REDUCING RADIO-FREQUENCY-INTERFERENCE FROM SPACECRAFTS IN THE FREQUENCY RANGE FROM 20 Hz to 200 kHz

by

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I. INTRODUCTION

The performance of a satellite-borne radio noise experiment can be very seriously degraded by radio-frequency-interference (RFI) generated by the spacecraft electrical system. Since the interference signals often occur in the same range of frequencies as the naturally occurring radio noises which are being investigated it is very difficult and sometimes impossible to discriminate against the interference. Therefore, for spacecrafts which carry radio noise experiments it is essential that the interference generated by the spacecraft be reduced to levels which are comparable to the sensitivity of the radio noise experiment.

It is the purpose of this paper to review the problem of spacecraft RFI in the frequency range from 20 Hz to 200 kHz and to recommend methods of reducing this interference on future spacecrafts. These recommendations are intended primarily for the IMP-I satellite on which the University of Iowa is conducting radio noise measurements. However, we hope that these recommendations will also be of assistance in the design of other spacecrafts which have radio noise experiments in the frequency range considered here.

II. THE FIELDS GENERATED BY RFI SOURCES IN THE FREQUENCY RANGE FROM 20 Hz to 200 kHz

A. Source Currents

Radio-frequency-interference from a spacecraft is generated by oscillating currents within the spacecraft electrical system. We shall briefly discuss the electromagnetic fields generated by these currents.

Current sources can in general be classified as either (1) magnetic or (2) electrostatic according to whether the divergence of the current density is zero or non-zero, respectively.

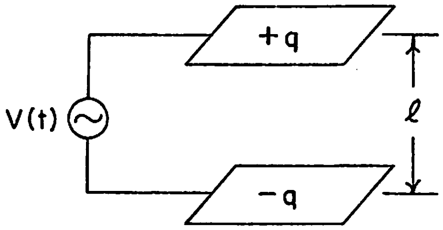
(1) Magnetic Sources

Magnetic sources are currents for which the current density is divergence free, $\vec{\nabla} \cdot \vec{J} = -\partial\rho/\partial t = 0$. Thus, there is no charge density oscillation associated with a magnetic source. An example of a magnetic current source is a closed loop carrying a time varying current.

The "strength" of a magnetic current source is given by the magnetic moment $M = IA$, where I is the current and A is the area of the current loop. Time varying currents in the spacecraft wiring harness and power supplies are examples of magnetic sources.

(2) Electrostatic Sources

Electrostatic sources are currents for which the current density is not divergence free, $\vec{\nabla} \cdot \vec{J} = -\partial\rho/\partial t \neq 0$. Thus, there is a charge density oscillation associated with an electrostatic source. Two conducting plates with a time varying potential difference between the plates is an example of an electrostatic source.



The "strength" of an electrostatic source is given by the electric dipole moment $p = q\ell$, where ℓ is the separation between the charges +q and -q, or for the above example by $V\ell$, where V is the potential difference between the plates. Time varying potentials on the spacecraft solar cells is an example of an electrostatic source on a spacecraft.

B. Fields Generated by Current Sources

Two types of fields can be generated in the plasma surrounding the spacecraft by current sources on the spacecraft: (1) electromagnetic and (2) electrostatic.

1. Electromagnetic Fields

For the frequencies being considered (<200 kHz) the wavelength of electromagnetic waves ($\gtrsim 10^3$ meters) is much greater than the dimensions of the spacecraft. Consequently, the electric and magnetic fields in the vicinity of the spacecraft are dominated by the near fields (amplitude proportional to r^{-3}) of the current source. To a very good approximation the near fields of the source at any given time can be considered identical to the fields one would obtain from a static current and charge (potential) system of magnitude equal to the amplitudes of the oscillatory currents and charges at that time. Thus, for magnetic sources (current loops) the near field is dominately magnetic with

$$B \propto \frac{M}{r^3} \quad (r = \text{distance to source}),$$

and for electrostatic sources the near field is dominately electric with

$$E \propto \frac{p}{r^3} \quad .$$

In summary the electromagnetic fields generated by an interference source in the frequency range being considered are dominated by the near fields of the source in the vicinity of the spacecraft (up to several hundred meters) and to a good approximation the near fields can be considered to be the fields one would obtain if the oscillating currents and charges in the spacecraft were static.

For reference the field strength of a magnetic dipole is given in Figure 1 as a function of the magnetic moment M and the distance to the source r. The noise level of the IMP-I radio noise experiment is also shown for comparison at various frequencies. In Figure 2 we show the maximum magnetic moment allowable without causing magnetic interference for the IMP-I E.M. fields experiment as a function of frequency and distance from the spacecraft. As an example we see that for a loop antenna located on a boom two meters from the spacecraft the maximum magnetic moment allowable for a power supply operating at 1 kHz is about 70 ma cm^2 (i.e., 1 ma in a current loop with dimensions 7 cm by 10 cm).

Electromagnetic fields can be shielded by enclosing the source within a closed conducting container. The skin depth (depth for the fields to be attenuated by e^{-1}) for aluminum is given by

$$\delta = 8.85\, f^{-1/2} \text{ (cm)}$$

(f in Hz).

The thickness of aluminum required to obtain a specified attenuation is shown in Figure 3 as a function of frequency. For typical power supply frequencies of 1 kHz or so several centimeters of aluminum are required to provide significant attentuation at these frequencies. Because of the weight penalty imposed by such thick shielding it is generally impractical to use conductive shielding below about 100 kHz.

By using materials with a large permeability (ferromagnetic) the attenuation of a conducting shield can be significantly increased (δ proportional to $K_m^{-1/2}$, K_m = relative permeability). However, the sensitivity (vibration, temperature, etc.), D.C. magnetic field, and weight of ferromagnetic shielding make this method of shielding unattractive except in small isolated applications.

2. Electrostatic Plasma Waves

In addition to the electromagnetic radiation discussed above, a wide variety of electrostatic waves can be excited in a plasma. These waves have no analogy in free space. The closest analogy to these electrostatic plasma waves is ordinary sound waves with coulomb forces in the plasma taking the place of collisions in transmitting the wave energy. In the ionosphere and magnetosphere the wave length of these electrostatic plasma waves can vary from a few centimeters to a few meters for the frequencies being considered.

Since these plasma waves are purely electrostatic they are excited by charge (potential) oscillations only. These waves are not excited by magnetic sources (no charge fluctuations). On a spacecraft any potential (charge) fluctuation on the exterior of the spacecraft (a.c. voltage fluctuations on the solar cells, for example) can be expected to excite these plasma waves. Since the field amplitude for these waves decays relatively slowly with distance from the source, $E \propto {}^{1}/r$, these waves may be a potentially serious source of interference for electric field measurements.

Electrostatic fields can be very effectively shielded by enclosing the electrostatic source within a conducting container. The conducting outer shell of a satellite thus provides an excellent shield for electrostatic sources.

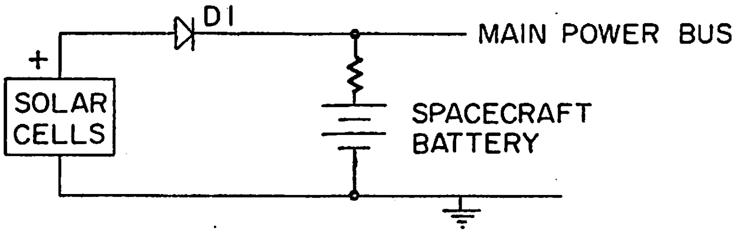
III. SUMMARY OF VLF INTERFERENCE ON PREVIOUS SPACECRAFTS

In this section we summarize the RFI problems which have occurred on previous spacecrafts in the very-low-frequency region of the radio spectrum.

A. Alouette 1

The very-low-frequency radio noise experiment on the Alouette 1 satellite consisted of a wide-band (400 Hz to 10 kHz) receiver connected to a 150 foot tip to tip electric dipole antenna. Spectral analysis of signals from the wide band receiver has shown the presence of strong interference at the frequencies of the d.c. to d.c. converters within the spacecraft [F. J. F. Osborne et al., Plasma-Induced Interference in Satellite V.L.F. Receivers, Canadian J. of Phys. 47-56, 1966].

A principle characteristic of this interference is that the intensity is much greater in the sunlit portion of the orbit compared to the dark portion of the orbit. This fact and other evidence strongly suggests that the d.c. to d.c. converter generated signals are coupled to the electric antennas via the satellite solar cells. The accepted explanation of the coupling is that the chopping action of the d.c. to d.c. converters causes an a.c. voltage of approximately 0.5 volts on the main power bus. When the satellite is in the darkness the solar panels are not connected to the main power bus because the isolation diode D1 (see illustration below) is back biased



Thus, no a.c. voltages are present on the solar panels. When the satellite is in the sunlight, diode D1 is forward biased so that a.c. voltages on the main power bus appear on the solar cells. The coupling of the a.c. solar cell voltages to the electric antenna is believed to arise because of modulation of the electron current collected by the solar cells due to the varying solar cell potential (see Osborne *et al*. for further details).

B. Injun III

The very-low-frequency radio noise experiment on the Injun III satellite consisted of a wide-band (200 Hz to 7 kHz) receiver connected to a 1 foot diameter magnetic loop antenna [see Gurnett and O'Brien, High Latitude Geophysical Studies with Satellite Injun 3. 5. Very-Low-Frequency Electromagnetic Radiation, *J. Geophys. Res.*, *69*, 65-89, 1964]. The threshold sensitivity of the loop antenna and receiver system was about 10^{-3} gamma. The loop antenna was mounted very close (about 18 inches) from the center of the spacecraft.

The Injun III VLF experiment is mentioned here because *no* interference above the noise level of the system was detected from the spacecraft throughout its operational life. *This low level of interference was accomplished by requiring that all d.c. to d.c. converters and other interference generating equipment* (magnetometers, subcarrier oscillators, etc.) *be operated at frequencies above 12 kHz so that the interference frequencies did not fall within the bandwidth of the VLF receiver*. The success of the Injun III VLF experiment demonstrates that VLF interference can be reduced to an acceptable level by careful planning at an early stage in the design of the spacecraft system.

Some of the conclusions arrived at during the design of the Injun III spacecraft system are summarized below:

1. *Amplitude modulation of the satellite transmitter*

cannot be used. It was found to be very difficult to obtain sufficient attenuation at the VLF receiver input to prevent detection of an amplitude modulated transmitter signal. It was decided, therefore, to use a phase modulated transmitter (1.5 watts) which had a maximum incidental amplitude modulation of 3%. No difficulty was experienced with this transmitter.

2. Currents in the power cables to a subsystem often cause more interference than the subsystem itself. It was found to be very important to keep the loop area between the power lead and the ground return lead as small as possible (preferably a twisted pair running from the spacecraft battery to the subsystem).

It is essential, therefore, to have a well defined and carefully designed grounding system in the spacecraft.

3. Generally the digital data system does not produce objectionable VLF interference. No interference was detected from the digital encoding system on Injun III despite the fact that many of the flip flop circuits and logic operated at frequencies in the VLF range. The low level of interference from the encoding system is due to the fact that in any one flip flop the current require-

ments did not exceed about 100μa, and due to the high packing density the loop area for these currents usually did not exceed about 10 cm^2. Thus, the magnetic moment for these currents (about 1 ma cm^2) is small enough that the interference is not detectable (see Figure 2).

C. OGO-I, II, and III

Spacecraft generated interference has been a serious problem for radio noise measurements on the OGO spacecrafts. Comments by various experimenters have been presented in an OGO Experiment Bulletin, No. C-137, E-87, distributed by G. H. Ludwig; Goddard Space Flight Center, Greenbelt, Maryland. The discussions presented below have been summarized from conversations with two experimenters.

1. The Dartmouth VLF Experiment (summarized from discussions with T. Laaspere)

The Dartmouth VLF experiment on OGO II consisted of a wide-band (300 Hz to 20 kHz) receiver connected to an electric dipole antenna approximately 10 ft. long tip to tip. The center of the electric antenna is located approximately 5 ft. from the spacecraft body.

Strong spacecraft generated interference (40-60 db above the noise level) is detected at 400 Hz and even harmonics of this frequency and at the d.c. to d.c. converter frequency (2.461 kHz) whenever the spacecraft is in the sunlight. During darkness this interference is almost completely absent. Although no definite conclusions have been established it seems probable, in view of the similar interference found on Alouette 1, that this electric field interference arises from a.c. potential fluctuations on the spacecraft solar panels.

2. The Stanford VLF Experiment (summarized from discussions with B. P. Ficklin)

The Stanford VLF experiment on OGO I, II, and III consisted of four VLF receivers covering the frequency range from 200 Hz to 100 kHz [Rorden et al., Instruments for the Stanford University/Stanford Research Institute VLF Experiment on the EOGO Satellite, SRI Instrument Rept., Stanford Research Institute, Menlo Park, Calif., May 1966]. These receivers are connected to a 9.5 ft. diameter magnetic loop antenna mounted on a boom approximately 20 ft. from the spacecraft body.

Spacecraft generated interference is detected by this experiment over almost the entire frequency range.

The interference signals detected include the following: (a) 400 Hz and its harmonics, and (b) the d.c. to d.c. converter frequency and its harmonics up to frequencies as high as 100 kHz. The amplitude of these interference signals is often very strong (40 to 60 db above the receiver noise level). Although the detailed origin of these interference signals is not entirely known it appears that inadvertent ground loops in the spacecraft wiring harness are partly responsible.

D. The TRW Electric Field Experiment on OV3-3

The TRW a.c. electric field experiment on the OV3-3 satellite consisted of a 2.5 inch diameter spherical wire cage antenna mounted on the end of a boom approximately 5 ft. from the spacecraft body [Scarf et al., First Results of the TRW Electric Field Experiment on OV3-3; Report 99900-6019-R000; TRW Systems, One Space Park, Redondo Beach, Calif; August 1966]. The electric antenna is connected to a high input impedance preamplifier and the a.c. potential fluctuations of the antenna are measured at four frequencies 75 Hz, 400 Hz, 1.7 kHz, and 7.35 kHz.

Several types of spacecraft generated interference have been found in the OV3-3 electric field data. First, the noise intensity is often observed to increase abruptly when the satellite passes from darkness to sunlight and vice versa. Because of the similarity of this sunlight-darkness effect to the solar cell generated electric field interference observed on Alouette 1 and OGO II it seems very likely that a.c. voltage fluctuations on the OV3-3 solar panels may be causing interference with the electric field measurements when the spacecraft is in the sunlight [personal communication, F. L Scarf].

Second, electric field interference is detected from an a.c. Faraday cup on board the same spacecraft whenever the second grid (the one just below the outer grid) is driven with a 2 kHz square wave at an amplitude of several keV. The amplitude of this interference signal is often very strong (1 mV in the 1.7 kHz and 7.35 kHz channels). Since no interference was detected during ground based tests Scarf concludes that these interference signals are electrostatic plasma oscillations excited when the second grid of the Faraday cup is modulated.

IV. MEASUREMENTS OF VLF INTERFERENCE FROM THE INJUN IV AND IMP-F SPACECRAFTS

In order to obtain approximate magnitudes for the interference intensities to be expected from a spacecraft, measurements have been made of the VLF interference from the Injun IV and IMP-F spacecrafts. For both of these spacecrafts no attempt was made in the design of the electrical system to reduce VLF interference. Consequently, these interference levels should represent a worst case situation for spacecrafts of similar design and total power.

A. Injun IV

The principal interference producing elements on the Injun IV spacecraft can be summarized as follows: one tape recorder (motor driven, 400 Hz), two magnetometers (frequency ~ 3.0 kHz), one main spacecraft power converter (frequency ~ 2.4 kHz), and eleven high voltage power supplies (frequency ~ 2.5 kHz). The total power required for all these elements is approximately 20 watts.

1. Electric Field Interference

All electrical systems on the Injun IV spacecraft were enclosed within a closed aluminum outer shell.

This conducting outer shell provides an excellent electrostatic shield for electrostatic sources within the spacecraft. The effectiveness of this shielding was verified by measuring the a.c. electric field as a function of distance from the spacecraft. The electric field detector consisted of a high gain, high input impedance ($R > 10^7$ ohm, $C_{in} > 10$ pf), audio amplifier (100 Hz to 10 kHz) connected to a six foot tip to tip electric dipole antenna. It was found that electric field interference was undetectable (less than 30 μvolts) at all distances greater than about 3 ft. from the spacecraft. Since this interference level is entirely acceptable it was concluded that a conducting spacecraft shell enclosing all the spacecraft electronics provided an excellent shield for electrostatic sources. The solar panels were not connected for these tests.

2. Magnetic Field Interference

The amplitude of the a.c. magnetic field generated by the Injun IV spacecraft was measured as a function of distance from the center of the spacecraft. The detector used consisted of a 1 ft. diameter loop antenna connected to a VLF receiver covering the frequency range from approximately 200 Hz to 7 kHz. In Figure 4 we show the r.m.s. amplitude of the wide-band (200 Hz to 7 kHz) magnetic interference as a function of the distance (r) from the center of the spacecraft. No significant dependence was found on the orientation of either the spacecraft or the loop antenna. All systems in the spacecraft were on when these measurements were being made. The best fit to the expected r^{-3} dependence of the field amplitude is shown. From Figure 1 it can be determined that the effective a.c. magnetic moment of all current sources in the spacecraft is approximately 6.5×10^3 ma cm^2. Thus, in order to reduce the magnetic field interference to a level acceptable for the IMP-I E.M. fields experiment it would be necessary to mount the loop antenna on a boom approximately 10 meters from the Injun IV spacecraft.

The most intense interference was found to be generated by the main spacecraft power converter. The interference generated by the tape recorder at 400 Hz was found to be approximately a factor of 3 below the levels shown in Figure 4.

B. <u>IMP-F</u>

The principal interference producing systems on the IMP-F spacecraft can be summarized as follows:

one main voltage regulator (frequency ~ 5 kHz)
one encoder power supply (frequency ~ 4 kHz)
one three axis Magnetometer power supply (frequency ~ 1.6 kHz) (Magnetometer operates at ~ 10 kHz)
and eight experiment power supplies.

The total power required for all these systems is approximately 30 watts.

Unfortunately, because of high winds on the day of the test, the solar panels could not be mounted on the spacecraft. Consequently, the magnetic interference generated by currents in the solar panels could not be determined.

1. Electric Field Interference

Because of the conclusive nature of the Injun IV electric interference tests no electric interference tests were performed on IMP-I.

2. Magnetic Field Interference

The amplitude of the a.c. magnetic field generated by the IMP-F spacecraft was determined using the same instrument described for the Injun IV magnetic interference measurements. In Figure 5 we show the r.m.s. amplitude of the wide-band (200 Hz to 7 kHz) magnetic interference as a function of the radius (r) from the center of the spacecraft. All measurements were made in the equatorial plane of the spacecraft (perpendicular to the spin axis). No significant dependence of the interference amplitude on angular rotations of the spacecraft about the spin axis or on the loop antenna orientation were found.

Two cases were considered: (1) spacecraft on and experiments on, and (2) spacecraft on and experiments off. It was found that the interference intensity approximately doubled when the experiments were turned on. Consequently, the experiments and spacecraft were contributing approximately equally to the magnetic interference. No attempt was made to track down the origin of each frequency component of the observed interference. From previous experience, however, it seems almost certain that the spacecraft d.c. to d.c. converters were the principle source.

V. SUMMARY OF INTERFERENCE SOURCES

From the evidence presented here we would summarize the sources of radio frequency interference (20 Hz to 200 kHz) on spacecrafts as follows:

A. Electric Field Interference

1. Major Sources
    - a. A.c. potential fluctuations on solar panels caused by d.c. to d.c. converters, tape recorder motors, etc.
    - b. Detectors with a.c. potentials applied to grids or collectors mounted externally to the spacecraft shell.
2. Minor Sources
    - a. Detection of amplitude modulation from high frequency transmitters.

B. Magnetic Field Interference

1. Major Sources
    - a. D.c. to d.c. converters, magnetometers, tape recorder motors and other systems which require fairly large a.c. currents (10 ma or more).
    - b. Large area current loops in the spacecraft harness, solar panels, etc.

2. Minor Sources

   a. Digital circuits, tuning fork oscillators and other circuits with typical a.c. currents of a few hundred μamps.

   b. Detection of amplitude modulation from high frequency transmitters.

VI. DISCUSSION AND RECOMMENDATIONS

A. Electric Field Interference

1. Electric Field Interference from Solar Panels

It has been shown that a.c. potential fluctuations on the spacecraft solar panels are a very serious source of electric field interference in the frequency range from 20 Hz to 200 kHz. For a.c. voltages of approximately 1.0 volt on the solar panels the electric field interference levels are typically from 40 to 60 db above the VLF receiver noise levels.

Since the coupling of the solar cell potential fluctuations to the electric antennas is not very well understood it is difficult to be very precise about the maximum a.c. potential fluctuations which can be tolerated on the solar panels. Being conservative we would estimate that the a.c. voltage on the solar panels should not exceed approximately 100 μvolts r.m.s. (80 db down from 1.0 volt) over the frequency range covered by the radio noise experiment. If the a.c. potential on the solar panels cannot be maintained below this level by filtering then the following possibilities remain.

a. Operate the power supplies and other systems that produce interference signals on the solar panels at frequencies outside the range of frequencies covered by the radio noise experiment.

b. Cover the solar panels with a grounded wire screen to provide an electrostatic shield around the entire spacecraft, including the solar cells.

2. Electric Field Interference from Detectors Which Use A.C. Voltages on Collection Grids etc.

It has been demonstrated by the OV3-3 experiment that detectors which have large (several hundred volts) a.c. signals applied to grids and collectors external to the spacecraft can produce strong electric field interference. Depending on the detector involved it may be possible to apply some of the following suggestions.

a. Cover the detector probe with one or more grounded wire screens to provide electrostatic shielding.

b. Operate the a.c. frequency of the probe outside of the frequency range of the radio noise experiment.

c. Time share the sampling of the radio noise experiment to coincide with an off time for the a.c. detector probe.

B. Magnetic Field Interference

It has been shown that the a.c. magnetic field from d.c. to d.c. converters, tape recorder motors, magnetometers, currents in solar panels, etc. generally produce very strong magnetic interference when compared to the sensitivity of typical loop antenna receiving systems. Magnetic interference is particularly bad because it is so difficult to shield. The only practical method of reducing the magnetic field strength of an interference source appears to be distance. Figures 4 and 5, however, illustrate that for the proposed IMP-I E.M. fields experiment the loop antenna would have to be located on a boom 30 ft. from the spacecraft (assuming the interference level is comparable to Injun IV and IMP-I). Since a boom 30 ft. long is undesirable from several standpoints (weight, reliability, cabling problems, etc.) it is necessary to seek some other solution.

It appears that the only possible solution is to confine the interference frequency to certain discrete frequencies and to avoid making radio noise measurements near these frequencies. Since most d.c. to d.c. converters generate interference at all harmonics of the fundamental the interference spectrum will in general consist of the fundamental and all harmonics.* To insure that the interference spectrum of all sources is identical it is necessary that all sources be synchronized to very stable master oscillator in the spacecraft.

On the basis of interference considerations alone there are several reasons to make the fundamental frequency as high as possible. (i) Since all frequencies below the fundamental are completely interference free it is obvious that we would want the fundamental frequency as high as possible. (ii) Most radio noise measurements on satellite are at frequencies below ~ 4 MHz because higher frequencies can be observed from the ground. Obviously the number of harmonics which have to be contended with in the frequency range 0 - 4 MHz decreases inversely with the fundamental frequency. For example, a d.c. to d.c. converter operating at 2 kHz

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*The fact that the intensity of the higher harmonics decrease with increasing frequency is not of much help because the sensitivity of the loop antenna increases linearly with frequency.

would produce 2000 harmonic interference frequencies in the range 0 - 4 MHz, whereas a d.c. to d.c. converter operating at 200 kHz would produce only 20 harmonics in this range. (iii) At frequencies on the order of 100 kHz the attenuation that can be provided by the conducting shell of the spacecraft increases rapidly (see Figure 3). For example, the attenuation of a 2 kHz field by 0.2 cm of aluminum is 10 db, whereas at 200 kHz the attenuation is 80 db. Similarly, the attenuation that can be provided by thin ferromagnetic foils and sheets is much better at higher frequencies.

Since it is evident that the interference frequencies of a source should be as high as possible it now becomes a question of technical feasibility. We shall consider several of the more common interference sources.

1. D.C. to D.C. Converters

Present practice is to operate d.c. to d.c. converters at frequencies on the order of 2 kHz. Unfortunately, this frequency range, below about 10 kHz, is of considerable interest for VLF radio noise investigations. It would be more convenient for VLF experimenters if power supplies were operated at about 20 kHz, as was done on Injun III. This higher frequency can be used with present techniques at the cost of only a few per cent in efficiency.

It is, however, possible to operate d.c. to d.c. converters at much higher frequencies with excellent efficiency (~ 100 kHz) using ferrite core transformers. A 100 kHz d.c. to d.c. converter of a practical design has been operated at the University of Iowa with an efficiency of 65%.

2. Magnetometers

Magnetometers operating at 22 kHz have been constructed and flown. No additional power or weight were required for operating at this frequency.

3. Tape Recorders

Tape recorders require motors which are usually operated at frequencies in the range from 100 Hz to 400 Hz. There appears to be no practical way to avoid this interference. In some instances it may be possible to use an electronic memory in place of the tape recorder.

If a tape recorder must be used then it would be desirable to operate at as high a frequency as possible and to try to keep the harmonic content of the drive currents as small as possible by careful filtering.

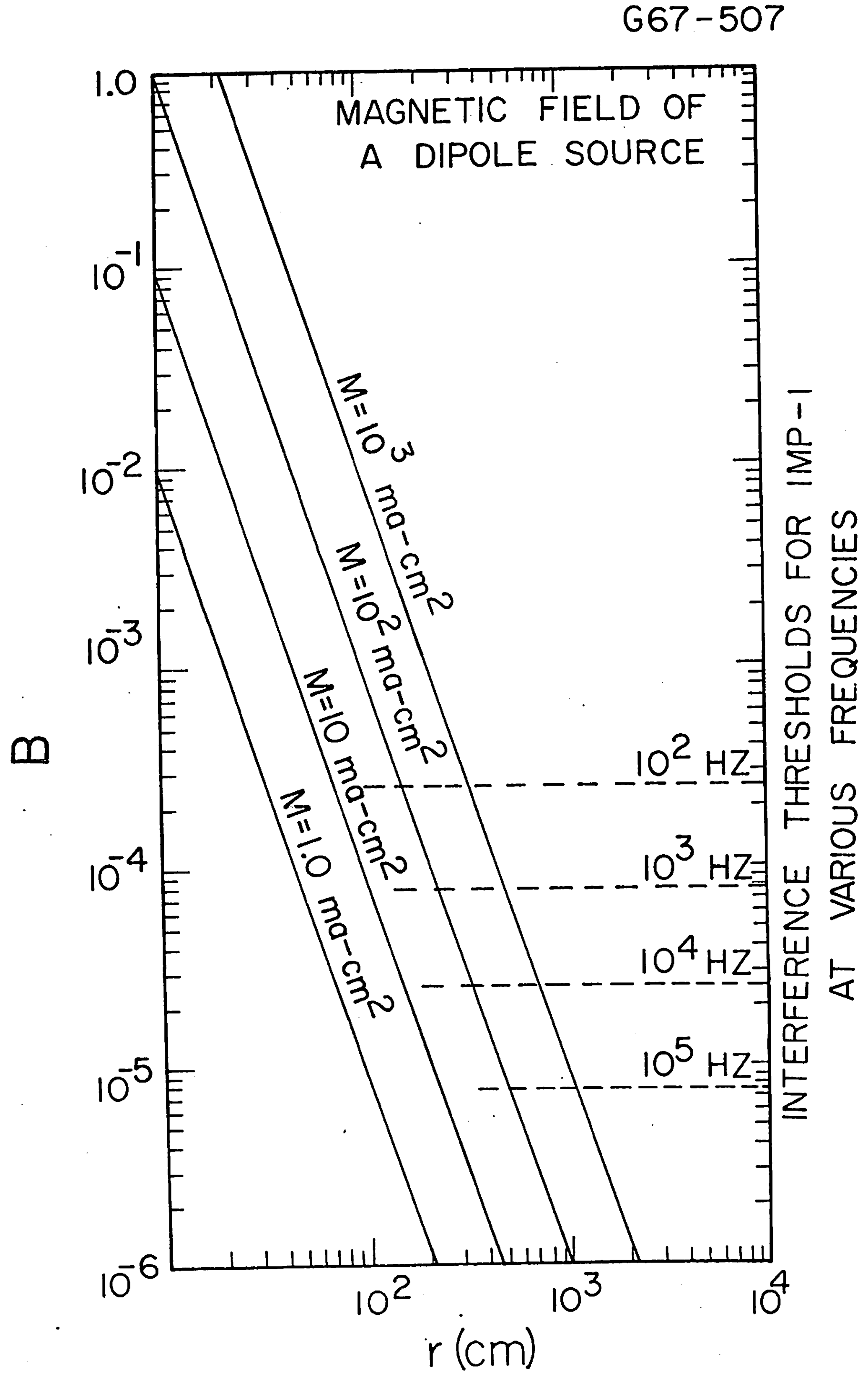
G67-507
MAGNETIC FIELD OF A DIPOLE SOURCE
B
1.0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{2}
10^{3}
10^{4}
r (cm)
$M=10^3$ ma-cm^2
$M=10^2$ ma-cm^2
M=10 ma-cm^2
M=1.0 ma-cm^2
10^2 HZ
10^3 HZ
10^4 HZ
10^5 HZ
INTERFERENCE THRESHOLDS FOR IMP-I AT VARIOUS FREQUENCIES

Figure 1

G 67-508

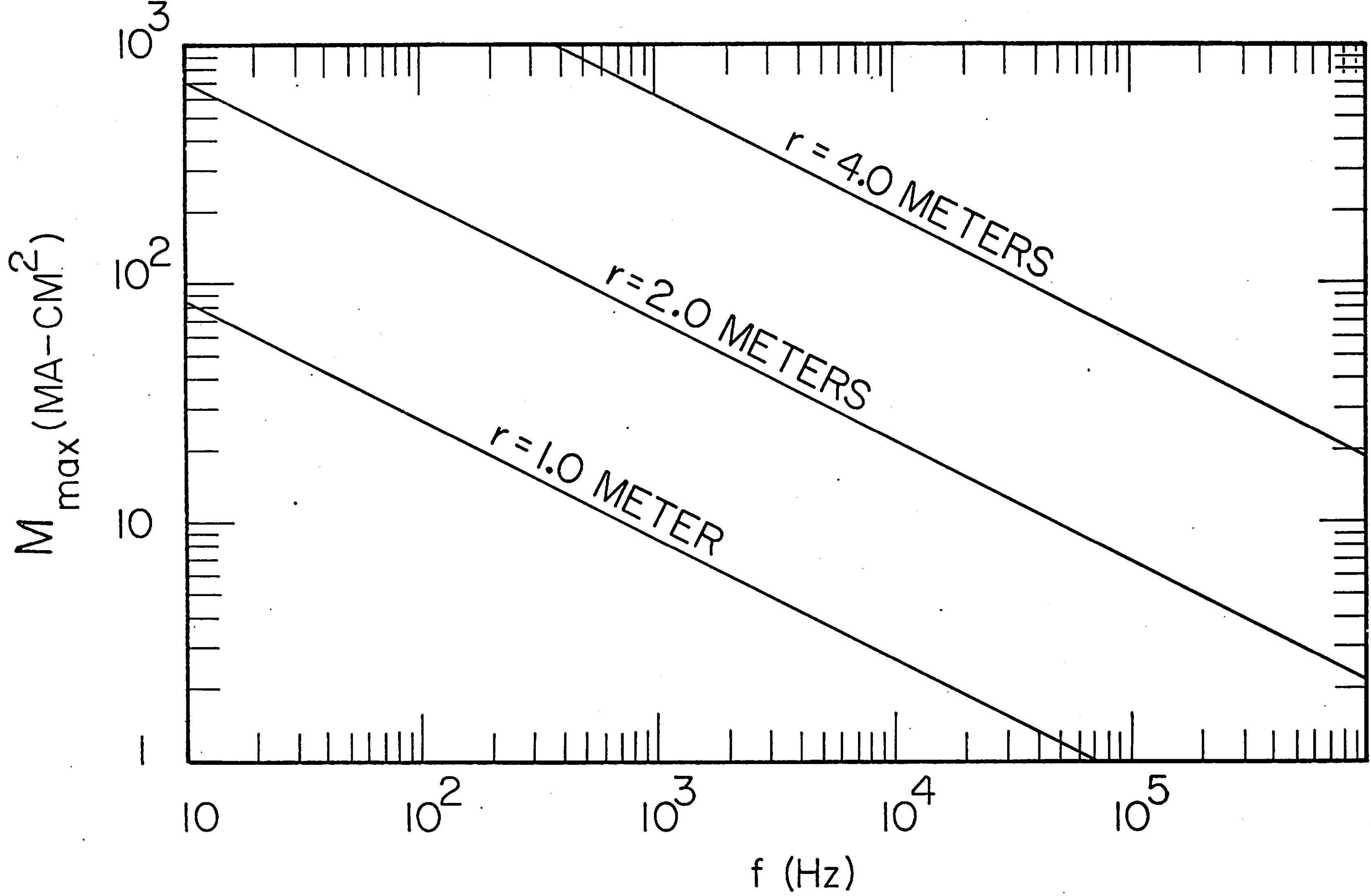

Figure 2

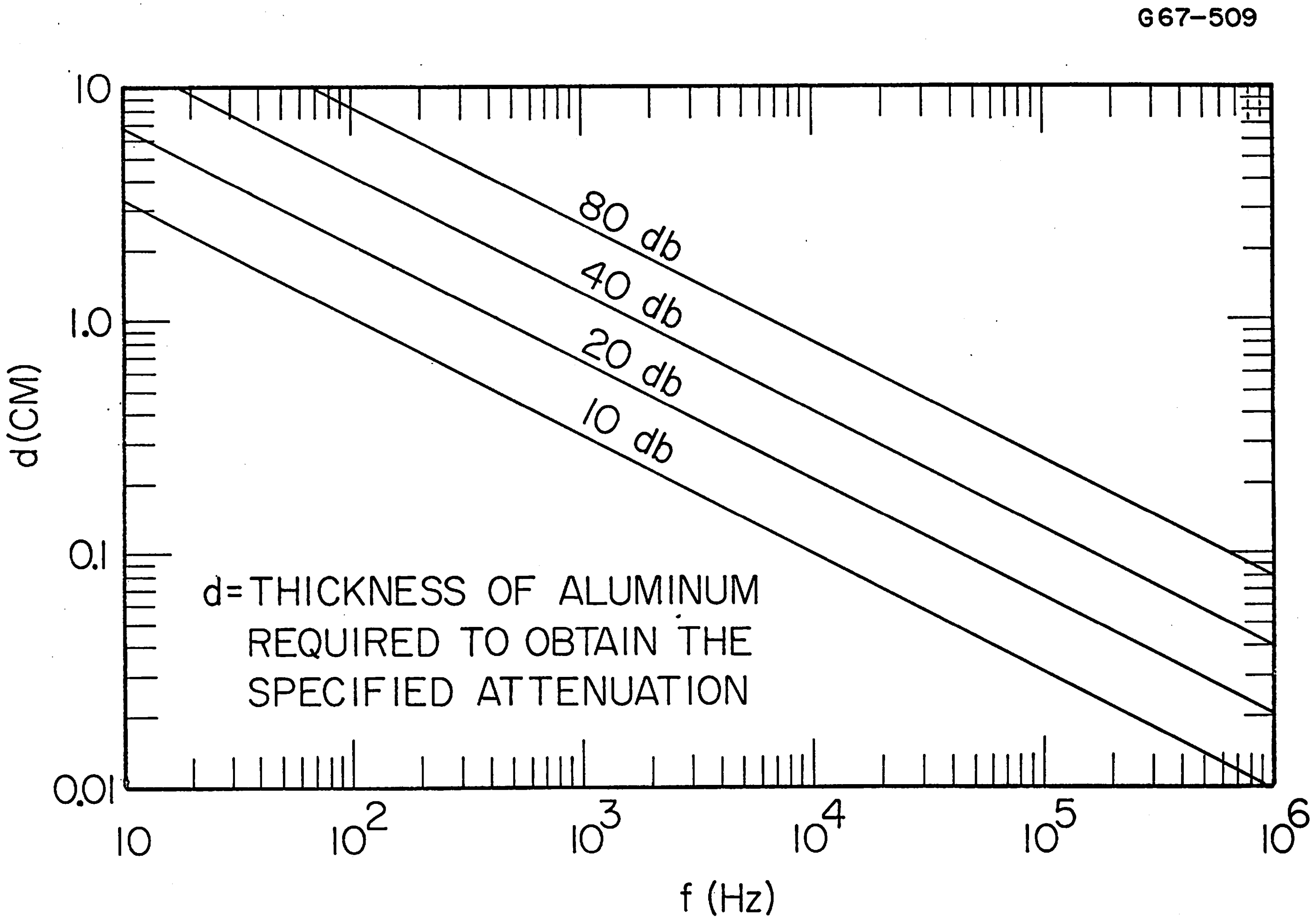
G67-509
80 db
40 db
20 db
10 db
d=THICKNESS OF ALUMINUM
REQUIRED TO OBTAIN THE
SPECIFIED ATTENUATION
d(CM)
10
1.0
0.1
0.01
10
10^2
10^3
10^4
10^5
10^6
f (Hz)

Figure 3

G67-510

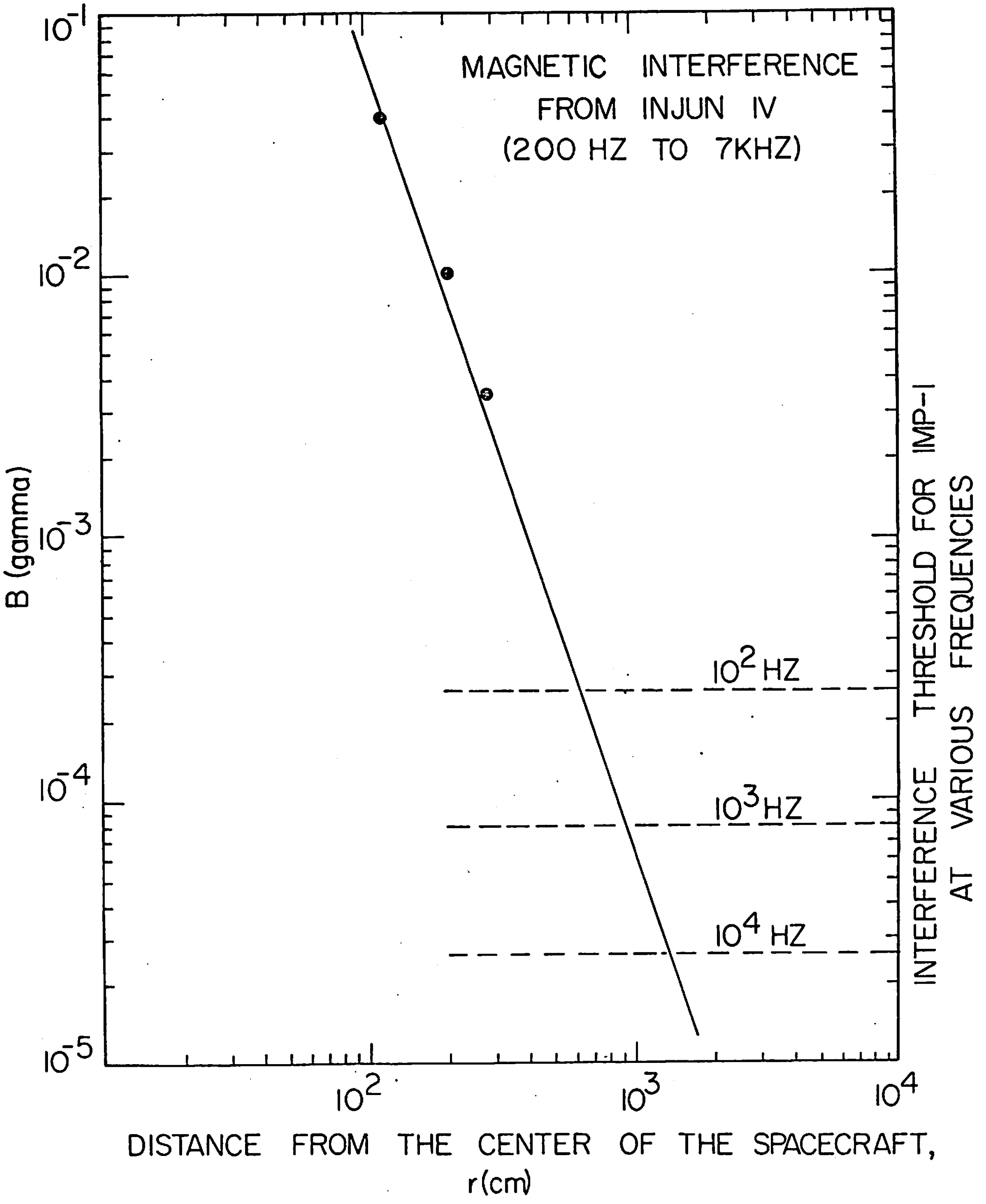

Figure 4

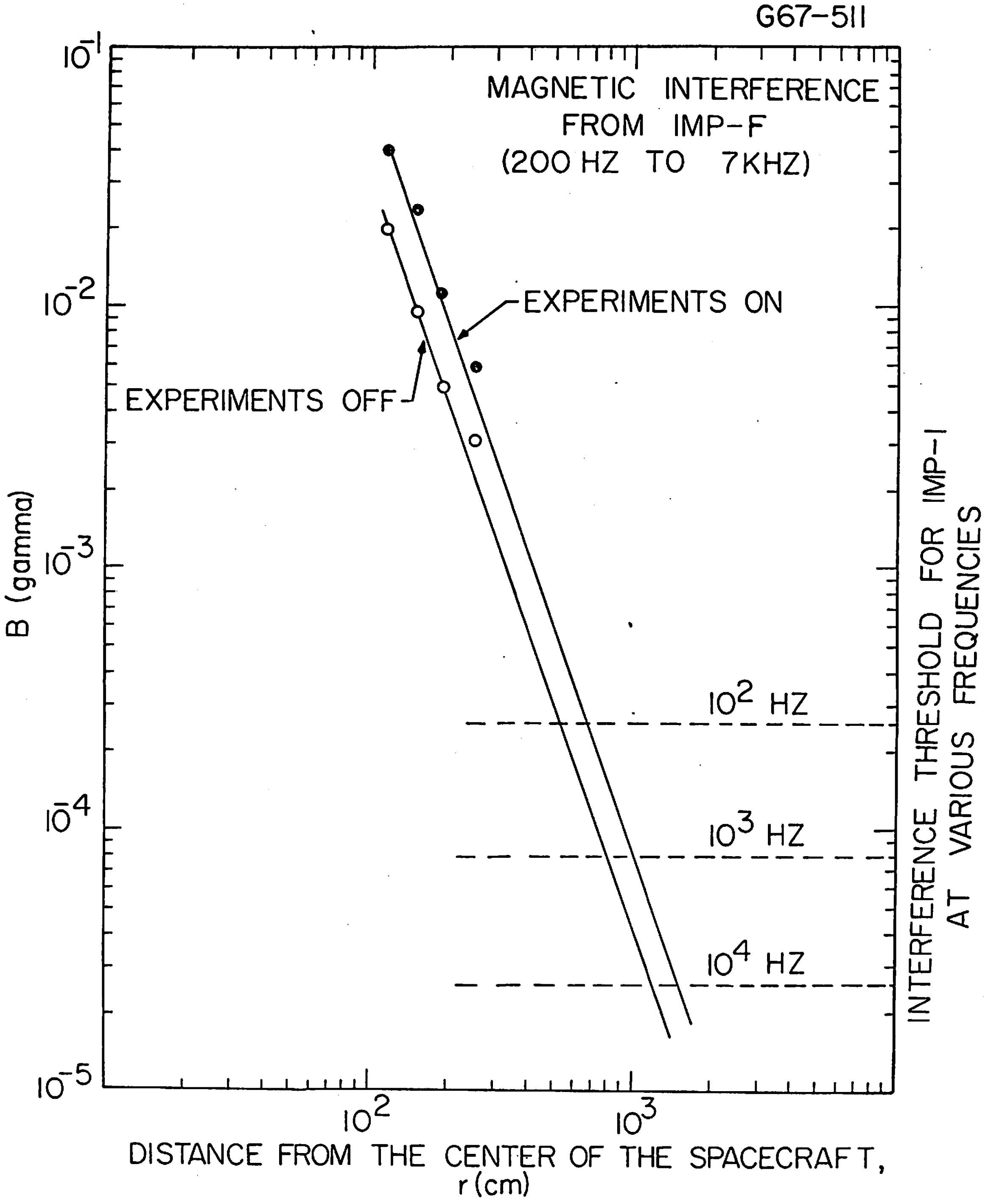
G67-511
MAGNETIC INTERFERENCE FROM IMP-F (200 HZ TO 7KHZ)
EXPERIMENTS ON
EXPERIMENTS OFF
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
B (gamma)
10^2 HZ
10^3 HZ
10^4 HZ
INTERFERENCE THRESHOLD FOR IMP-I AT VARIOUS FREQUENCIES
10^2
10^3
DISTANCE FROM THE CENTER OF THE SPACECRAFT, r(cm)

Figure 5