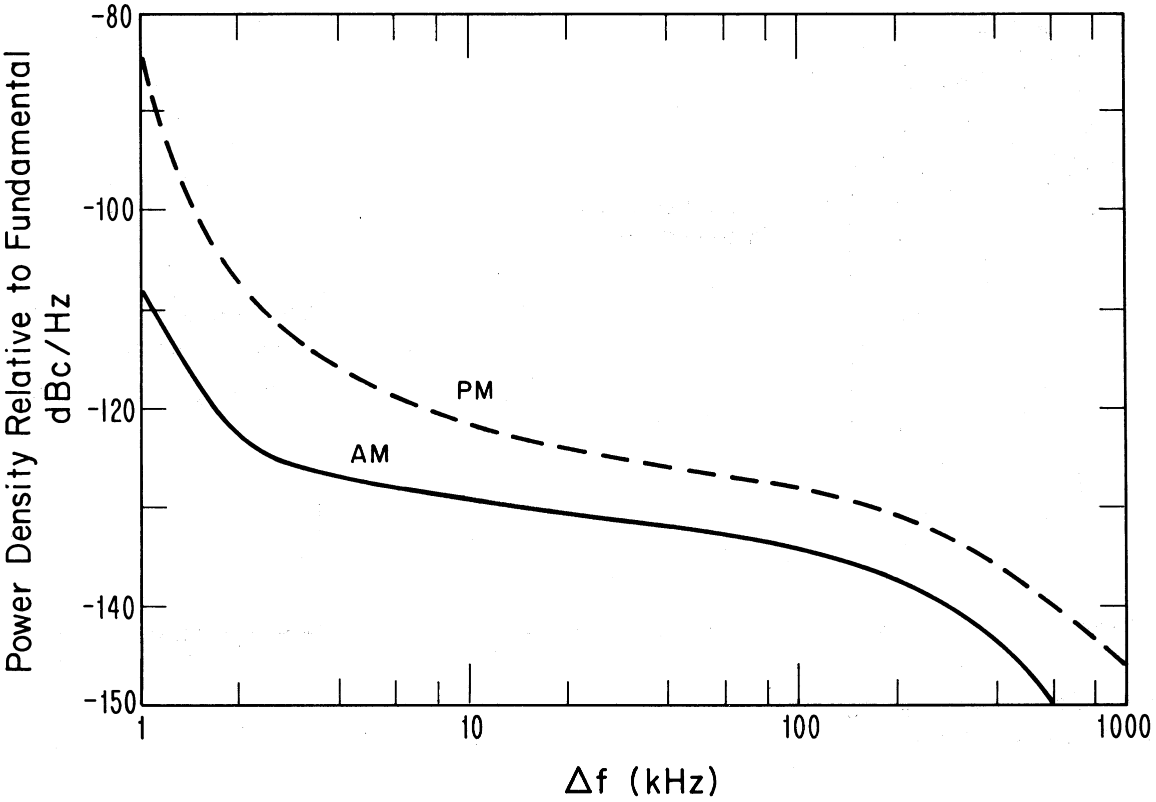

Figure 10. Typical noise emissions from a high power klystron.

4.4 Interference to Satellite Earth Terminals

4.4.1 Estimates of Interference Levels

It is difficult, with the present state of knowledge, to estimate the magnitude of the harmonic and out-of-band interference levels that can be expected from SPS. The lack of knowledge about the response of the SPS transmit antenna at harmonics is one of the unknowns encountered. Data describing the characteristics of the klystrons with filters, waveguide, and phase control are also required in order to accurately assess interference levels. The following material will attempt to make some rough estimates of interfering signal levels based on current technology.

A typical noise spectrum from a high power cw klystron is shown in Figure 10. Shown here are spectral components generated by random amplitude modulation (AM) and phase modulation (PM) of the klystron. It should be noted that these values can vary considerably with tube operating conditions. Spurious signals and modulation components generated in the synchronization process can also be significant factors in the noise spectrum.

Until more accurate SPS emission estimates are available, this report will assume that the out-of-band noise spectral density that is emitted in the frequency bands adjacent to SPS is no greater than -160 dBc/Hz where dBc denotes power in dB relative to the total power in the signal or carrier. Given the preceeding estimate of power density, the noise power in either a 4 kHz or 1 MHz bandwidth can be computed as

$$P_d(\text{adjacent channel}) \leq -124 \text{ dBc/4 kHz}$$

or

$$P_d(\text{adjacent channel}) \leq -100 \text{ dBc/1 MHz.}$$

The effects of frequency spreading add another uncertainty as explained in Section 4.3. At the present time, there is no evidence to support the assumption that frequency spreading of the fundamental will substantially reduce the out-of-band noise. Thus, until better information is developed, the adjacent channel noise will be assumed to be the same with and without frequency spreading.

Estimates of harmonic radiation from klystrons are given in the book by Skolnik (1970) as summarized in Table 4.

TABLE 4. Estimates of Harmonic Radiation from Klystrons in dB Relative to Fundamental

Harmonic	High/Low Range	Mean
2	-38/-119 dBc	-71.3 dBc
3	-57/-105	-78.2
4	-56/-101	-76.9
5	-59/-111	-73.9
6	-73/-89	-82.3
7	-72/-97	-87.2

These results are summarized in Figures 11 and 12 which show the expected harmonic levels in Table 4 along with the out-of-band or adjacent channel noise estimates described previously. These figures assume that without frequency spreading, the spectra of the fundamental and harmonics is contained within a 4 kHz bandwidth. With frequency spreading, the power density of the Nth harmonic is given by

$$P_d(\text{Nth harmonic}) = A_h - 10 \log (N \cdot b_s / b_r) \tag{6}$$

where b_s is the bandwidth over which the fundamental is spread, b_r is the reference bandwidth, and A_h is the harmonic value shown in Table 4.

At the present time, the behavior of the SPS transmit antenna at frequencies other than the fundamental is unknown. The following discussion will review some of the factors that determine antenna performance at frequencies other than the fundamental, and will attempt to make some crude gain estimates for analysis purposes.

What is known, is that the antenna gain at the fundamental is 86.6 dBi. Achieving this gain requires that the microwave signals generated within each of the approximately 7220 subarrays be properly phase locked to each other. When phase synchronization is lost, due to the loss of the retrodirective pilot beam, each of these subarrays radiates independently and the gain decreases to a value of approximately 49 dBi.

The effective antenna gain that can be expected in frequency bands adjacent to SPS, ± 50 MHz removed, will probably be no greater than 49 dBi. This is due to the fact that the out-of-band noise radiated by SPS will be uncorrelated between subarrays and microwave tubes within subarrays. An exception to this would be residual spectral components that might exist due to the phase synchronization process. It is conceivable that out-of-band spectral components could be generated by the synchronization process and that these components would exhibit some degree of coherency throughout the entire transmit array.

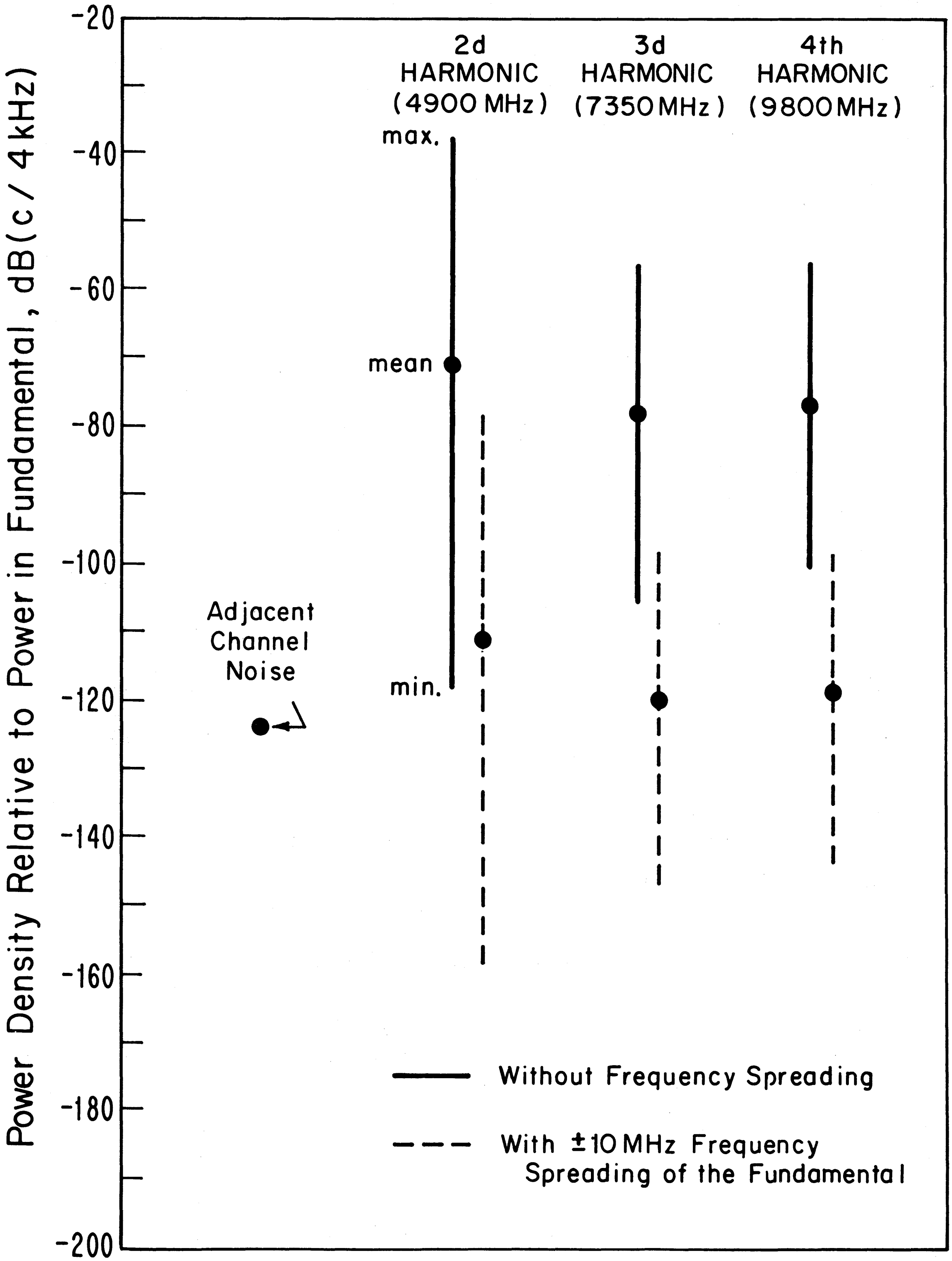

Figure 11. Summary of expected SPS signal levels in a 4 kHz bandwidth.

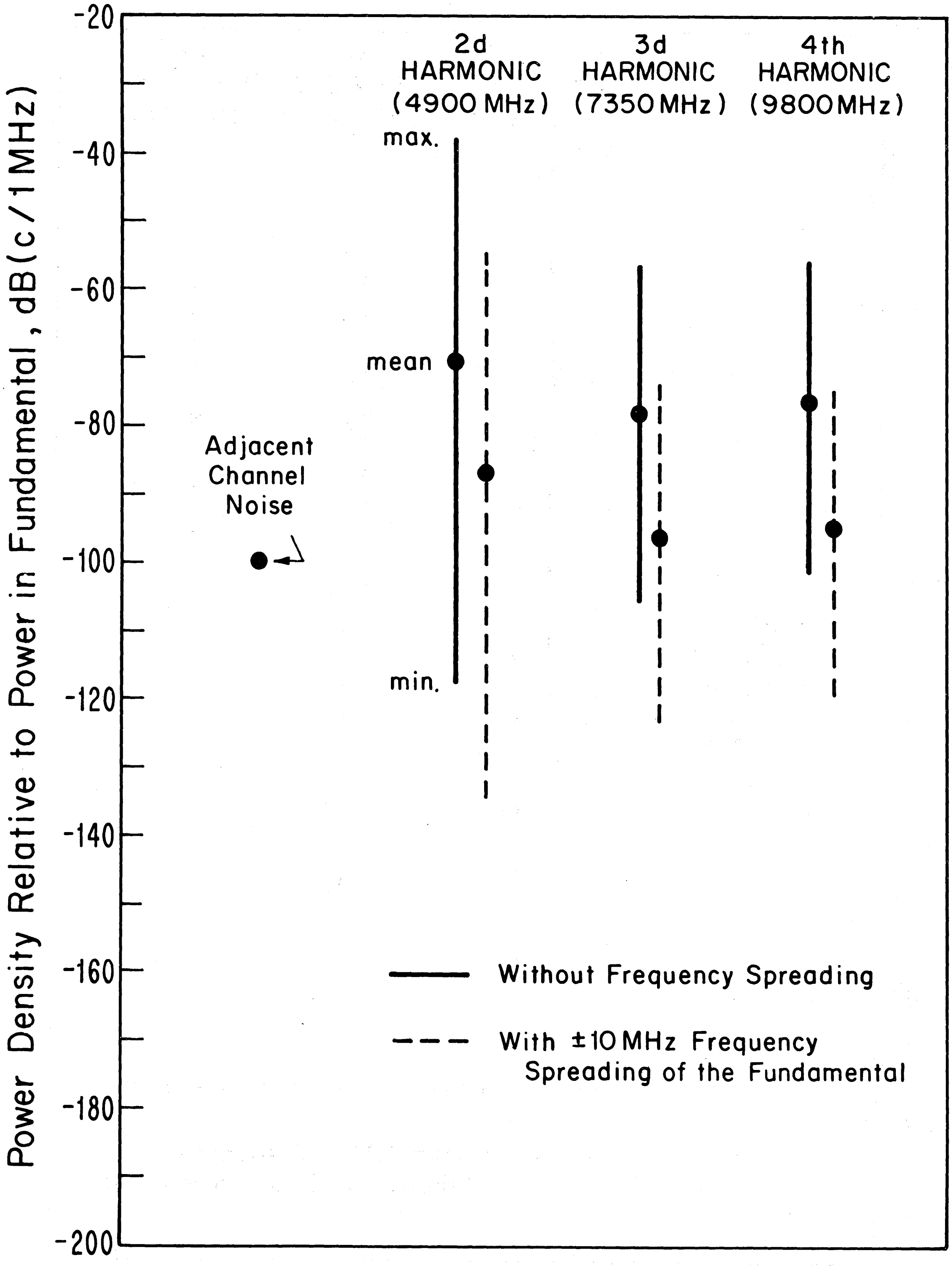

Figure 12. Summary of expected SPS signal levels in a 1 MHz bandwidth.

A factor that will tend to decrease the gain is that some defocusing can also be expected in each subarray since the out-of-band noise is at least 50 MHz removed from the fundamental frequency. This report will assume an adjacent channel antenna gain of 49 dBi for analysis purposes.

The antenna gain at harmonics of the SPS fundamental is also a complex problem. The transmit antenna's performance will be affected by a number of factors such as nonoptimum slot spacing at the higher harmonics. The antenna's performance is also affected by the propagation characteristics of the SPS waveguide. In the rectangular waveguide proposed, the second and all higher harmonics are at frequencies above that of the TE_{02} cutoff frequency. For the 3d harmonic, there exists 14 possible modes of propagation including the cutoff. Without special precautions in the waveguide, such as filtering, all 14 modes will propagate at the 3d harmonic. For the 9.094 cm by 18.8 cm rectangular guide, currently being proposed, the higher order modes have a cutoff wavelength given by

$$(\lambda_c)_{nm} = \frac{18.18}{\sqrt{n^2+4m^2}} \text{ cm}$$

where 18.18 cm is the cutoff wavelength of the fundamental mode and n, m are the conventional mode numbers. The antenna gain at harmonics is also affected by the fact that one can expect some degree of coherency of the harmonic signals throughout the array since the fundamentals are phase coherent. In the following, a range of gain at harmonics of 87 to 27 dBi will be arbitrarily assumed in order to provide an indication of potential interference levels.

Figures 13 and 14 show estimates of the interference levels that would be produced at the surface of the earth given the assumptions described previously. An example showing how these power flux density (pfd) estimates were obtained for the 2d harmonic is as follows:

SPS transmitter power at 2450 MHz	97 dBW
Estimate of mean transmitter power at 2d harmonic (97-71)	26 dBW
Estimate of minimum transmitter power at 2d harmonic (97-119)	-22 dBW
Estimate of range of SPS antenna gain at 2d harmonic	87 to 27 dBi
10 log $4\pi r^2$	162 dB·m^2
pfd using mean 2d harmonic (26+87-162) to (26+27-162)	-49 to -109 dBW·m^2
pfd using minimum 2d harmonic (-22+87-162) to (-22+27-162)	-97 to -157 dBW·m^2

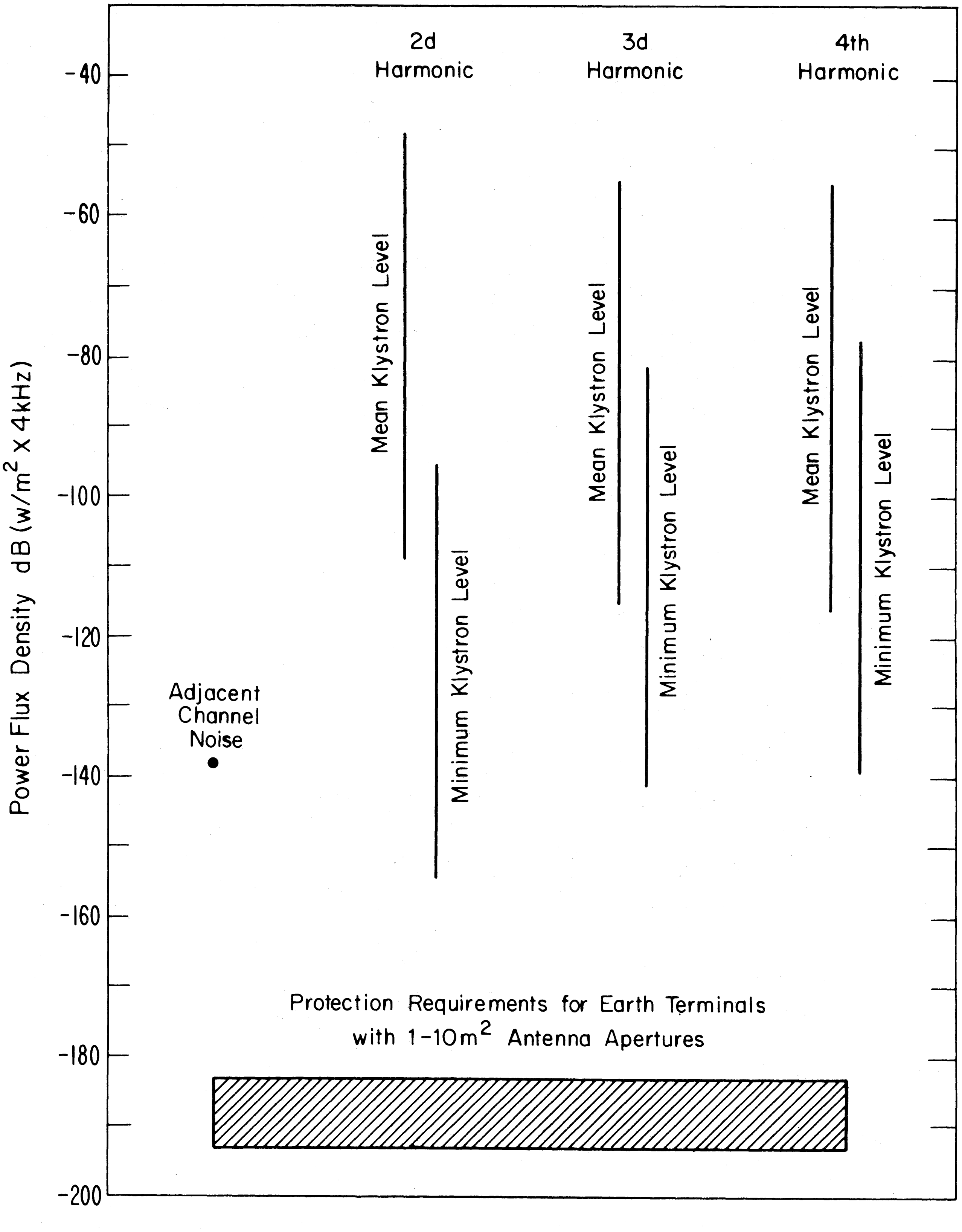

Figure 13. Expected signal levels and protection requirements for systems with a 4 kHz reference bandwidth.

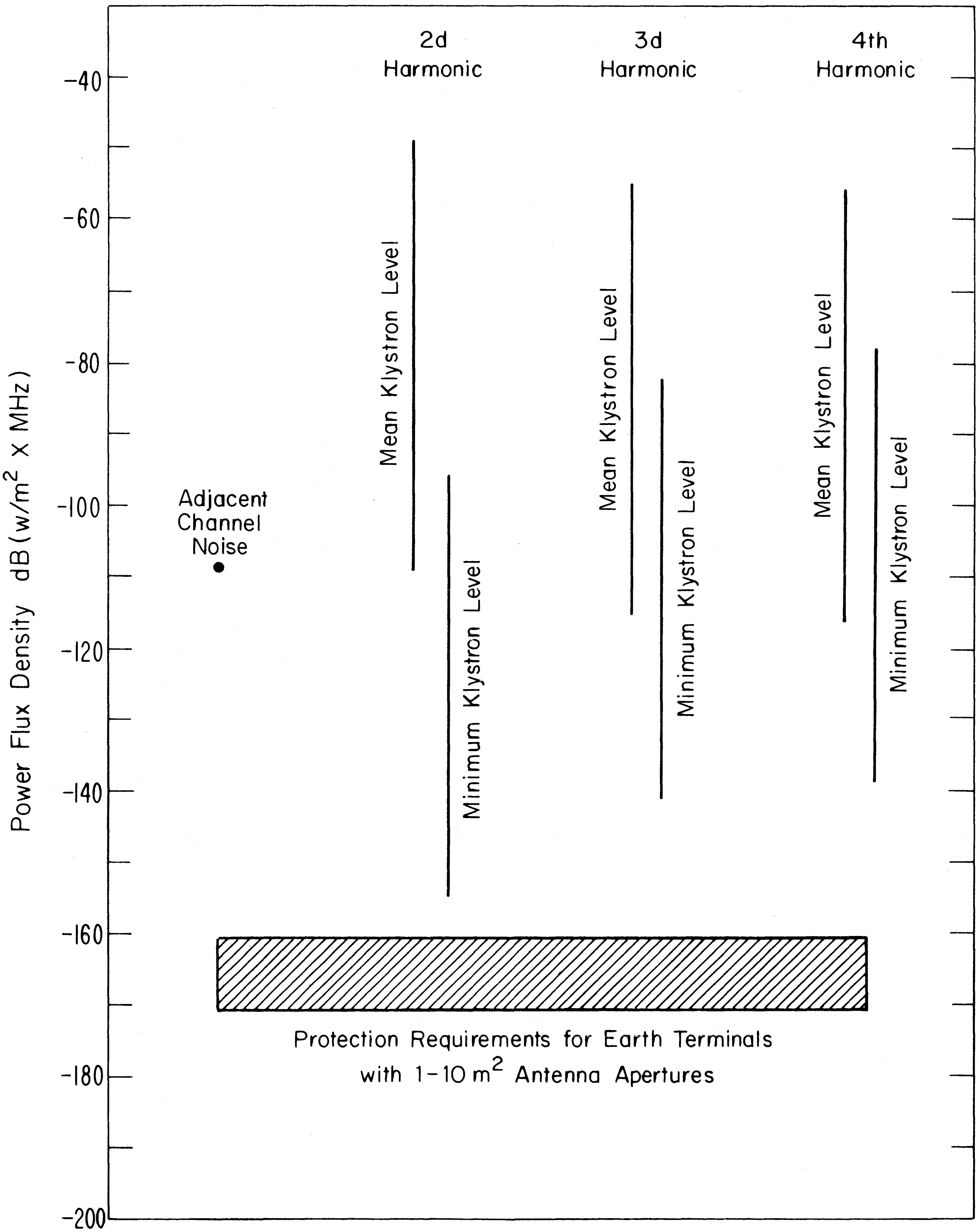

Figure 14. Expected signal levels and protection requirements for systems with a 1 MHz reference bandwidth.

Also shown in the figures is the protection requirements for earth terminals with 1-10 m^2 antenna apertures. Figure 13 is for systems with the narrower 4 kHz reference bandwidth while Figure 14 is for the wider reference bandwidth of 1 MHz. The power flux density shown in these figures was calculated using the formula

$$f_d = \frac{p_t\, g_t}{4\pi\, r^2}$$

where p_t is the power transmitted at the particular frequency in question, g_t is the antenna gain, and r is the distance from the surface of the earth to geosynchronous orbit (3.57×10^7m). The estimates are shown for both median and minimum harmonic levels shown in Table 4. It should be pointed out that these estimates are made only to show what might be expected with current technology. Advances in technology and improved filtering will undoubtedly reduce out-of-band signals beyond current levels. However, signals cannot be filtered ad infinitum and the degree of improvement to be expected is beyond the scope of this study.

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. As can be seen from Figures 13 and 14, significant levels of SPS adjacent channel noise can be expected. The satellite band most susceptable to harmonic interference is the 7300 MHz to 7450 MHz band assigned to Government, fixed satellite, space-to-earth communications. This band is also likely to receive significant interference.

4.4.2 RF Filtering

Interference to satellite earth terminals can also occur from a victim receiver's inability to reject energy within the SPS band. This type of interference will persist even if the adjacent channel and harmonic noise from SPS are eliminated. This interference is described as Type 2 and 3 in Section 3, and is usually due to the quality of rf filtering in the victim receiver.

The attenuation of a typical receiver rf filter can be obtained by examining the characteristics of a bandpass, Butterworth filter. If we assume that this filter is tuned to center frequency f_o and has an rf bandwidth b_{rf}, then the attenuation that this filter gives to a signal on the SPS frequency f_{sps} is approximated by

$$A \cong 10 \log \left(1 + \left(\frac{\Delta f}{\Delta f_c}\right)^{2N}\right) \quad \text{dB} \qquad (6)$$

where

$$\Delta f = f_{sps} - f_o,$$

$$\Delta f_c = b_{rf}/2,$$

and

N = number of poles in the filter design.

A plot of the attenuation versus difference frequency Δf is given in Figure 15. Table 5 summarizes these equations by showing the amount of attenuation that an SPS signal will receive with a N = 4 pole, Butterworth rf filter tuned to various satellite frequencies. For this table, the rf bandwidths have been arbitrarily selected as being typical of those in use in the given band. Attenuation values greater than 100 dB are not given since leakage from circuit connectors and cables are instrumental in limiting any filtering benefits beyond this value. As can be seen from the table, only 47 dB of attenuation is provided at 2450 MHz with a N = 4 pole, Butterworth bandpass filter tuned to 2517 MHz. However, additional filtering could be obtained with more complex types of filters.

TABLE 5. Summary of RF Attenuation Provided by a 4 Pole, rf, Butterworth, Bandpass Filter that is Tuned to a Center Frequency of f_o

SATELLITE BAND	f_o	b_{rf}	Δf_c	Δf	f_o/b_{rf}	rf Attenuation to a 2450 MHz signal (N=4)
1690-1700 MHz	1695 MHz	10 MHz	5 MHz	755 MHz	170	>100
2290-2300	2295	10	5	155	230	>100
2500-2535	2517	35	17.5	67	72	47
2535-2655	2545	20	10	95	127	78
2655-2690	2677	45	22.5	227	59	80
3700-4200	3950	100	50	1500	40	>100
7300-7450	7375	100	50	4925	74	>100

4.5 Specific Examples

It is helpful to examine some specific cases so that one can get a feel for the problems involved with interference to earth terminals. The following examples will investigate potential interference problems to the NAVSTAR or Global Position Satellite (GPS) navigation receivers, as well as the MARISAT maritime receivers. Interference estimates are made at SPS signal levels of 0.01 mw/cm^2 (-10 dBw/m^2) and 0.00001 mw/cm^2 (-40 dBw/m^2).

4.5.1 GPS Navigation Receivers

Current plans for GPS envision a constellation of 24 satellites that provide accurate three-dimensional position and velocity information to users anywhere in the world (Milliken, 1978; Lassiter and Parkinson, 1977). The navigation signal is transmitted at two rf frequencies of f_1 = 1575.42 MHz and f_2 = 1227.6 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

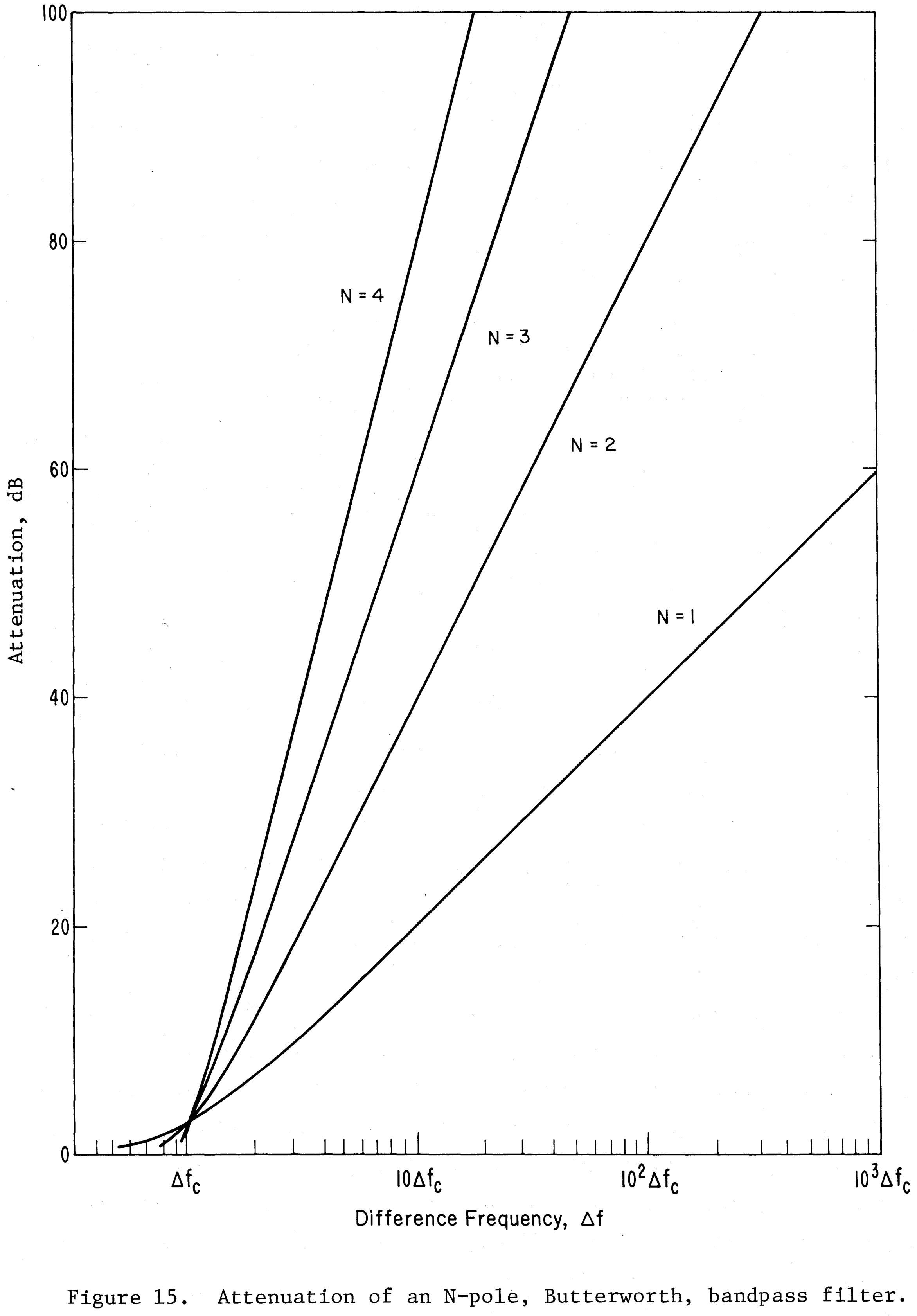

Figure 15. Attenuation of an N-pole, Butterworth, bandpass filter.

techniques, with the P code occupying an rf bandwidth of approximately 10 MHz while the C/A code occupies a bandwidth of 1 MHz. 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 dBW/m^2
Power flux density; 1575.42 MHz P signal at surface of earth	-165 dBW/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 dBW/m^2·4 kHz
Power flux density per 4 kHz, 1575.42 MHz P signal at surface of earth	-199 dBW/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 dBW/4 kHz.

The GPS navigation signals are inherently interference resistant. This is due to the fact that GPS has been specifically designed so that it can survive in a hostile jamming environment. In fact, as shown in the following material, 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

$$D = 10 \log \left(1 + \frac{i}{s} \cdot \frac{s}{n_o} \cdot \frac{1}{b_{rf}}\right) \text{ dB} \tag{7}$$

where

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

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

and

b_{rf} = receiver rf bandwidth.

A plot of equation (12) for b_{rf} is shown in Figure 16. Since these receivers can typically withstand a degradation of 3 dB or more 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 the question of what consitutes interference. Consider the hypothetical example of an interferer with i/s = 5 dB. Strictly speaking, this is not considered interference since it does not significantly affect the GPS receivers output, which is tracking information. However it does affect the receiver in other ways since it results in a significant increase in the noise that the receiver normally operates in. This increase in noise affects the signal acquisition capabilities as well as the ability to reject additional interferers or jammers. Thus, in this report, we will determine if interference between SPS and GPS exists by looking for any significant increase in receiver background noise.

Calculations of the SPS signal levels coupled into a GPS receiver are relatively straightforward, as shown in Table 6. One of the parameters in the table is the amount of receiver filtering that can be expected for the interfering SPS signal. A value of -130 dB has been chosen because of the large frequency separation between victim and interferor (1575 MHz and 2450 MHz, respectively). Leakage from connectors, chassis, components, etc., generally limits the maximum filtering of modern receivers to values in this range.

TABLE 6. 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 to receiver filtering attenuation (1575 MHz to 2450 MHz)	130 dB	130 dB
I/N after filtering	9 dB	-21 dB

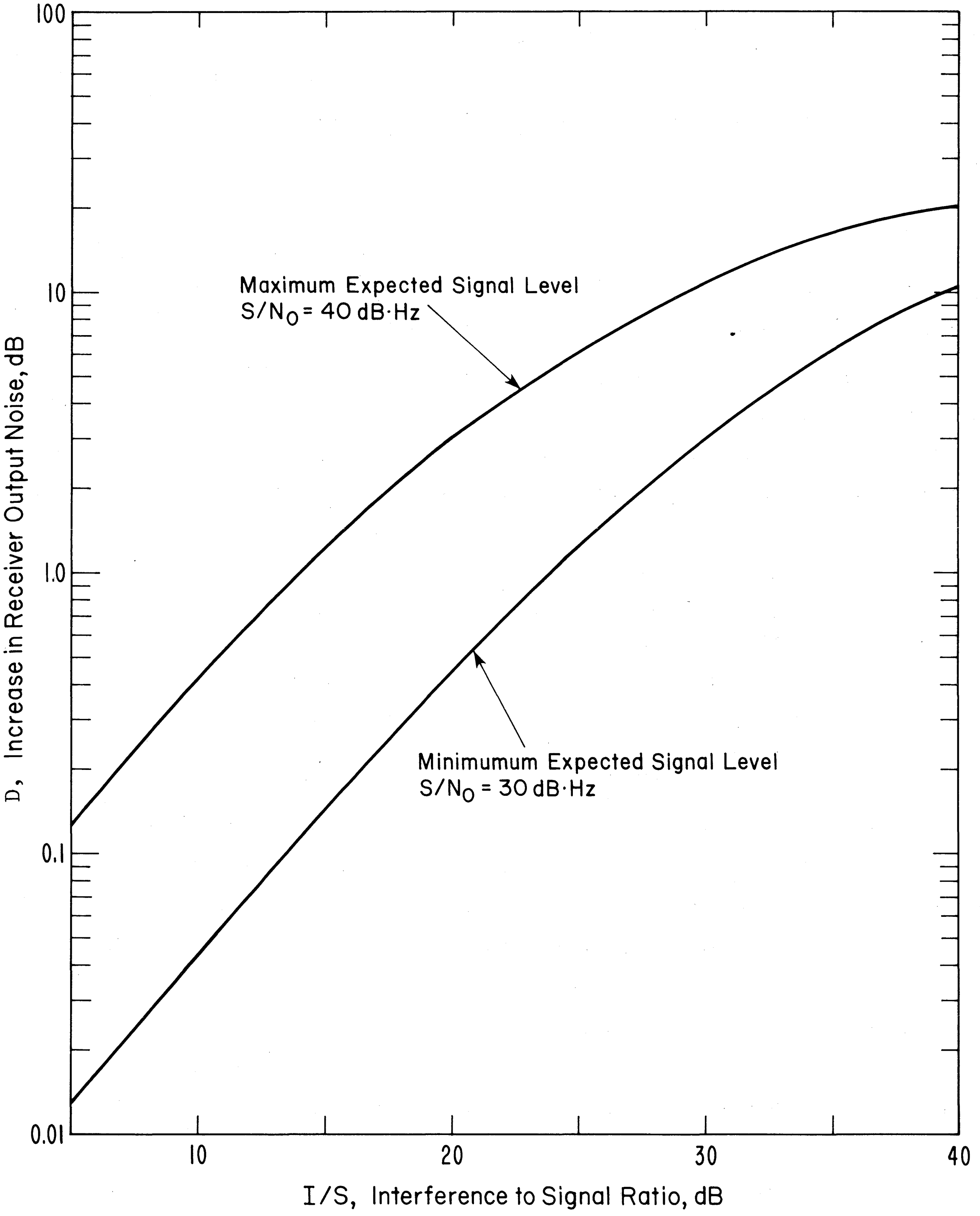

Figure 16. Expected degradation of a GPS navigation receiver in interference. Bandwidth of receiver is b_{rf} = 1 MHz.

Table 6 shows that, 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 one would like the I/N ratio to be less than 0 dB in order to be assured of no interference. Although the I/N ratio is greater than 0 dB in a -10 dBW/m^2 field, it is significantly less than 0 dB in the -40 dBW/m^2 field. Neither of these interference to noise ratios would be expected to significantly alter the receivers tracking accuracy.

4.5.2 MARISAT Ship Terminals

A similar situation is the MARISAT satellite system, which 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 17 (Gould and Yum, 1975). The closest MARISAT frequency to SPS is the 1540 MHz satellite-to-ship link.

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

EIRP at satellite	26 dBW
Power flux density at surface of earth	-137 dBW/m^2
FM signal bandwidth	25 kHz
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 previously for GPS, MARISAT does not use spread spectrum techniques and therefore cannot operate with the positive I/S ratios shown for GPS.

Table 7 describes the SPS signal levels that can be expected in a MARISAT shipboard receiver. Tables 6 and 7 show that in a -40 dBW/m^2 SPS field, the estimated I/N ratio after receiver filtering is -21 dB for GPS and 5.3 dB for MARISAT. Ideally both of these figures should be less than zero to insure that no interference exists. However, neither estimate shows a 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.

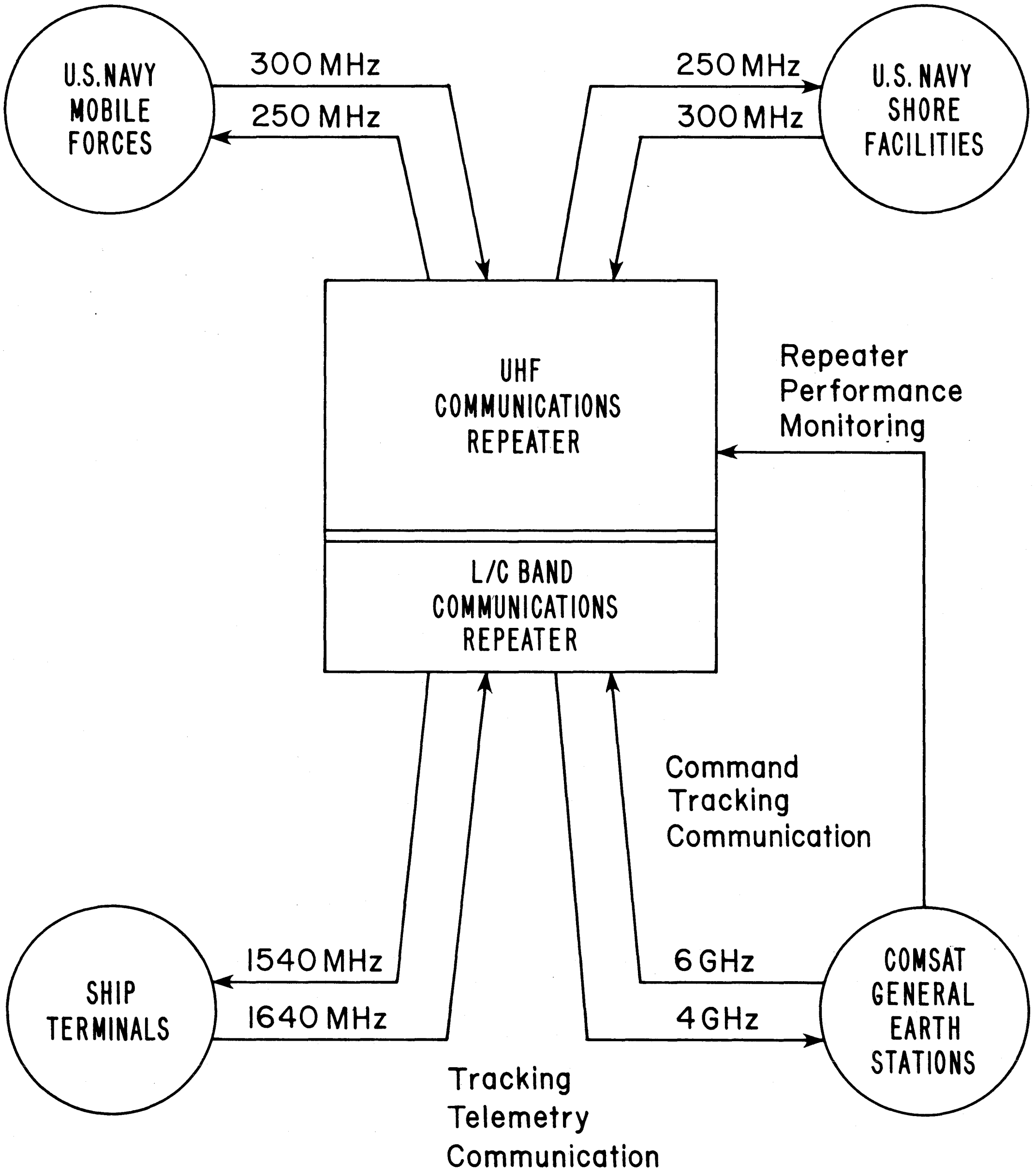

Figure 17. MARISAT communications frequencies.

TABLE 7. Estimate of SPS Signal Levels in a 540 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°K)	-175 dBW/4 kHz	-175 dBW/4 kHz
Effective MARISAT antenna aperture (1.3 m diameter, 80% efficiency)	0.3 dB·m^2	0.3 dB·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

5. CONCLUSIONS AND RECOMMENDATIONS

The potential for interference between a solar power satellite and satellite earth terminals is evaluated in this report. The report begins with a general discussion of the different ways that communications systems are interfered with, and estimates are made as to the frequency band in which interference is likely. Detailed calculations are made to determine which satellite systems are likely to experience interference.

The conclusion of this study is that a potential for interference exists in the 2500 MHz to 2690 MHz, direct broadcast satellite, frequency band adjacent to SPS. Estimates of the adjacent channel noise from SPS in this frequency band are -124 dBc/4 kHz and -100 dBc/1 MHz. A second problem is the 7350 MHz 3d harmonic from SPS that falls within the 7300 MHz to 7450 MHz space-to-earth, government satellite band. Estimates of 3d harmonic signal levels based on current klystron technology are from -57 to -105 dBc/4 kHz.

The report shows that co-channel interference levels below -185 dB(W/m^2, 4 kHz) will be needed to protect earth terminals with antenna apertures of one square meter. These figures are applicable for narrow band systems such as single channel voice systems and FM-FDM voice systems with a reference bandwidth of 4 kHz.

Wideband satellite earth terminals with a reference bandwidth of 1 MHz can withstand higher interference levels of up to -161 dB(W/m^2 MHz). Earth terminals whose operating frequency is significantly removed from SPS can withstand interference levels substantially higher than those quoted above because of the filtering in the receiver. It is noted that tests need to be conducted to more precisely define the maximum filtering available in receivers.

Specific calculations were made of the possibility of interference between SPS and NAVSTAR Global Position Satellite Navigation receivers. The conclusion is that SPS does not represent a threat to the 1575.42 MHz navigation signals. 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 dB(W/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 dB(W/m^2) or 1 x 10^{-5}mw/cm^2. However, a potential interference problem exists with MARISAT terminals in a field of -10 dB(W/m^2).

The report also examined the effects of frequency spreading of the SPS signal. Although this technique is beneficial in reducing the power flux density per 4 kHz of the interfering signal, its advantages in reducing adjacent channel noise are questioned. The calculations in this report assume a frequency spreading of ± 10 MHz on the 2450 MHz SPS signal. This assumption is important since it reduces the fundamental power flux density in any 4 kHz band by 37 dB.

A number of significant areas were encountered where additional study is needed. These are briefly listed as follows:

1. The radiation characteristics of the SPS transmission and antenna system at harmonics is unknown. This study has assumed values for radiated harmonic signal levels based on current technology. However, there are no studies at the present time to confirm or deny these values.
2. Measured data is needed that describes the harmonic and noise characteristics of the transmitting klystrons. Of particular interest is the spectral characteristics of the klystrons outside of the ± 50 MHz SPS frequency assignment.
3. Measurements of receivers in simulated SPS fields of the order of 0.01 mw/cm^2 are needed in order to better understand the interference mechanisms involved. This is particularly true of those receivers whose operating frequencies are considerably removed from the SPS frequency.

The lack of experimental data where satellite receivers are actually subjected to expected SPS interference levels is a significant hinderance in this study. The ability to test equipment in a simulated SPS environment would provide considerable insight into the interference question.

6. ACKNOWLEDGEMENT

The authors wish to acknowledge the support for this investigation provided by the U.S. Department of Energy under the direction of F. A. Koomanoff, Chief, Environmental and Resource Assessment Programs, Solar Technology, Washington, D.C., Contract No. DE-A101-80ER10160.

7. REFERENCES

Bargellini, P. L. (1972), The Intelsat IV communication system, COMSAT Technical Review, 2, No 2, pp 437-572.

Batson, B. H., S. W. Novosad, and T. W. Sheehan (1977), Space shuttle utilization of TDRSS services, IEEE NTC'77 Conference Record, Vol I, pp 09:4-1, 09:4-5.

CCIR, International Radio Consultative Committee (1978a), Report 713, The radiation of spurious emissions from earth stations and space stations of the fixed satellite service, XIVth Plenary Assembly, Vol II, Koyoto, Japan, pp 307-313.

CCIR, International Radio Consultative Committee (1978b), Report 679, Characteristics and effects of radio techniques for the transmission of energy from space, XIVth Plenary Assembly, Vol II, Koyoto, Japan, pp 52-59.

CCIR, International Radio Consultative Committee (1978a), Report 558-1, Satellite antenna patterns in the fixed satellite service, SIVth Plenary Assembly, Vol IV, Koyoto, Japan, pp 243-262.

Gould, R. G., and Y. F. Yum (1975), Communications Satellite Systems: An overview of the technology, (IEEE Press, New York), pp 57-63.

Johnson, Floyd O. (1969), Interference emission filtering in high power microwave transmitters, IEEE EMC Symposium Record, Asbury Park, N.J., pp 336-341.

Lassiter, Edward M., and Bradford Parkinson (1977), The operational status of NAVSTAR/GPS, Journal of Navigation, No 1, pp 35-41.

Milliken, R. J., and C. J. Zeller (1978), Principle of operation of NAVSTAR and system characteristics, Navigation Journal of the Institute of Navigation, Vol 25, No 2, pp 75-105.

Poza, H. B. (1977), TDRSS telecommunications payload: an overview, IEEE NTC'77 Conference Record, Vol I, pp 19:1-1, 19:1-7.

Satellite Communications (1979), CATV earth station sites, (special publication insert), May.

Schunemann, K. (1972), Noise in cavity stabilized microwave oscillators, Philips Research Reports, Vol 27, pp 486-507.

Skolnik, Merril I. (1970), Radar Handbook (McGraw-Hill Book Company, New York) pp 29-4, 29-7.

U.S. Dept. of Energy (1978), Satellite power system, concept development and evaluation program, reference report DOE/ER-0023, Washington, D.C., October.

White, D. R. (1972), Electromagnetic interference and compatibility, Vol 5, (Don White Consultants, Germantown, MD), pp 4.24-4.50.

FORM **NTIA-29**
(4-80)

U.S. DEPARTMENT OF COMMERCE
NAT'L. TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION

BIBLIOGRAPHIC DATA SHEET

	1. PUBLICATION NO. NTIA Report 81-64	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE
Analysis of Interference caused by the Solar Power Satellite to Satellite Earth Terminals

5. Publication Date
February 1981

6. Performing Organization Code

7. AUTHOR(S)
John R. Juroshek

9. Project/Task/Work Unit No.

8. PERFORMING ORGANIZATION NAME AND ADDRESS
National Telecommunications & Information Administration
Institute for Telecommunication Sciences
325 Broadway
Boulder, CO 80303

10. Contract/Grant No.

11. Sponsoring Organization Name and Address
U.S. Department of Energy
Washington, D.C. 20545

12. Type of Report and Period Covered

13.

14. SUPPLEMENTARY NOTES

15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The solar power satellite (SPS) is a concept for generating electrical power from solar energy via a geosynchronous orbiting satellite. A facility, such as this, would be able to send approximately 5 to 10 gigawatts of power to earth on a highly focused 2450 MHz microwave beam. The electromagnetic compatibility problems cause by this amount of microwave power transmission are recognized as a critical factor in the implementation of such a system. This report examines the potential for interference between SPS and conventional satellite earth terminals.

The report begins with a general discussion of the different ways that interference between SPS and satellite systems can occur. Estimates are made of the levels of harmonics and out-of-band noise that are likely to be radiated by SPS. These levels are then compared to the interfer-

(Continued next page)

16. Key Words *(Alphabetical order, separated by semicolons)*

Key Words: interference, satellite; solar power satellite

17. AVAILABILITY STATEMENT

☒ UNLIMITED.

☐ FOR OFFICIAL DISTRIBUTION.

18. Security Class. *(This report)*
UNCLASSIFIED

19. Security Class. *(This page)*
UNCLASSIFIED

20. Number of pages
37

21. Price:

15. ABSTRACT (Cont.)

ence threshold for various representative satellite scenarios. The report concludes that a potential for interference exists in the 2500 MHz to 2690 MHz direct broadcast satellite frequency assignments. Another potential problem is SPS radiation at the 7350 MHz 3d harmonic that falls within the 7300 MHz to 7400 MHz space-to-earth government satellite band.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1981—779-092/260 Region No. 8