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JPL PUBLICATION 82-27

(NASA-CR-168985) FEASIBILITY OF SIMULTANEOUS OPERATION OF PASSIVE REMOTE MICROWAVE SENSORS AND ACTIVE SERVICES OCCUPYING ADJACENT FREQUENCY BANDS (Jet Propulsion Lab.) 65 p HC A04/MF A01 N82-25421
Unclas
G3/32 27974

Feasibility of Simultaneous Operation of Passive Remote Microwave Sensors and Active Services Occupying Adjacent Frequency Bands

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Acknowledgment

This author would like to thank N. F. de Groot of JPL for editing this report and for the many suggestions that he has offered during the course of this study. In addition, this author would like to thank John Kiebler of NASA for reviewing this report, Taylor Hines of Systematic General, Julius Harper of EACA, and Fred S. Soltis, Pete Olsen, M. T. Chahine, and J. M. Stacey, all of JPL, for the information they provided.

Abstract

Passive microwave remote sensing often is performed in or near frequency bands occupied by other active services. The combination of wide bandwidth and high sensitivity required for the sensors makes them very susceptible to interference. To ensure proper sensor operations, it is necessary to understand the situation of potential interference to sensors due to active equipment sharing common frequency bands as well as equipment occupying adjacent bands. The feasibility of sharing common frequency bands between passive sensors and other active services has been analyzed in CCIR (International Radio Consultative Committee) Report 694. Complementary to Report 694, this report examines and identifies potential interference to sensors due to equipment in bands adjacent to sensor frequency bands, and develops criteria to avoid interference.

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1. Introduction

Passive microwave sensing has been playing an increasingly important role in areas such as earth resource exploration and earth environment study. Many frequency bands have been allocated for passive microwave sensing. Some of these bands are adjacent to bands allocated for services capable of interfering with the proper operation of the sensors. In order to protect the sensors and to insure compatibility between the sensors and the active services, it is necessary to determine the potential interference that may exist due to equipment in bands adjacent to the sensor frequency bands. The feasibility of sharing common frequency bands and the criteria for sharing have been examined in CCIR Report 694 [1]. The purpose of this report is to examine the potential interference between passive microwave sensors and active services occupying adjacent frequency bands and to develop necessary criteria for simultaneous operation. In this report, simultaneous operation of two services in adjacent bands is referred to as simultaneous adjacent band operation.

Technical characteristics of systems examined in various services are mostly derived from Report 694.

2. Approaches and System Models

The approach used here is similar to that in Report 694. For a given interference situation, the interference level as seen by the radiometer (passive microwave sensor) is first calculated and then compared to a predetermined value called the sensor interference threshold. When the received interference level exceeds the sensor interference threshold, interference exists and thus simultaneous operation may not be feasible. The sensor interference threshold is defined in Report 694 and is taken as 20% of the sensor threshold, which is related to the sensor sensitivity. The interference threshold and the required bandwidth as a function of frequency are shown in Table 1. The received interference level due to a direct coupling of the interfering signal can be calculated as follows:

$$P_R = P_T \, G_T(\theta) \, G_R(\phi) \, \beta/(4\pi R^2)$$

where

P_R = received interference power,

P_T = transmitter output power,

$G_T(\theta)$ = transmitting antenna gain in the direction of θ degrees from the main axis,

$G_R(\phi)$ = receiving antenna effective area in the direction ϕ degrees from the main axis,

β = out-of-band rejection factor due to difference in both frequency and bandwidth between the receiver and the transmitter, and

R = distance between the receiver and the transmitter.

It has been assumed in the above expression that the radiometer is located in a direction θ degrees from the main axis of the transmitting antenna and that the transmitter is ϕ degrees off the main axis of the radiometer antenna.

It is necessary to include in the above expression an out-of-band rejection factor in order to account for the mismatch in both the frequency and the bandwidth between the radiometer and the transmitter. The out-of-band rejection factor is a function of the receiver transfer function, the spectrum of the interfering signal, and the frequency separation between the receiver and the transmitter. Specifically, if $A(\omega)$ and $B(\omega)$ denote respectively the amplitude response of the receiver and the power spectrum of the interfering signal, the out-of-band rejection factor is then given by the following equation:

$$\beta = \frac{\int_{-\infty}^{\infty} A^2(\omega)\ B(\omega)\ d\omega}{\int_{-\infty}^{\infty} B(\omega)\ d\omega}$$

It is noted that the amplitude response of the receiver, $A(\omega)$, is assumed to have a maximum gain of unity in the passband.

To evaluate the out-of-band rejection factor, it is necessary to know the exact shape of the receiver amplitude response and the spectrum of the interfering signal. Both of these vary from equipment to equipment. For adjacent band study, it is sufficient to model the receiver as a four-pole bandpass filter with a 3-dB bandwidth B_R and to model the spectrum of the interfering signal as a bandpassed signal with 3-dB bandwidth B_I and an asymptotic roll-off rate of 60 dB/decade outside the 3-dB bandwidth. The low-pass equivalents of the receiver and transmitter models are shown in Figure 1. The maximum attenuation of the receiver model is limited to 70 dB outside the passband.

The out-of-band rejection factor in terms of the normalized bandwidth B_N and the normalized frequency separation ΔF_N has been derived in Annex 1 and is given by the following expression.

$$\beta = \int_{-\infty}^{\infty} (x^{2N_R}+1)^{-1} \left[\left(\frac{x-(1+B_N)\Delta F_N}{B_N}\right)^{2N_I}+1\right]^{-1} dx \Bigg/ \int_{-\infty}^{\infty} \left[\left(\frac{x}{B_N}\right)^{2N_I}+1\right]^{-1} dx$$

The normalized bandwidth is defined as

$$B_N = B_I/B_R$$

and the normalized frequency separation is

$$\Delta F_N = 2\Delta F/(B_R + B_I).$$

The out-of-band rejection factor has been plotted in Figures 2 through 9 as a function of the normalized frequency separation for different combinations of N_R and N_I. The out-of-band rejection factor represents the attentuation of the interference power due to mismatch in frequency and bandwidth between transmitter and receiver. For the receiver and transmitter model considered in this report, the value of N_R is 4 and the value of N_I is 3. The out-of-band rejection corresponding to this model is shown in Figure 2.

The roll-off rate of actual radiometer filters usually is much more than 80 dB/decade in the region immediately outside the 3-dB bandwidth; but as the frequency increases, i.e., farther away from the 3-dB corner frequencies, the roll-off rate gradually reduces to the asymptotic roll-off rate of a four- or five-pole filter. The use of 80-dB/decade roll-off rate represents a very conservative approach.

3. Analysis

The frequency separation between two services in adjacent bands plays a very important role in determining the feasibility of simultaneous operation of these services. The frequency separation between two services is defined as the separation between their center frequencies. Generally, this quantity can vary over a wide range. In the analysis that follows, the minimum value has been used to determine the potential interference. This represents a worst-case condition.

The minimum frequency separation between two services occurs when their 3-dB bandwidths are next to each other. This is the smallest possible separation between services in adjacent bands. Specifically, if ΔF_{MIN} is the minimum frequency separation, then

$$\Delta F_{MIN} = 0.5 (B_R + B_I)$$

and the corresponding normalized frequency separation is unity. Figure 10 depicts the situation when ΔF equals ΔF_{MIN}.

If it is feasible to operate two services in adjacent bands simultaneously at the mininum frequency separation, it is then feasible for all values of frequency separation.

When it is not feasible for the simultaneous operation at the minimum frequency separation, criteria are then developed whenever possible to allow such an operation. These criteria generally are stated in terms of the required frequency separation, the guard band and sometimes the transmitter e.i.r.p. limits. The guard band is defined as the spacing between the 3-dB point of the frequency response of the sensor and the edge of the occupied bandwidth of the active service. The occupied bandwidths of the interference is the bandwidth that contains 99 percent of the total interference power. The relationship between guard band and the frequency separation has been derived in Annex 2 and is given by:

$$\text{Guard band} = \Delta F - 0.5\ B_R - 0.8\ B_I \quad \text{for } N_I = 3.$$

Using the models developed in Section 2 and the out-of-band rejection factor given in Figure 2, the potential interference between passive microwave sensors and the following services occupying adjacent bands has been examined in Annex 3 to Annex 8:

- o Fixed and Mobile Services
- o Fixed-Satellite Service
- o Mobile-Satellite Service
- o Inter-Satellite Service
- o Radiolocation and Aeronautical Radionavigation Services
- o Broadcasting Satellite Service

The results are summarized in the following paragraphs.

4. Feasibility and Criteria for Simultaneous Adjacent Band Operations

The feasibility of simultaneous adjacent band operations of the passive microwave sensors and the Fixed and Mobile Services has been examined in Annex 3 for systems operating near 1.4 GHz, 15 GHz, and 21 GHz. Such an operation is generally not feasible near 1.4 GHz at the minimum frequency separation. For typical systems in the Fixed and Mobile Services having an e.i.r.p. in the range of 37 to 55 dBW, simultaneous operation is feasible only if the frequency separation is increased according to Table 2. For systems operating near 15 GHz, potential interference can be avoided if a guard band of 126 MHz or more is used. For systems in the 21-GHz region, no potential interference is expected.

The feasibility of simultaneously operating the passive microwave sensors and equipment in the Fixed Satellite Service has been examined. The frequency bands studied are near 5 GHz, 11 GHz, 18 GHz, and 37 GHz for the space-to-earth links and near 6 GHz, 15 GHz, and 37 GHz for the earth-to-space links. It is generally feasible to simultaneously operate the passive microwave sensors and the space-to-earth links in the Fixed-Satellite Service without restrictions on the frequency separation or guard bands for all bands examined, except for the 18-GHz band where a guard band on the order of 35 MHz or more is necessary. For the earth-to-space links, it is not feasible near 6 GHz due to the large frequency separation required to avoid interference. Near 15 GHz, it is feasible provided that the criteria in Table 3 are met. Near 37 GHz, simultaneous operations are possible if a guard band of 575 MHz or more is used.

Potential interference to the proper operation of passive microwave sensors due to equipment in the Mobile-Satellite Service has been examined in Annex 5 for systems near 1.4 GHz, 20 GHz, and 37 GHz. Simultaneous adjacent band operation with the space-to-earth links is possible near 1.4 GHz for guard bands equal to or larger than 19 MHz. This operation is also possible near 20 GHz and 37 GHz provided that the criteria as indicated in Tables 4 and 5 are met. Simultaneous operation with the earth-to-space link is feasible if the guard band is at least 96 MHz, 390 MHz, and 750 MHz for systems near 1.4 GHz, 20 GHz, and 37 GHz respectively.

It is generally feasible to operate the passive microwave sensors simultaneously with the Inter-Satellite Service in the 50- to 70-GHz range. The same is true for the Radiolocation and the Aeronautical Radionavigation Services near 4 GHz and 15 GHz. For systems near 1.4 GHz, severe interference prevents such operations.

The feasibility of operating a broadcasting satellite and a radiometer simultaneously in adjacent bands has been examined in Annex 8 in the 12-GHz region. The interference level at the radiometer due to mainlobe coupling of the backscattered signal from a broadcasting satellite is only one decibel below the sensor threshold. A frequency separation of slightly more than the minimum separation would ensure the proper operation of the sensor.

5. Conclusion

The potential interference between passive microwave sensors and equipment in various services operating in adjacent bands has been examined using the transmitter and receiver models developed in Section 2. These models assume an out-of-band asymptotic roll-off rate of 60 dB and 80 dB per decade for the transmitter and the receiver respectively. These characteristics represent a very conservative, worst-case condition.

The feasibility of simultaneous adjacent band operation between radiometers and active services varies from one active service to another and from one frequency band to another. Based on the active services and frequency bands examined, three conclusions can be drawn regarding the feaibility of simultaneous operation:

(1) Feasible without restriction on frequency separation. Services that fall in this group include the Fixed and Mobile Services at 21 GHz, the space-to-earth link in the Fixed-Satellite Service at 5 GHz, 11 GHz, and 37 GHz, the Inter-Satellite Service, and the Radiolocation and Aeronautical Radionavigation Services at 4 GHz and 15 GHz.

(2) Conditionally feasible with the proper choice of frequency separation.

The proper choice of frequency separation makes simultaneous adjacent band operation feasible for some active services that would otherwise not be possible. These services include the Fixed and Mobile Service at 1.4 GHz and 15 GHz, the space-to-earth link in the Fixed-Satellite Service at 18 GHz, the earth-to-space link in the Fixed-Satellite Service at 15 GHz and 37 GHz, the Mobile-Satellite Service, and the Broadcasting Satellite Service. The required frequency separation is detailed in Tables 2-5.

(3) Not feasible.

Among various active services examined, some cannot be operated simultaneously with passive microwave sensors in adjacent bands due to serious potential interference. These services usually have high e.i.r.p. and the frequency separation necessary to provide sufficient out-of-hand rejection would be too large to be practical for adjacent band services. The earth-to-space link in the Fixed-Satellite Service at 6 GHz and the Radiolocation and Aeronautical Radionavigation Services at 1.4 GHz belong to this group.

The feasibility of simultaneous operation analyzed is based on the characteristics of typical or representative equipment. Results of this report are therefore applicable for systems with similar charactertistics. For systems with different characteristics, the sharing feasibility may be analyzed by following the approach and procedures of this report.

Reference

(1) Recommendations and Reports of the CCIR, 1978, Vol. II, Space Research and Radioastronomy, International Radio Consultative Committee (CCIR), Report 694, pp. 292-313.

TABLE 1. Sensor Interference Thresholds and Sensor Bandwidths

Frequency (GHz)	Interference Threshold (dB(W))	Bandwidth (MHz)
Near 1.4	-165	100
Near 2.7	-166	60
Near 5	-158	200
Near 6	-158	400
Near 11	-156	100
Near 15	-160	200
Near 18	-160	200
Near 21	-160	200
22.237	-155	300
Near 24	-157	400
Near 30	-156	500
Near 37	-146	1000
Near 55	-157	250
Near 90	-138	6000
Above 100	-150	2000

TABLE 2. Criteria for Simultaneous Operations of the Passive Microwave Sensors and the Fixed and Mobile Service Near 1.4 GHz

Earth Station e.i.r.p. (dBW)	Required Frequency Separation (MHz)	Required Guard Band (MHz)
≤ 17	55	--
20	60	2
30	88	30
40	115	57
50	154	96
60	198	140

TABLE 3. Criteria for Simultaneous Operations of the Passive Microwave Sensors and the Earth-to-Space Link of the Fixed Satellite Service Near 15 GHz.

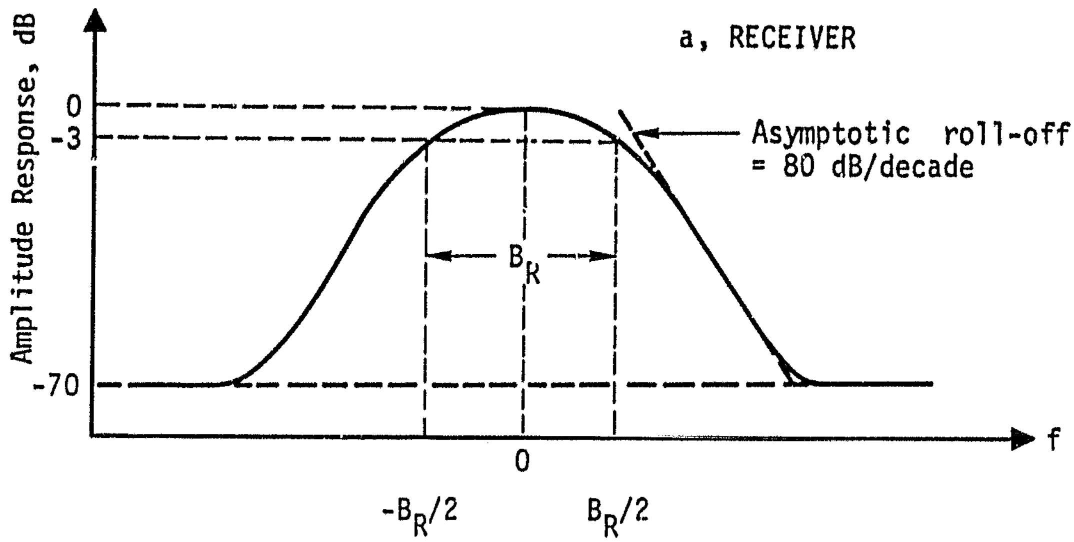
Earth Station e.i.r.p. (dBW)	Required Frequency Separation (MHz)	Required Guard Band (MHz)
40	144	10
50	192	58
60	252	118
70	324	190
80	432	298
90	576	442
100	768	634

TABLE 4. Criteria for Simultaneous Operations of the Passive Microwave Sensors and the Mobile-Satellite Service Near 20 GHz (Space-to-Earth Link)

Pfd at Earth's Surface dBW/($m^2 \cdot$MHz)	Required Frequency Separation (MHz)	Required Guard Band (MHz)
-110	260	0
-100	340	70
-90	460	190
-80	560	290
-70	760	490

TABLE 5. Criteria for Simultaneous Operations of the Passive Microwave Sensors and the Mobile-Satellite Service Near 37 GHz (Space-to-Earth Link)

Pfd at Earth's Surface dBw/(M^2.MHz)	Required Frequency Separation (MHz)	Required Guard Band (MHz)
-100	1300	0
-90	1700	350
-80	2300	950
-70	2800	1450



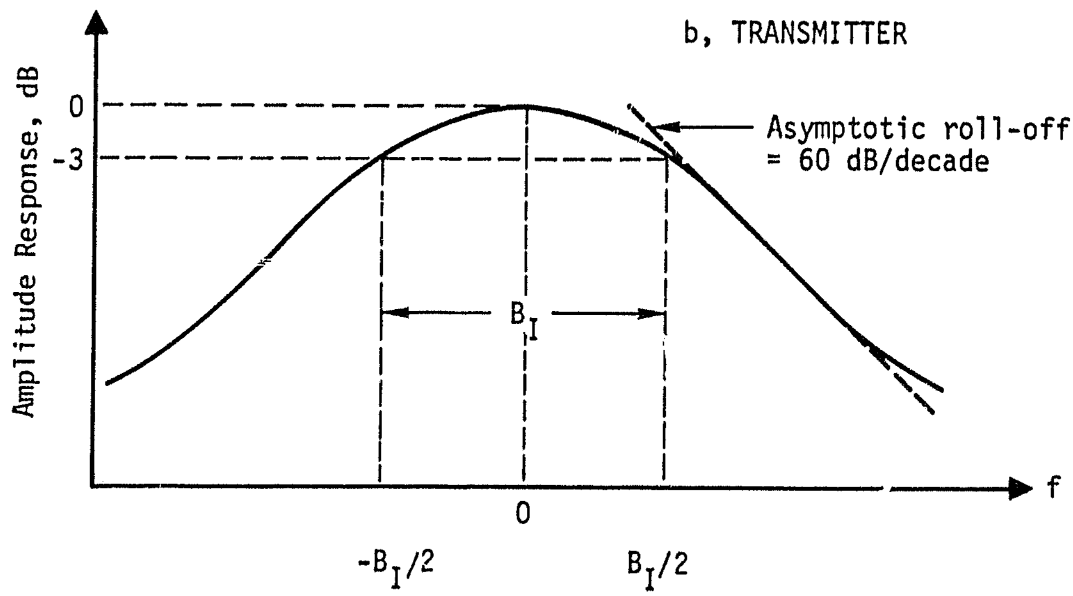


Figure 1 The Low-Pass Equivalents of the Receiver and the Transmitter Amplitude Response

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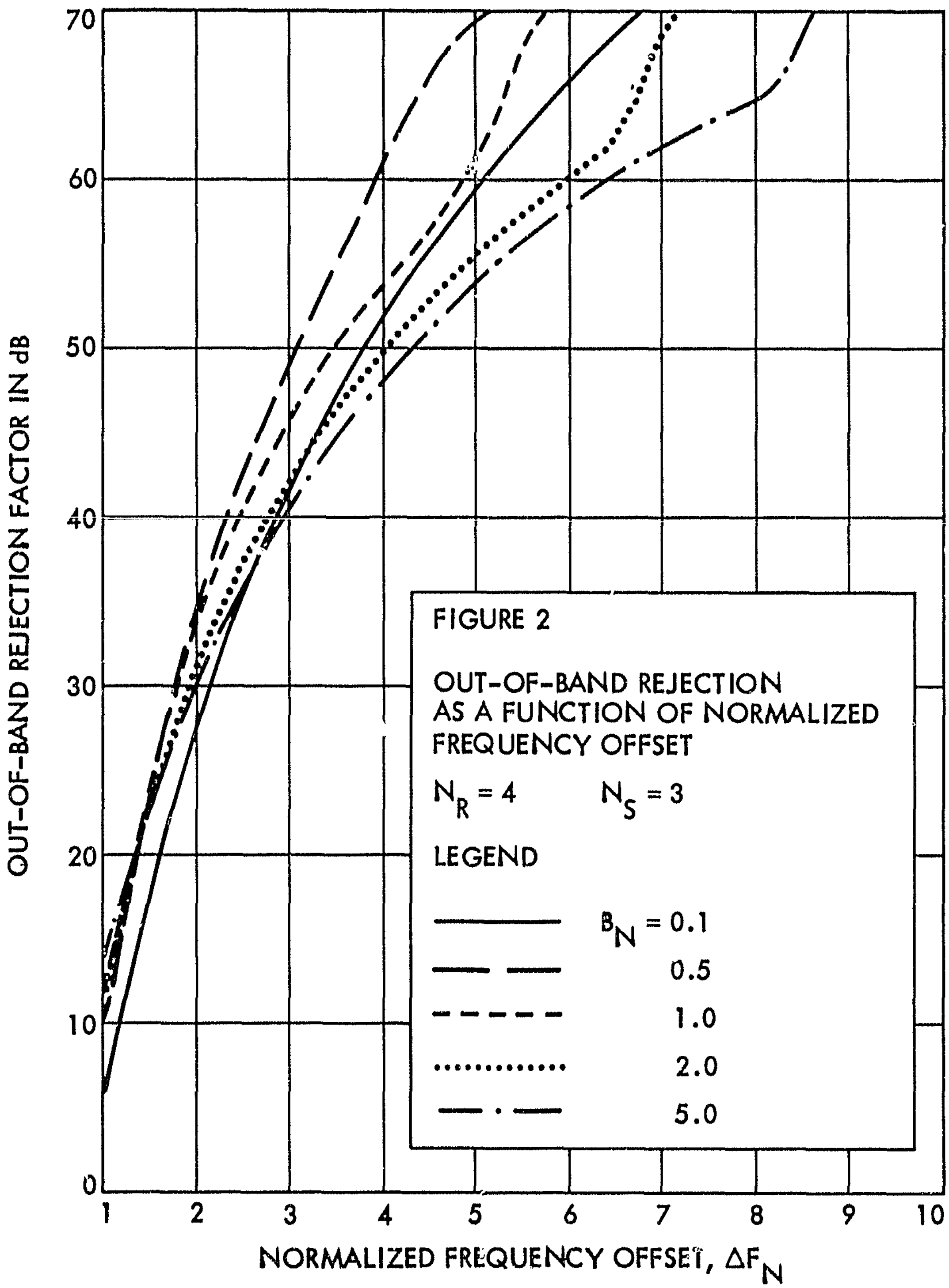

FIGURE 2

OUT-OF-BAND REJECTION AS A FUNCTION OF NORMALIZED FREQUENCY OFFSET

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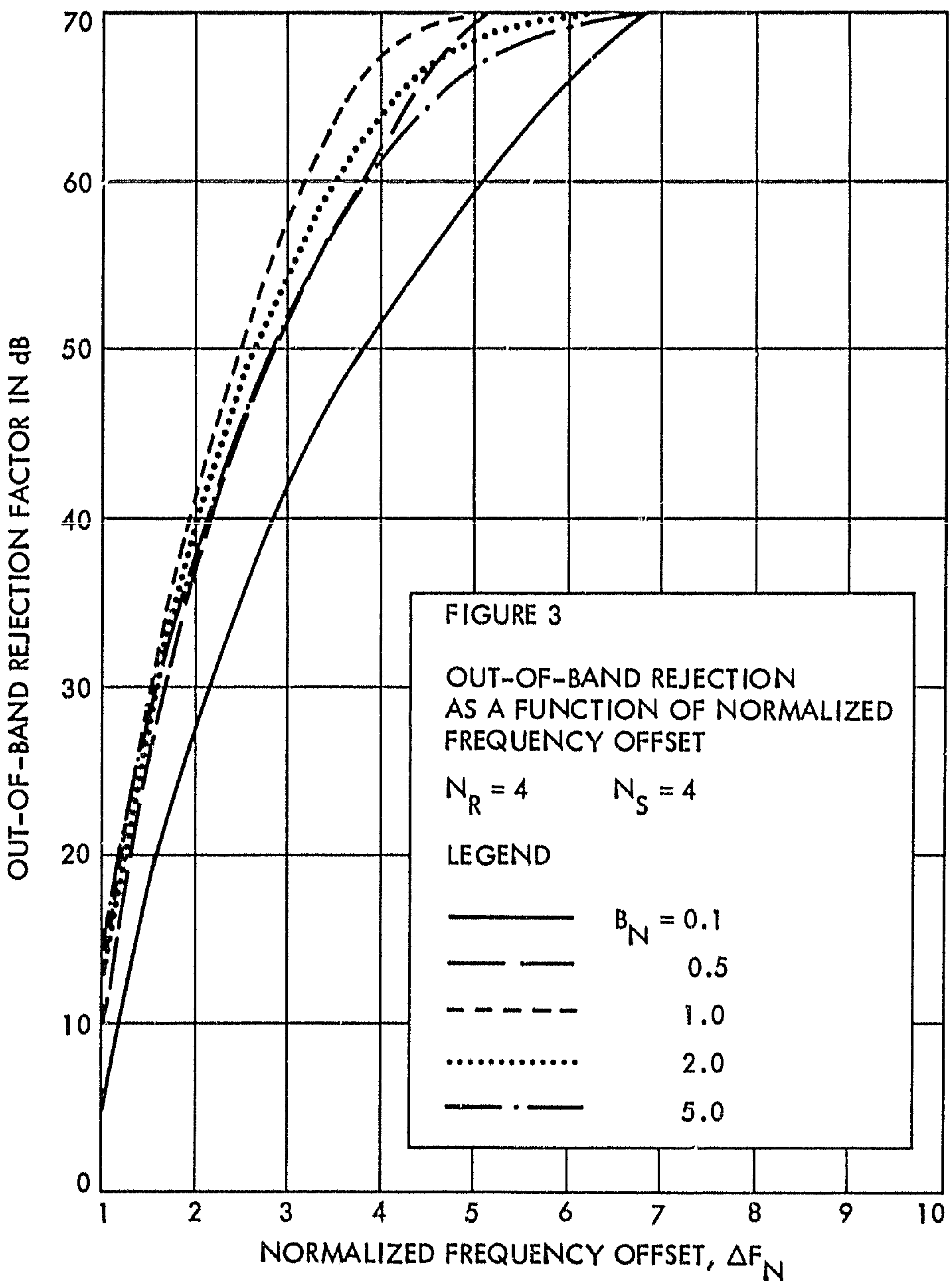

FIGURE 3

OUT-OF-BAND REJECTION AS A FUNCTION OF NORMALIZED FREQUENCY OFFSET

$N_R = 4$ $N_S = 4$

LEGEND

———	$B_N = 0.1$
— —	0.5
- - - -	1.0
········	2.0
—·—	5.0

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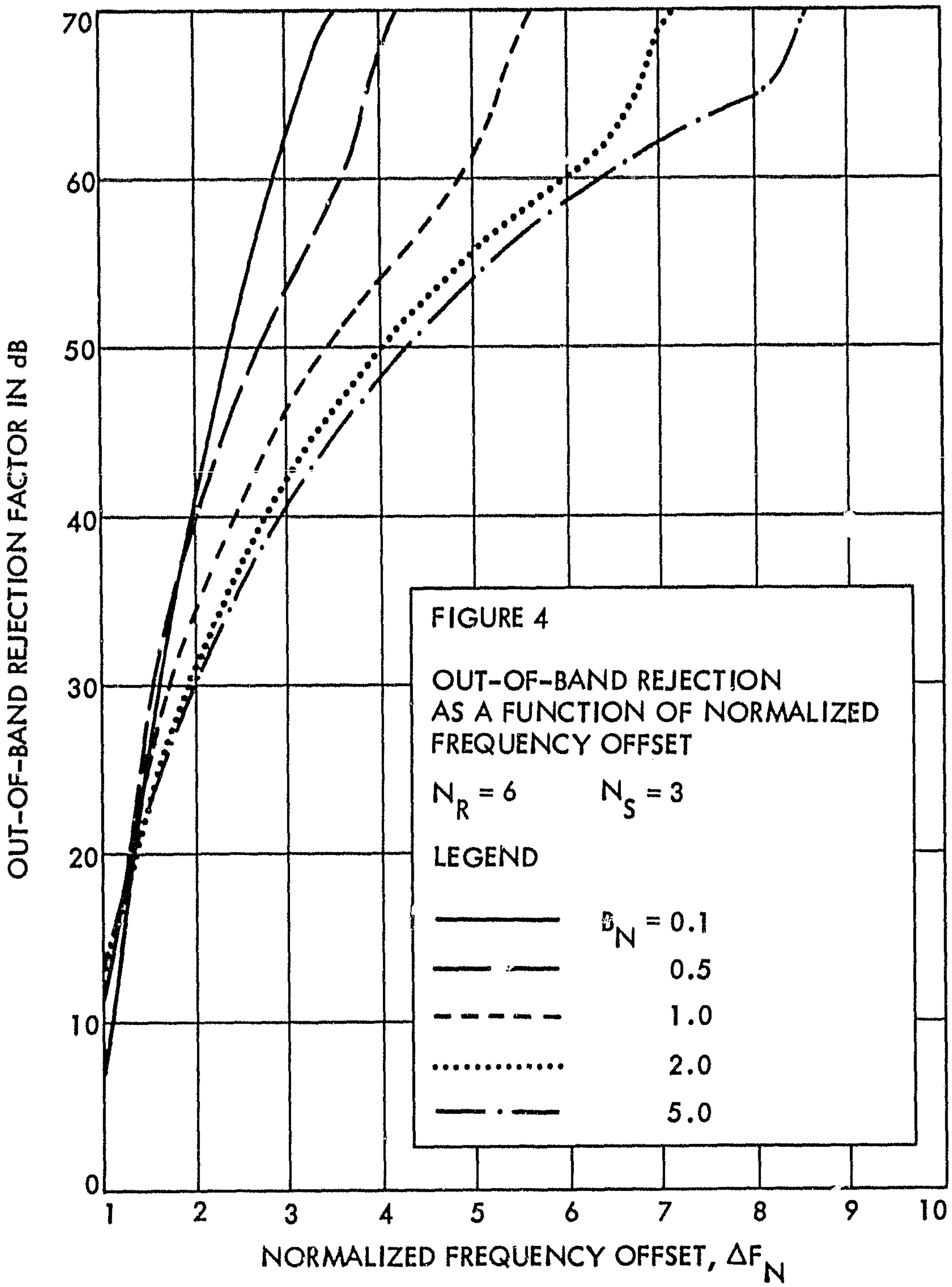

FIGURE 4

OUT-OF-BAND REJECTION AS A FUNCTION OF NORMALIZED FREQUENCY OFFSET

$N_R = 6$ $N_S = 3$

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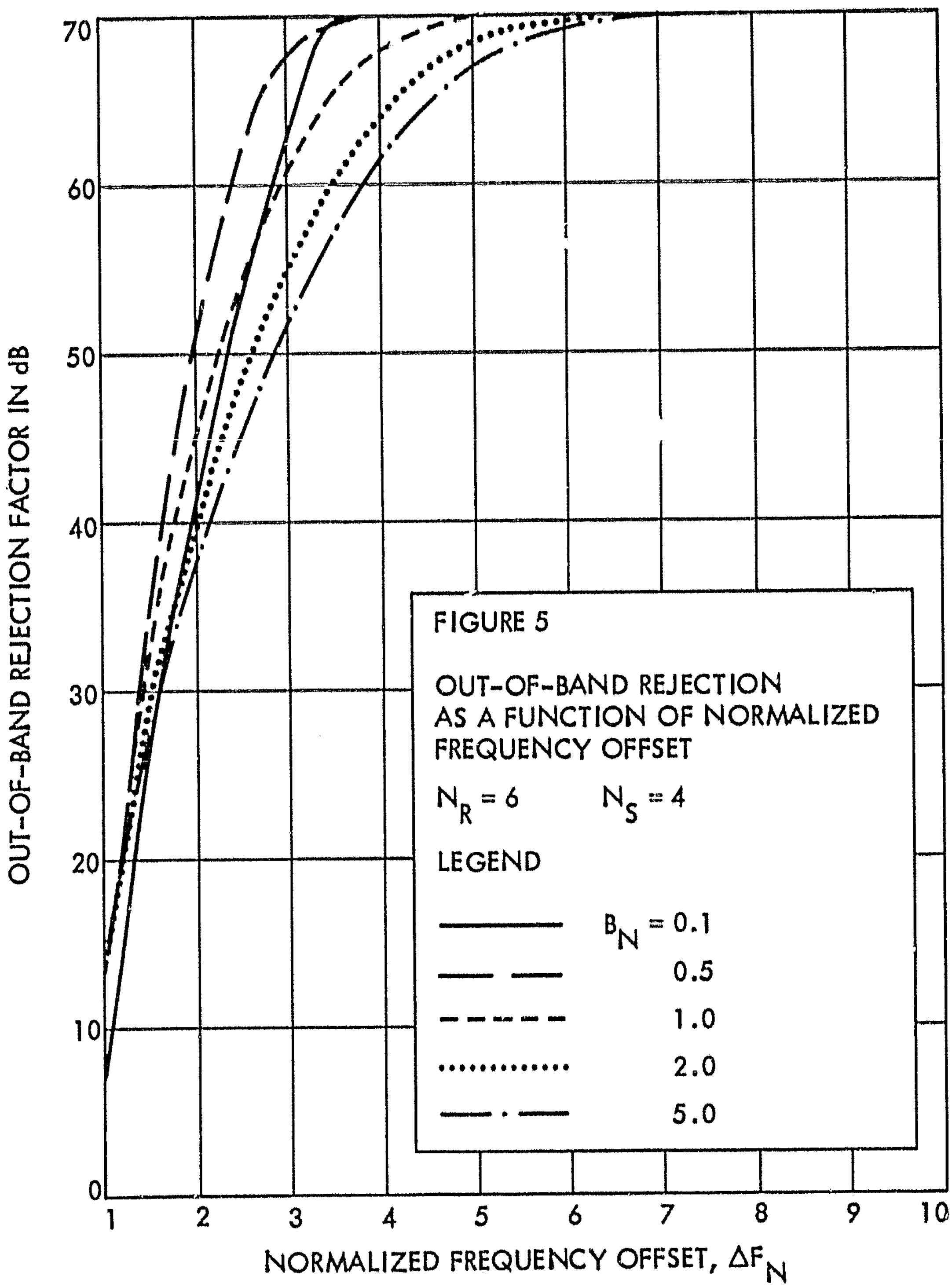

FIGURE 5

OUT-OF-BAND REJECTION AS A FUNCTION OF NORMALIZED FREQUENCY OFFSET

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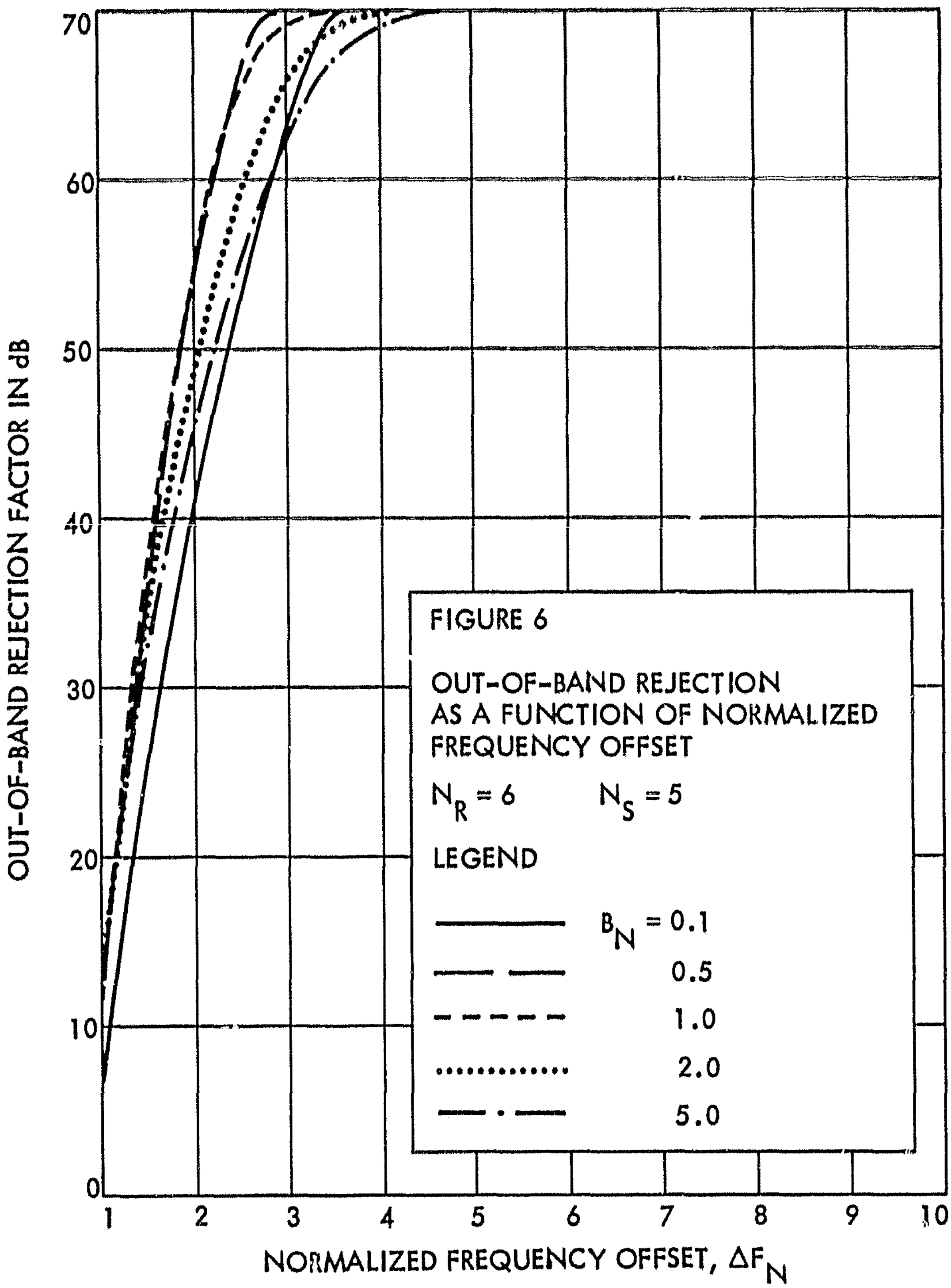

FIGURE 6

OUT-OF-BAND REJECTION AS A FUNCTION OF NORMALIZED FREQUENCY OFFSET

$N_R = 6$ $N_S = 5$

LEGEND

$B_N = 0.1$
0.5
1.0
2.0
5.0

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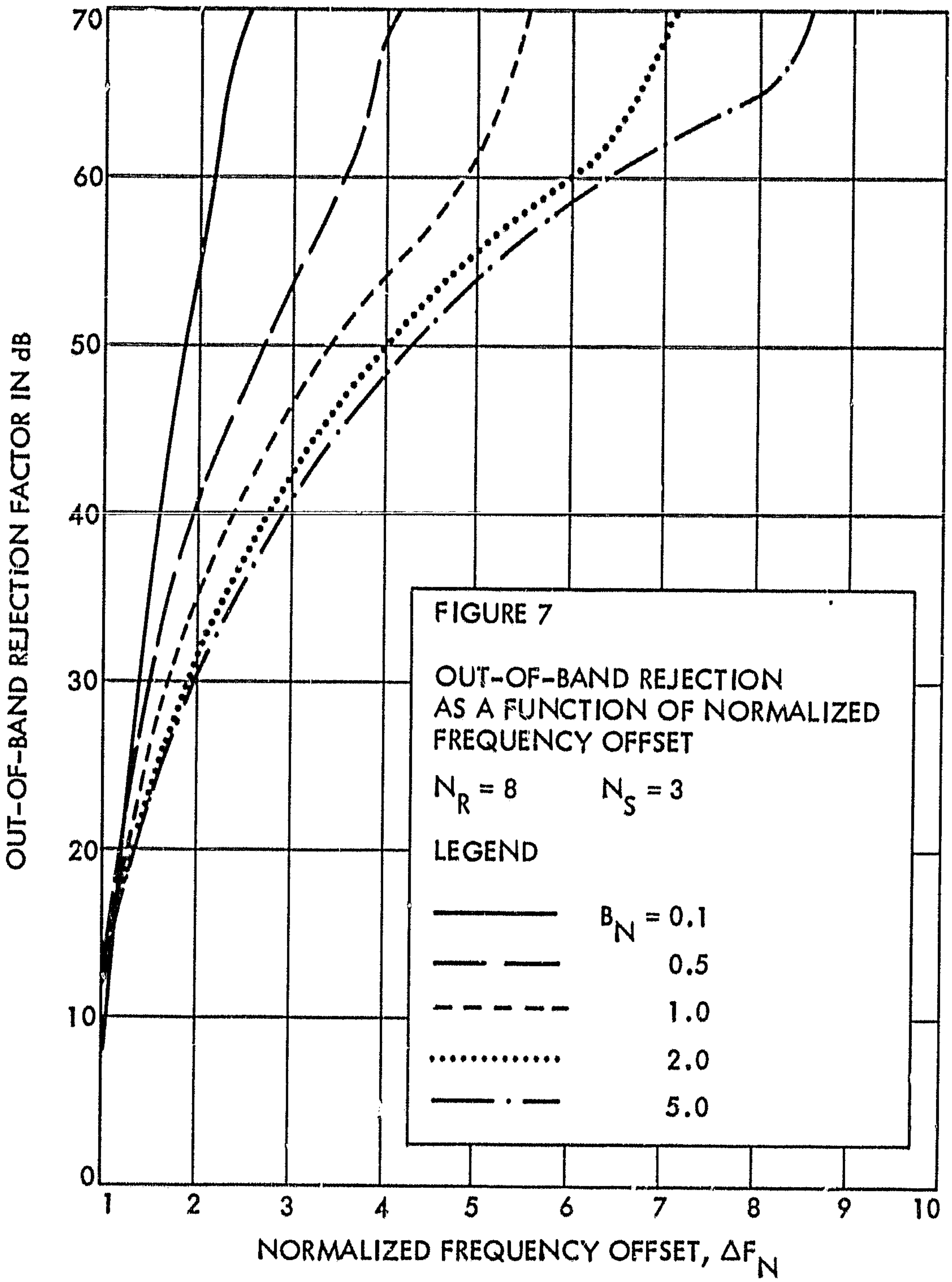

FIGURE 7

OUT-OF-BAND REJECTION AS A FUNCTION OF NORMALIZED FREQUENCY OFFSET

$N_R = 8$ $N_S = 3$

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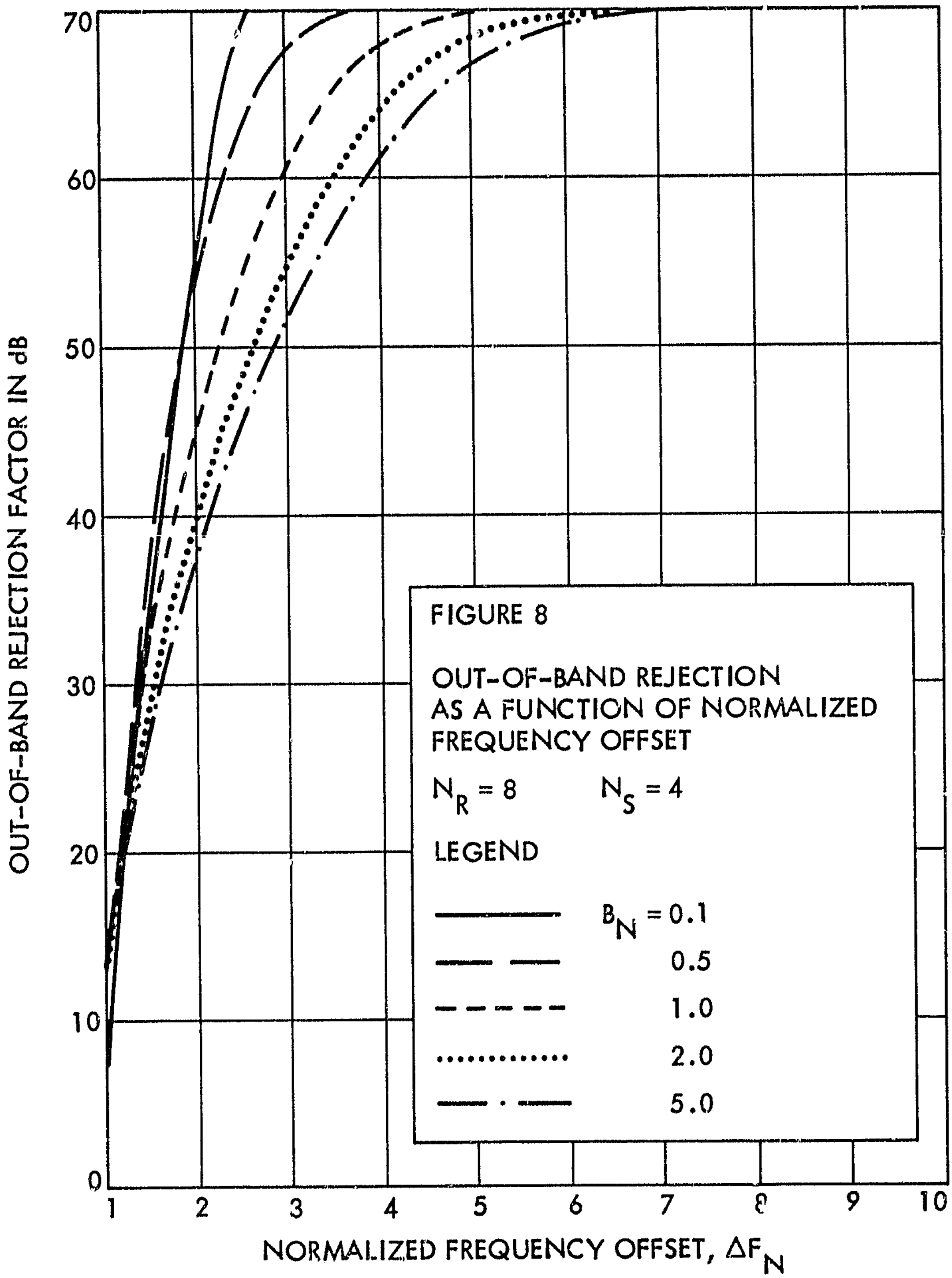

FIGURE 8

OUT-OF-BAND REJECTION AS A FUNCTION OF NORMALIZED FREQUENCY OFFSET

$N_R = 8$ $N_S = 4$

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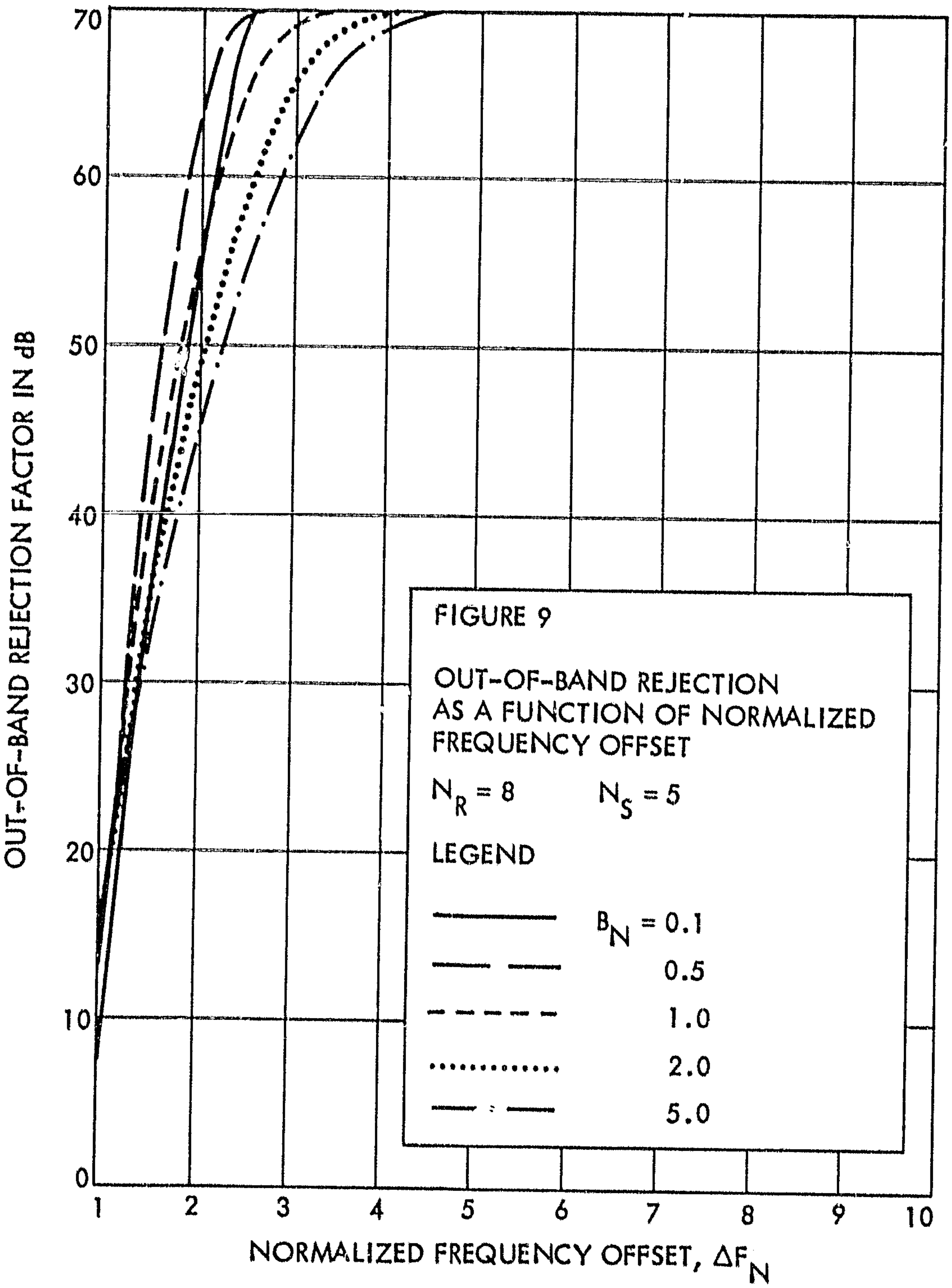

FIGURE 9

OUT-OF-BAND REJECTION
AS A FUNCTION OF NORMALIZED
FREQUENCY OFFSET

$N_R = 8$ $N_S = 5$

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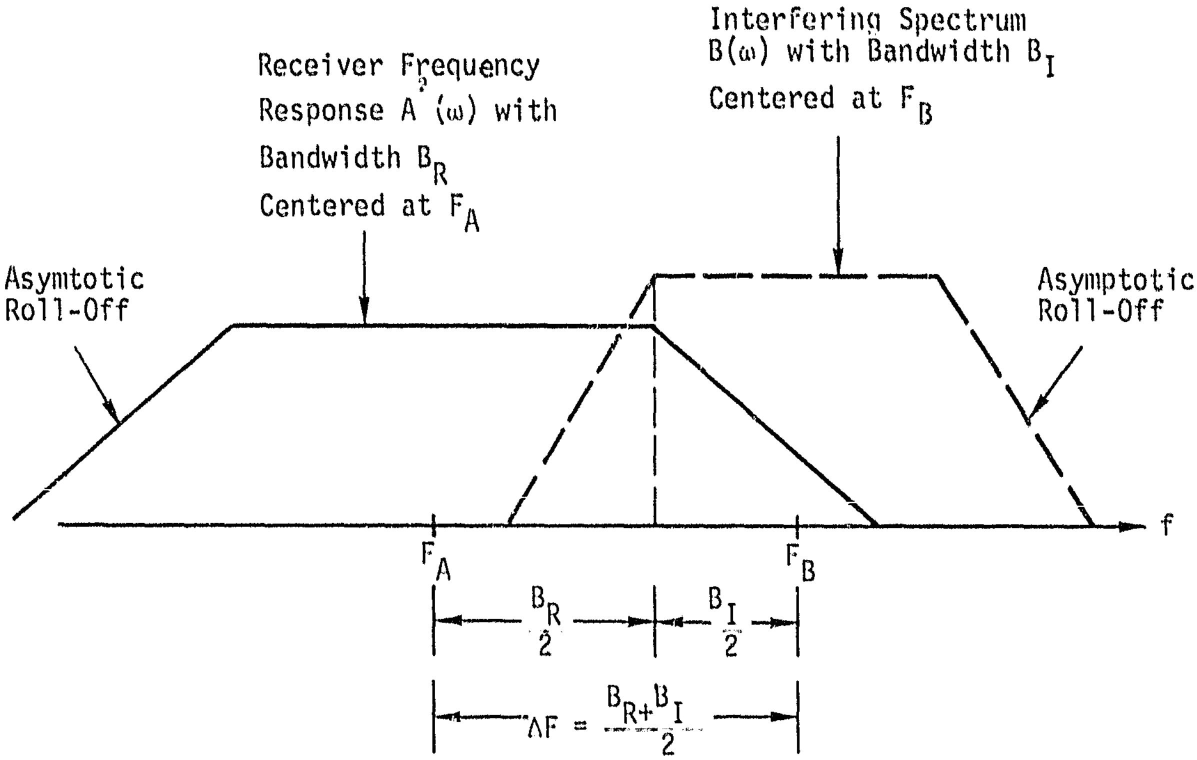

($\Delta F_N = 1$)

Figure 10 Interfering Spectrum and Receiver Frequency Response with Minimum Frequency Separation ($\Delta F_N = 1$)

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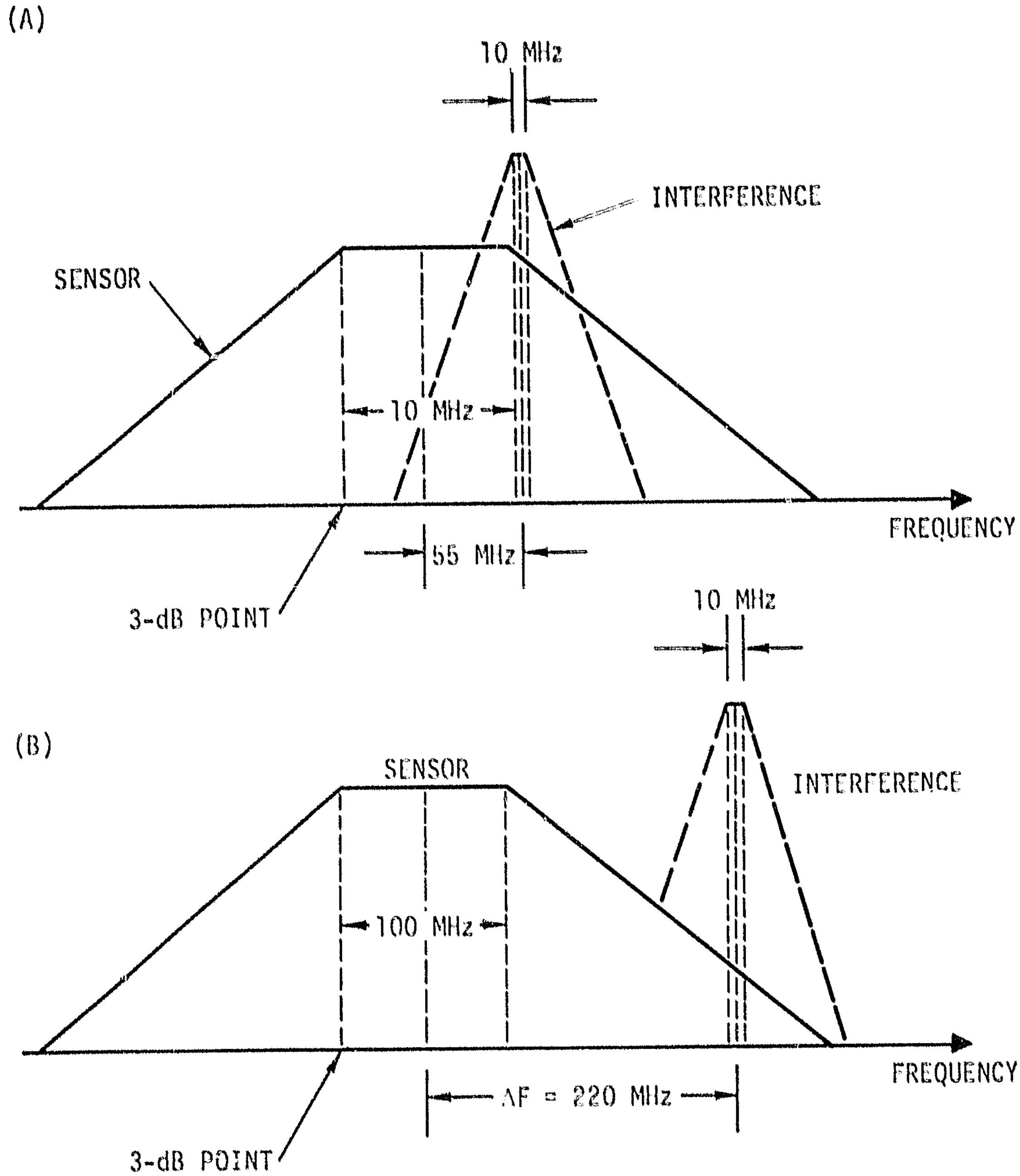

Figure 11 Illustration of Interference Situation For Examples 1 and 2 of ANNEX 1

(A) $\Delta F = 55$ MHz

(B) $\Delta F = 220$ MHz

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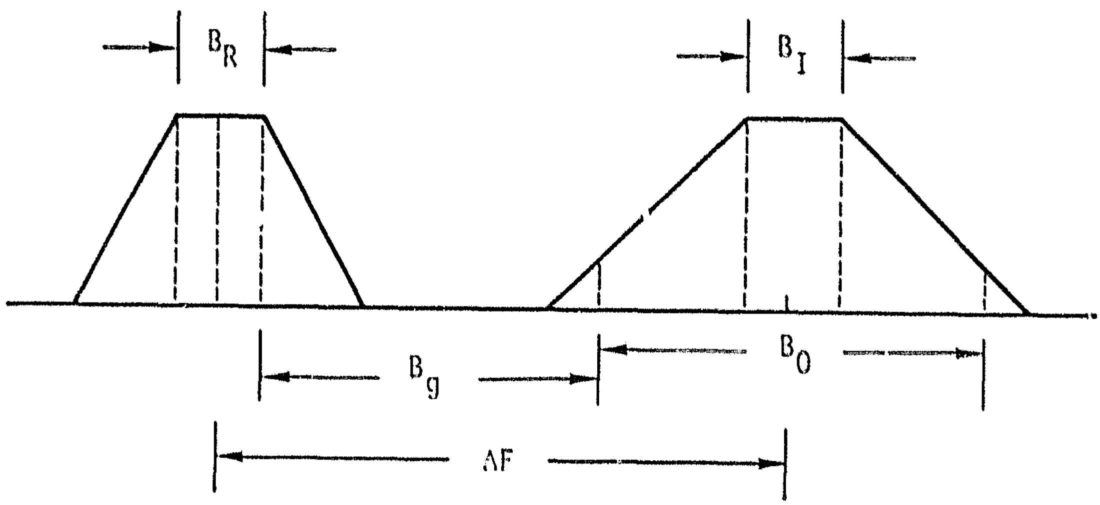

Figure 12

Definition of Guard Band

Legend: B_R = 3 dB Bandwidth of the Sensor

B_I = 3 dB Bandwidth of the Interference

ΔF = Frequency Separation Between Sensor and Interference

B_0 = Occupied Bandwidth of Interference

B_g = Guard Band

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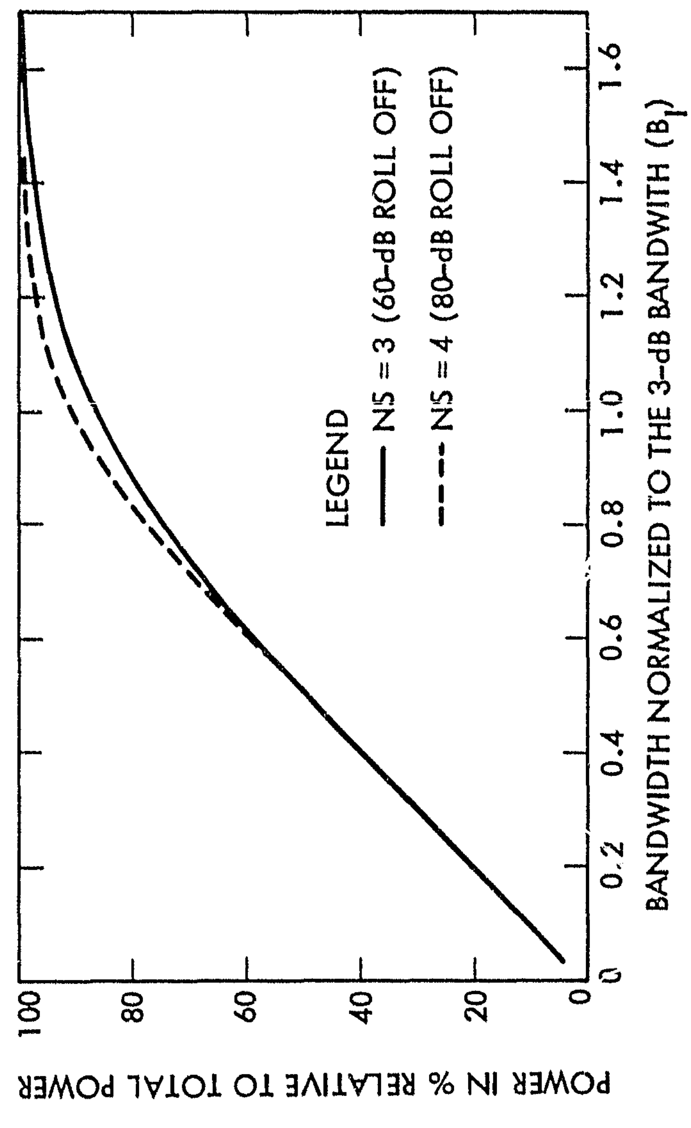

FIGURE 13 Interference Power Contained in a Given Bandwidth Centered at the Center Frequency of the Interference

Annex 1

Derivation of Out-of-Band Rejection Factor

The out-of-band rejection factor is to account for the mismatch in frequency and bandwidth between the transmitter and the radiometer. It is a function of the frequency response of the radiometer and the spectrum of the interference. The out-of-band rejection factor, denoted by β, is defined as:

$$\beta = \frac{\int_{-\infty}^{\infty} A^2(\omega)\ B(\omega)\ d\omega}{\int_{-\infty}^{\infty} B(\omega)\ d\omega}$$

where $A(\omega)$ and $B(\omega)$ represent the radiometer amplitude response, normalized to have unity gain, and the interference spectrum respectively. For the purpose of this report, $A^2(\omega)$ is modeled as a bandpass filter with a 3-dB bandwidth B_R Hertz and $B(\omega)$ is modeled as a bandpassed signal with a 3-dB bandwidth B_I Hertz. The low-pass equivalent of $A(\omega)$ and $B(\omega)$ denoted respectively by $A_L(\omega)$ and $B_L(\omega)$ are of the following forms:

$$A_L{}^2(\omega) = \frac{1}{\left(\frac{\omega}{\pi B_R}\right)^{2N_R} + 1}$$

$$B_L(\omega) = \frac{1}{\left(\frac{\omega}{\pi B_I}\right)^{2N_I} + 1}$$

where N_R an N_I represent the number of poles in the receiver and the transmittor filters respectively.

If the interference is ΔF hertz away from the receiver, i.e., the distance between the center frequency of the interference and the radiometer center frequency is ΔF hertz, then the out-of-band rejection factor in terms of $A_L(\omega)$ and $B_L(\omega)$ is:

$$\beta = \frac{\int_{-\infty}^{\infty} A_L^{2}(\omega)\ B_L(\omega-2\pi\Delta F)\ d\omega}{\int_{-\infty}^{\infty} B_L(\omega)\ d\omega}$$

It is noted that ΔF is referred to as the frequency separation between $A(\omega)$ and $B(\omega)$. Substituting the expression for $A_L(\omega)$ and $B_L(\omega)$ into the above equation, becomes

$$\beta = \frac{\int_{-\infty}^{\infty} [(\frac{\omega}{\pi B_R})^{2N_R} + 1]^{-1}\ [(\frac{\omega-2\pi\Delta F}{\pi B_I})^{2N_I} + 1]^{-1}\ d\omega}{\int_{-\infty}^{\infty} [(\frac{\omega}{\pi B_I})^{2N_I} + 1]^{-1}\ d\omega}$$

It is apparent from the above expression that β depends on B_I and B_R for a given ΔF, N_R and N_I. The dependence of β on B_I and B_R can be eliminated by introducing two parameters into the above expression. The first parameter is the normalized bandwidth, B_N, defined as:

$$B_N = B_I/B_R.$$

The second is the normalized frequency separation, ΔF_N, defined as:

$$\Delta F_N = 2\Delta F/(B_R+B_I)$$

Using the definition of B_N and ΔF_N, the out-of-band rejection factor becomes:

$$\beta = \int_{-\infty}^{\infty} (x^{2N_R} + 1)^{-1} \left[\left(\frac{x-(1+B_N)\Delta F_N}{B_N}\right)^{2N_I} + 1\right]^{-1} dx \bigg/ \int_{-\infty}^{\infty} \left[\left(\frac{x}{B_N}\right)^{2N_I} + 1\right]^{-1} dx$$

which depends, for a given ΔF_N, N_R, and N_I, only on the ratio of the bandwidth of the transmitter and the receiver.

A computer program has been written to evaluate the out-of-band rejection factor. A set of curves have been generated to provide the out-of-band rejection as a function of the normalized frequency separation for selected values of B_N, N_R, and N_I. These curves are shown in Figures 2 through 9.

Two examples are given below to illustrate how to determine the out-of-band rejection factors assuming $N_R = 4$ and $N_S = 3$.

Example 1

If the radiometer bandwidth (B_R) is 100 MHz, the interference bandwidth (B_I) is 10 MHz, and the frequency separation (ΔF) between the center frequencies of the radiometer and the interference is 55 MHz, then one can determine the out-of-band rejection factor as follows:

Step 1. Determine the normalized bandwidth B_N.

$B_N = B_I/B_R = 10$ MHz/100 MHz $= 0.1$

Step 2. Determine the normalized frequency separation ΔF_N.

$\Delta F_N = 2\Delta F/(B_R+B_I) = 2 \times 55$ MHz/(100 + 10) MHz

$= 1.0$

Step 3. Determine the out-of-band rejection factor from Figure 2 using the curve for $B_N = 0.1$.

At $\Delta F_N = 1.0$, out-of-band rejection = 5 dB (approximately).

Since the bandwidth of the interference is relatively narrow compared to the radiometer bandwidth, the out-of-band rejection factor is approximately equal to the attenuation of the radiometer filter at ΔF hertz away from the center frequency (see Figure 11A). Specifically,

$$\beta \sim A_L^{-2}(\omega)\Big|_{\omega=2\pi\Delta F} = \left(\frac{1}{(\frac{\omega}{\pi B_R})^8 + 1}\right)^{-1}\Bigg|_{\omega=2\pi(55\text{ MHz})}$$

$$= (\frac{\omega}{\pi B_R})^8 + 1\Big|_{\omega=2\pi(55\text{ MHz})}$$

$$= \left[\frac{(2\pi)(55\text{ MHz})}{\pi\ (100\text{ MHz})}\right]^8 + 1$$

$$= 3.14 \text{ or } 4.97\text{ dB}$$

The out-of-band rejection as determined above agrees with Figure 2.

Example 2

Assuming all conditions remain the same as those in Example 1 with the only exception that ΔF is now 220 MHz instead of 55 MHz, the out-of-band rejection can be determined as follows:

Step 1. Determine the normalized bandwidth B_N.

$B_N = B_I/B_R = 10\text{ MHz}/100\text{ MHz} = 0.1$

Step 2. Determine the normalized frequency separation ΔF_N.

$\Delta F_N = 2\Delta F/(B_R + B_I) = 2 \times 220\text{ MHz}/(10 + 100)\text{ MHz}$

$= 4.0$

Step 3. Determine the out-of-band rejection factor β from Figure 2 using the curve for $B_N = 0.1$.

At $\Delta F_N = 4.0$, $\beta \cong 52$ dB

Again, the out-of-band rejection can be verified by computing the attenuation of the radiometer for $\omega = 2\pi\Delta F$ (see Figure 11B), i.e.,

$$\beta \cong A_L^{-2}(\omega)\Big|_{\omega=2\pi\Delta F} = \left(\frac{\omega}{\pi B_R}\right)^8 + 1\Big|_{\omega=2\pi(220\ \text{MHz})}$$

$$= \left[\frac{(2\pi)}{\pi}\frac{(220\ \text{MHz})}{(100\ \text{MHz})}\right]^8 + 1$$

$$= 1.4 \times 10^5 \text{ or } 51.4\ \text{dB}$$

which also agrees with the results of Figure 2.

Annex 2

The Revision of the Expression for Guard Bands

One of the criteria developed in this report to enable simultaneous operacion of radiometers and other active services is expressed in terms of guard bands, Bg. For the purpose of this report, the guardband is the minimum allowable distance in frequency between the bandedge of the occupied bandwidth of the interference and the 3-dB corner frequency of the radiometer filter (see Figure 12). The occupied bandwidth of the interference is the bandwidth that contains 99 percent of the total interference power. For practical purposes, the total power of the interference is defined as:

$$P_T = \int_{-10B_I}^{10B_I} \frac{1}{(\frac{2f}{B_I})^{2N_I} + 1}\, df$$

where B_I is the 3-dB bandwidth of the interference, N_I is a parameter that determines the roll-off rate of the interference spectrum and is assumed to be 3 for this report.

The occupied bandwidth, B_0, can be obtained by equating the following equation.

$$\int_{-\frac{B_o}{2}}^{\frac{B_o}{2}} \frac{1}{(\frac{2f}{B_I})^{2N_I} + 1}\, df = 0.99 \int_{-10B_I}^{10B_I} \frac{1}{(\frac{2f}{B_I})^{2N_I} + 1}\, df$$

Using numerical method, the occupied bandwidth is found to be:

$$B_O \simeq \begin{cases} 1.7\ B_I & \text{for } N_I = 3 \\ 1.5\ B_I & \text{for } N_I = 4 \end{cases}$$

In general, B_O is a function of N_I.

The cumulative interference power as a function of the normalized frequency is shown in Figure 13 for $N_I = 3$ and $N_I = 4$. The normalized frequency is equal to the frequency from the center of the interference spectrum divided by one-half of the 3-dB bandwidth, $B_I/2$. The cummulative power at a given frequency F_p is determined by the following equation.

$$\begin{bmatrix} \text{cumulative} \\ \text{power at } F_p \end{bmatrix} = \begin{bmatrix} \text{power contained} \\ \text{in } (-F_p,\ F_p) \end{bmatrix} = \int_{-F_p}^{F_p} \frac{1}{\left(\frac{2f}{B_I}\right)^{2N_I} + 1}\, df$$

Having determined B_O, the guard band, Bg, can be easily obtained. From Figure 12, it is obvious that

$$Bg = \Delta F - 0.5\ B_O - 0.5\ B_R.$$

Substituting B_O into the above expression yields an expression that relates Bg to the frequency separation (ΔF), the bandwidth of the radiometer (B_R) and the bandwidth of the interference (B_I).

$$Bg \simeq \begin{cases} \Delta F - 0.5\ B_R - 0.85\ B_I & \text{for } N_I = 3 \\ \Delta F - 0.5\ B_R - 0.75\ B_I & \text{for } N_I = 4 \end{cases}$$

Annex 3

Analysis of Potential Adjacent Bands Interference Between Passive Microwave Sensors and the Fixed and Mobile Services

1. Introduction

This Annex analyzes the potential adjacent band interference between passive microwave sensors and the fixed and mobile services. The analysis is performed at three selected frequencies: 1.4 GHz, 15 GHz, and 21 GHz. The results of the 1.4-GHz analysis are typical for bands below 10 GHz, the results of the 15-GHz analysis are typical for bands between 10 GHz and 20 GHz, and the results of the 21-GHz analysis are typical for bands above 20 GHz. Analysis approaches and equipment characteristics are based on Report 694.

2. Near 1.4 GHz

Passive microwave sensors operating near 1.4 GHz have an interference threshold of -165 dBW and a bandwidth of 100 MHz. The worst interference condition exists when the sensor is located in the main beam of the interference source. This happens when the satellite is on the horizon of the terrestrial station. The distance from the interference source to the satellite in a 500-km orbit is about 2500 km.

Assuming that the normalized frequency separation between the microwave sensor center frequency and the terrestrial transmitter center frequency is 1 and that the Fixed and Mobile Services have a bandwidth of about 10 MHz, the maximum allowable e.i.r.p. of the terrestrial station in order for the interference threshold not to be exceeded can be calculated as follows:

Interference threshold	-165 dBW
Sensor Antenna effective area (side lobe)	-38 dB·m^2
Spreading loss	-139 dB/m^2
Atmospheric loss	0 dB
Out-of-band rejection (B_N = 0.1)	5 dB
Maximum allowable e.i.r.p.	17 dBW

Fixed and mobile stations near 1.4 GHz typically have an e.i.r.p in the range of 37 to 55 dBW which exceeds the maximum allowable e.i.r.p by as much as 38 dB. In order to avoid interference, the frequency separation between passive microwave sensors and the fixed and mobile stations must not be smaller than the following values:

Earth station e.i.r.p. (dBW)	Normalized frequency separation	Frequency separation (MHz)(1)
≤ 17	1.0	55
20	1.1	60
30	1.6	88
40	2.1	115
50	2.8	154
60	3.6	198

3. <u>Near 15 GHz</u>

The interference threshold for passive microwave sensors operating near 15 GHz is -160 dBW and the required bandwidth is 200 MHz. There are three potential interference paths:

- o interference which occurs when the sensor is located in the main beam of the interference source,
- o interference due to additive effects of the side lobe coupling from multiple interference sources, and
- o interference caused by direct overflight of an interference source through the main beam of the radiometer.

Based on analysis of these interference paths in Report 694, the worst interference condition is the interference caused by direct overflight of an interference source through the main beam of the radiometer. This interference path will be analyzed to determine the potential interference.

Note (1) Estimated frequency separation is for terrestrial stations with 10-MHz bandwidths.

The interference level, due to a single transmitter at a normalized frequency separation of unity with a bandwidth of 80 MHz, can be calculated as follows:

Transmitted power	-3 dBW
Transmitting antenna gain (side lobe)	-10 dBi
Spreading loss	-125 dB/m^2
Radiometer antenna effective area	+13 dB·m^2
Out-of-band rejection (B_N = 0.4)	-9.0 dB
Interference level	-134.0 dBW

This interference level would exceed the sensor interference threshold by 26.0 dB. It is thus not feasible to simultaneously operate the sensors and the Fixed and Mobile Services at a normalized frequency separation of unity. To make it feasible, the normalized frequency separation between the passive microwave sensor and the terrestrial stations must not be less than 2.1. This corresponds to an out-of-band rejection of 35 dB and a received interference level of -160.0 dBW. The corresponding frequency separation is 294 MHz.

4. Near 21 GHz

The feasibility of sharing the same frequency bands between passive microwave sensors and fixed and mobile services near 21 GHz has been analyzed in Report 694 and has been determined to be feasible. Simultaneous Operation in adjacent bands is therefore feasible for these services.

Annex 4

Analysis of Potential Adjacent Band Interference Between Passive Microwave Sensors and the Fixed-Satellite Service

1. Introduction

This Annex examines the feasibility of simultaneous operations of the passive microwave sensors and the Fixed-Satellite Service in adjacent bands. Both the space-to-earth (downlink) and earth-to-space (uplink) communication links of the Fixed-Satellite Service are analyzed. The frequencies selected for analysis are the frequencies either currently being used or being planned for possible future systems. These frequencies are near 5.0, 11.0, 18.0, and 37.0 GHz for the space-to-earth links and near 6.0, 15.0, and 37.0 GHz for the earth-to-space link.

2. Potential Interference as Determined by Space-to-Earth Links for Frequency Bands Near 5, 11, 18, and 37 GHz

There are two possible paths by which the downlink signal of a satellite in the Fixed-Satellite Service can cause interference to the radiometer. These two possible paths are:

(1) Coupling of the downlink signal via the back lobe of the radiometer antenna.

(2) Coupling of the downlink signal into the main lobe of the radiometer antenna due to the backscatter of the earth's surface.

Both interference paths will be examined for each of the frequency bands of interest.

2.1 Near 5 GHz

Many existing satellites in the Fixed-Satellite Service such as Intelsat IV, Comstar, and Satcom have their space-to-earth and earth-to-space frequency at about 4 GHz and earth-to-space frequency at about 6 GHz. The downlink frequency is near one of the preferred frequencies for passive microwave sensing, i.e., 5 GHz. Passive microwave sensors operating at 5 GHz require a bandwidth of 200 MHz and an interference threshold of -158 dBW. Satellite systems in the Fixed-Satelite Service at the 4/6-GHz frequency band typically have a downlink e.i.r.p. of about 40 dBW and a bandwidth of 35 MHz.

The received interference power level due to the coupling of the downlink signal via the back lobe of a radiometer can be computed as follows:

Fixed satellite e.i.r.p	40 dBW
Spreading Loss	-162.0 dB/m^2
Effective area of radiometer antenna (back lobe)	-40.0 dB·m^2
Out-of-band rejection (B_N=0.2, ΔF_N=1.0)	-7.0 dB
Received interference power level	-169.0 dBW

The received interference power level is 11 dB below the sensor interference threshold. It would take approximately 12 satellites simultaneously in view of the radiometer in order to exceed the -158-dBW sensor threshold.

The interference power level due to the coupling of the downlink signal into the main lobe of the radiometer antenna by isotropically backscattering from the Earth can be estimated as follows:

Fixed satellite e.i.r.p	40.0 dBW
Spreading loss (fixed satellite to earth)	-162.0 dB/m^2
Reflectivity factor (50% loss)	-3.0 dB
Surface area within main lobe of the radiometer antenna	+52.0 dB·m^2
Spreading loss (Earth to radiometer)	-125.0 dB/m^2
Radiometer antenna effective area	+35.0 dB·m^2
Out-of-band rejection (B_N = 0.2, ΔF_N = 1.0)	-7.0 dB
Received interference power level	-170.0 dBW

The received interference power level is 12 dB below the sensor interference threshold. This mode of interference is not expected to cause problems.

2.2 Near 11.0 GHz

Fixed satellites operating near this frequency typically have a downlink e.i.r.p. of 50 dBW and a bandwidth of 35 MHz. Radiometers operating near 11 GHz require a bandwidth of 100 MHz and a sensor interference threshold of -156 dBW. The effective area of the radiometer antenna at this frequency is estimated to be +13.0 dB·m^2 and -60 dB·m^2 for the main lobe and back lobe. The received interference level can be calculated as follows:

(a) back lobe coupling of the downlink signal

Fixed satellite e.i.r.p.	50.0 dBW
Spreading loss	-162.0 dB/m^2
Effective area of radiometer (back lobe)	-60.0 dB·m^2
Out-of-band frequency rejection (B_N = 0.2)	-7.0 dB
Received interference level	-179.0 dBW

The received interference level is 23 dB below the sensor interference threshold. This interference path therefore does not result in any potential interference.

(b) Coupling of the backscattered downlink signal into the main lobe of the radiometer antenna

Fixed satellite e.i.r.p	50.0 dBW
Spreading loss (fixed satellite to earth)	-162.0 dB/m^2
Reflectivity factor (50% loss)	-3.0 dB
Surface area within main lobe of radiometer antenna	67.0 dB·m^2
Spreading loss (earth to radiometer)	-125.0 dB/m^2
Radiometer antenna effective area	+13.0 dB·m^2
Out-of-band rejection (B_N = 0.2)	-7.0 dB
Received interference level	-167.0 dBW

The received interference level in both cases is significantly below the -156-dBW threshold.

2.3 Near 18.0 GHz

Fixed satellites operating in this frequency band are yet to be developed. For the purposes of this study, the satellite is assumed to have the characteristics given in Annex II, Report 694. It is assumed that the satellite would have 22.4-dBW transmitter power, 50-dBi antenna gain, and a bandwidth of 35 MHz.

Radiometers operating near 18 GHz have a sensor interference threshold of -160 dBW and a bandwidth of 200 MHz. The received interference level can be calculated by following the steps in Section 2.2 of this Annex and by substituting into the calculation the following applicable parameter values.

Radiometer antenna effective area (main lobe)	10.5 $dB \cdot m^2$
Radiometer antenna effective area (back lobe)	-63.0 $dB \cdot m^2$
Surface area in view of the radiometer antenna	63.0 $dB \cdot m^2$

The resultant interference level as received by the sensor is -159.6 dBW and -151.1 dBW for the first and the second interference paths respectively. These received levels are based on a unity normalized frequency separation. The received interference level for the second path (i.e., main lobe coupling of the back-scattered downlink signal) is almost 9.0 dB above the sensor interference threshold. To avoid potential interference, the frequency separation must be increased to equal to or greater than 1.4 times half of the sum of the 3-dB bandwidths of the radiometer and the fixed satellite. For a 35-MHz fixed satellite bandwidth, this corresponds to a frequency separation of at least 165 MHz. Thus simultaneous operation at this frequency is feasible only if the satellite downlink frequency is separated from the sensor center frequency by more than 165 MHz corresponding to a guard band of about 35 MHz.

2.4 Near 37 GHz

The feasibility of cochannel sharing at this frequency was examined in Annex II, Report 694 and it was determined that the space-to-earth link would not cause interference to the sensor. Therefore no interference is expected when the radiometer and the satellite in the Fixed Satellite Service are in adjacent bands.

3. Potential Interference as Determined by the Earth-to-Space Links for Frequency Bands Near 6, 15, and 37 GHz.

The uplink of an earth station in the Fixed-Satellite Service can potentially interfere with the operations of microwave sensors. The maximum interference level at the radiometer occurs when the radiometer is in the main beam of a fixed earth station. Assuming a 30° elevation angle of the earth station, the interference level at the radiometer is determined in the following paragraphs.

3.1 Near 6 GHz

As mentioned in Section 2.1, many satellites in the Fixed-Satellite Service utilize the 4- and 6-GHz bands for downlink and uplink respectively. The 6-GHz uplink signal of the fixed satellite is near one of the frequencies preferred for microwave sensing. Earth stations in the Fixed-Satellite Service operating at 6 GHz typically have approximately 40-MHz bandwidth and an e.i.r.p. up to 90 dBw. Some of these stations use large antennas (30 meter) having a gain of about 60 dBi. The radiometers operating at this frequency range have a -158-dBW sensor interference threshold and a 400-MHz bandwidth. The received interference level can be calculated as follows:

Earth station e.i.r.p	90 dBW
Spreading loss (30° elevation angle)	-130.0 dB/m^2
Radiometer effective area (side lobe)	-38.0 $dB \cdot m^2$
Out-of-band rejection (B_N = 0.1)	-5.0 dB
Received interference level	-83.0 dBW

The out-of-band rejection in the above calculation is based on a normalized frequency separation of 1. The resultant interference level exceeds the sensor interference threshold by as much as 75 dB. Simultaneous operation in this case generally is not feasible.

3.2 Near 15 GHz

Some satellites in the Fixed-Satellite Service use 11- and 14-GHz bands for downlink and uplink communications. The uplink signal of these satellites is near the 15-GHz band used by passive microwave sensors and poses an interference potential to radiometers operating near 15 GHz. At present, there are not too many earth stations operating at this frequency. However, wider use of this frequency band is expected in the future. The maximum e.i.r.p allowed for these earth stations in order not to exceed the acceptable sensor interference level can be calculated as follows:

Allowable interference threshold	-160.0 dBW
Radiometer antenna effective area (side lobe)	+59.0 dB·m^2
Spreading loss (30° elevation angle)	+130.0 dB/m^2
Out-of-band rejection (B_N = 0.2)	+7.0
Maximum allowable earth station e.i.r.p	+36.0 dBW

If the e.i.r.p of the earth station is limited to 36.0 dBW, there will be no potential interference between passive microwave sensors and the fixed earth stations operating in adjacent bands for all values of frequency separation.

If the e.i.r.p. of the earth stations exceeds 36 dBW, it is necessary then to increase the frequency separation accordingly.

Earth station e.i.r.p dBW	Normalized Frequency Separation, F_N	Frequency Separation F, MHz
40	1.2	144
50	1.6	192
60	2.1	252
70	2.7	324
80	3.6	432
90	4.8	576
100	6.4	768

The above values of frequency separation are based on a 40-MHz bandwidth of the earth station. For systems such as the Intelsat V earth stations which have a 80-MHz bandwidth and a 89-dBW e.i.r.p, the required frequency separation is about 670 MHz corresponding to a guard band of about 502 MHz.

3.3 Near 37 GHz

The characteristics of the earth station of this yet-to-be developed system is based on Annex II, Report 694 where it has been assumed that the earth station employs a broadband spread-spectrum system and the e.i.r.p is 86 dBW. The bandwidth of the radiometer at this frequency is 1000 MHz. The bandwidth of the earth station can be assumed to be 50% of the sensor bandwidth. The received interference level can be calculated as follows:

Earth station e.i.r.p.	86.0 dBW
Spreading loss (30° elevation angle)	-130.0 dB/m^2
Atmospheric absorption	-0.5 dB
Radiometer antenna effective area (side lobe)	-67.0 dB·m^2
Out-of-band rejection (B_N = 0.5)	-9.0 dB
Received interference power level	-120.5 dBW

The received interference power level exceeds the sensor interference threshold by 25.5 dB. To avoid interference, it is necessary to increase the frequency separation to about 1.5 GHz corresponding to a normalized frequency separation of 2.0 and a guard band of about 575 MHz.

4.0 Conclusion

Based on frequency bands examined, the downlink (space-to-Earth) of the satellite in the Fixed Satellite Service generally does not present any problems that would make it difficult to operate passive microwave sensors in bands adjacent to the Fixed Satellite Service bands, except near 18 GHz where a guard band of 35 MHz is needed. The uplink on the other hand is a potential interference source in all frequency bands examined. To avoid interference, it would be necessary to either limit the e.i.r.p of the earth stations in the Fixed Satellite Service or maintain a large frequency spacing of the order of 1 GHz between the radiometer and the earth station.

Annex 5

Analysis of Potential Interference Between Passive Microwave Sensors and the Mobile-Satellite Service Operating in Adjacent Bands

1. Introduction

The Annex analyzes the potential interference between passive microwave sensors and the Mobile-Satellite Service occupying adjacent bands. Three frequency bands have been chosen for analysis: 1.4 GHz, 21 GHz, and 37 GHz. The approach is similar to the approach used for the analysis of interference between passive microwave sensors and the Fixed-Satellite Service.

2. Near 1.4 GHz

Passive microwave sensors operating near 1.4 GHz have a sensor interference threshold of -165 dBW and a bandwidth of 100 MHz. There are a few bands near this frequency which are used by mobile satellites for uplink and downlink communications. The interference situation between passive microwave sensors and mobile satellites is very similar to the situation between passive microwave sensors and fixed satellites. The only difference is perhaps that the satellite downlink e.i.r.p. probably is higher than that of a fixed satellite. This is because the earth-based receive terminals in the Mobile-Satellite Service are in general small terminals. For the purpose of this study, it is assumed that the mobile satellite has a downlink e.i.r.p. of 42 dBW and a bandwidth of 10 MHz. This corresponds to a power flux density of -154 dBW/m^2 at the surface of the earth in a 4-kHz reference bandwidth. This is the maximum allowable pfd at this frequency for space stations sharing frequency bands with terrestrial services.

For the earth station, it is assumed that the uplink e.i.r.p. is 55 dBW. This is the maximum value allowed for Terrestrial Radiocommunication services sharing frequency bands with Space Radiocommunication services.

The earth station is further assumed to have a transmitter power of 13 dBW (20 watts) and an antenna with maximum gain of 42 dB.

The maximum interference due to the uplink of the mobile satellite occurs when the radiometer is in the main beam of the interference source. The maximum interference level as received by the radiometer can be calculated as follows:

Earth station e.i.r.p.	42.0 dBW
Spreading loss (30° elevation)	-130.0 dB/m^2
Radiometer antenna effective area (side lobe)	-38.0 dB·m^2
Out-of-band rejection (B_N = 0.1)	-5.0 dB
Received interference level	-131.0 dBW

The received interference level is 34 dB above the sensor interference threshold. Interference to the radiometer would occur whenever the radiometer is located within 9.1° of the mobile station main antenna axis. To prevent the loss of data, the spacing between the radiometer center frequency and the mobile station center frequency must not be less than 154 MHz. The corresponding guard band is 96 MHz.

The worst interference situation due to the downlink of the mobile satellite is caused by the isotropically backscattered signal. The received interference level can be estimated as follows:

Mobile satellie e.i.r.p	42.0 dBW
Spreading loss (from satellite to earth)	-162.0 dB/m^2
Reflectivity (50% loss)	-3.0 dB
Area in view of radiometer antenna	63.0 dB·m^2
Radiometer antenna effective area (main lobe)	35.0 dB·m^2
Spreading loss (from earth to radiometer)	-125.0 dB/m^2
Out-of-band rejection (B_N = 0.1)	-5.0 dB
Received interference level	-155.0 dBW

The received interference level is 10 dB above the sensor interference threshold. The mobile satellite downlink is therefore capable of interfering with the operation of the sensors in adjacent bands. To protect the sensor operations, a frequency separation of about 77 MHz or more is necessary. The corresponding guard band is about 19 MHz.

3. Near 20 and 37 GHz.

Mobile satellite systems in these frequency bands are yet to be developed. The feasibility of sharing the same frequency bands between microwave sensors and the Mobile-Satellite Service was analyzed in Report 694 for these bands based on a hypothetical model of the mobile-satellite system. This model assumes that the mobile-satellite system uses a broad-band spread-spectrum technique. Report 694 shows that it is feasible to share the same frequency bands between microwave sensors and the space-to-Earth links of the Mobile Satellite Service if the mobile satellites do not produce pfd levels at the surface of earth, in excess of -128 dBW/(m^2·MHz) at 20 GHz and -117 dBW/(m^2·MHz) at 37 GHz. For adjacent band operations, these pfd limits can be increased by an amount equal to the out-of-band rejection which is a function of the frequency separation between the radiometer and the mobile satellite downlink frequency. The sensor bandwidth is 200 MHz and 1000 MHz respectively for 20 GHz and 37 GHz. Assuming that the bandwidth of the mobile satellite downlink is comparable to the sensor bandwidth, the criteria for the sharing of adjacent bands can be calculated and are shown in the following table.

Criteria to protect passive microwave sensors against interference from the space-to-earth links of the mobile satellites operating in the adjacent bands.

Mobile Satellite pfd at earth surface, dBW/(m^2·MHz)	Frequency Separation (MHz)	
	20-GHz Band	37-GHz Band
-110	260	----
-100	340	1300
-90	460	1700
-80	560	2300
-70	760	2800

The maximum interference level at the radiometer due to a mobile satellite uplink occurs when the radiometer is in the main beam of the mobile earth station. Assuming a 30° elevation angle and a 86 dBW e.i.r.p. for the earth station, the received interference level is -111.5 dBW at 37 GHz for cochannel interference (Annex 2, Report 694). This corresponds to -122.5 dBW for adjacent band interference with a minimum frequency separation, i.e., 1000 MHz. This interference level is 23.5 dB above the sensor threshold. To avoid interference, it is necessary to separate the interferer and the sensor by 2100 MHz or more, corresponding to a guard band of 750 MHz or larger.

Interference due to mobile satellite uplink at 20 GHz is expected to be similar to the 37-GHz situation. The necessary frequency separation to avoid interference is 660 MHz corresponding to an out-of-band rejection of 18.5 dB and a guard band of 390 MHz.

ANNEX 6

Analysis of Adjacent Band Interference Between Passive Microwave Sensors and the Inter-Satellite Service

1. Introduction

This Annex illustrates the techniques used in analyzing the adjacent band interference between passive microwave sensors and the Inter-Satellite Service. The WARC '79 allocates these frequency bands for the Inter-Satellite Service: 22.55-23.55, 32-33, 54.25-58.2, 59-64, 116-134, 170-182, and 185-190 GHz. This Annex analyzes the adjacent band interference for systems in the 50- to 70-GHz region. System characteristics of the Inter-Satellite Service in this frequency region is based on Annex 3, Report 694. There are three possible inter-satellite transmission links that can interfere with sensor operations:

- o geostationary-to-geostationary links,
- o geostationary-to-low-orbit satellite links, and
- o low-orbit-to-geostationary links.

An analysis in Annex 3, Report 694 shows that the first link, i.e., the transmission from a geostationary satellite to another geostationary satellite, will not interfere with the operations of a passive microwave sensor operating in the same frequency band. Consequently, there will be no interference to sensors in adjacent bands and this link will therefore not be analyzed.

The analysis in Report 694 also shows that the interference caused by the second link, i.e., the transmission from geostationary satellite to a low-orbit satellite, is insignificant because the probability and duration of the occurrence of interference which exceeds the sensor threshold are very small. This link will therefore not pose any problems for the passive microwave sensors in adjacent bands.

The only inter-satellite link that must be analyzed is the transmission from a low-orbit satellite to a geostationary satellite.

2. Interference Due to Transmission from a Low-Orbit Satellite to a Geostationary Satellite

For the purpose of this analysis, the characteristics of the low-orbit satellite in the inter-satellite system operating in the 50- to 70-GHz region are derived from Report 694:

Transmitter e.i.r.p	23.1 dBW
Bandwidth	2 GHz

Radiometers operating in this frequency range are assumed to have a bandwidth of 250 MHz and an interference threshold of -157 dBW. The amount of interference received by the radiometer from a low-orbit satellite is a function of the frequency separation and the distance between the two spacecraft. Assuming that the frequency separation between the radiometer and the low-orbit satellite is such that the normalized frequency separation is unity, the minimum distance between the two spacecraft can be calculated as follows:

Transmitter e.i.r.p	23.1 dBW
Radiometer antenna effective area (sidelobe)	-56.3 dBm^2
Out-of-band-rejection ($B_N = 8$)	-14.0 dB
Sensor interference threshold	-(-157.0 dBW)
Required spreading loss	109.8 dB/m^2

At a normalized frequency separation of 1, the required spreading loss is 109.8 dB/m^2 in order for the interference level not to exceed the sensor interference threshold. This corresponds to a distance of 87.0 km. If the distance between the two spacecraft is less than 87.0 km, it would be necessary to increase the frequency separation accordingly.

Distance in km	Required frequency separation (GHz)
87	1.125
80	1.238
70	1.238
60	1.350
50	1.463

It is unlikely that two spacecraft would be closer to each other than 87.0 km. As a result, it is not expected that the low-orbit-to-geostationary satellite transmission would cause interference to microwave sensors operating in adjacent frequency bands.

3. Conclusion

Simultaneous adjacent band operation of the passive microwave sensors and the Inter-Satellite Service in the 50- to 70-GHz bands is feasible. There is no interference expected due to the geostationary-to-geostationary satellite transmission, the geostationary-to-low-orbit satellite transmission, and the low-orbit-to-geostationary satellite transmission.

Annex 7

Analysis of Potential Adjacent Band Interference Between Passive Microwave Sensors and the Radiolocation and Aeronautical Radionavigation Services

1. Introduction

The potential adjacent band interference between microwave sensors and the Radiolocation and Aeronautical Radionavigation Services has been analyzed for systems operating near 1.4 GHz, 4 GHz, and 15 GHz. Many of the transmitters in the Radiolocation and Aeronautical Radionavigation Services operating at these frequencies are pulsed radars. In general, the response of a receiver to a pulsed signal of given peak power and carrier frequency is different from the response to a CW signal of the same peak power and the same carrier frequency. The out-of-band rejection due to the mismatch of bandwidths and frequencies between the receiver and the transmitter is consequently very difficult to evaluate. Fortunately, for systems considered in this Annex, the out-of-band rejection can be approximated by treating the pulsed signal as a CW signal with an effective power equal to the transmitter power reduced by a factor equal to the duty cycle of the transmitted signal. This approximation is valid as long as the product of the receiver bandwidth and the pulse width is much greater than 1. This requirement is satisfied for the systems considered in the Annex.

2. Near 1.4 GHz

Microwave sensors operating at this frequency have a threshold of -165 dBW and a receiver bandwidth of 100 MHz. Transmitters in the Radiolocation and Aeronautical Radionavigation at this frequency are typically pulsed radars having the following characteristics:

Transmitter power (peak)	67 dBW
Antenna gain	34.5 dBi
Pulse repetition rate	310 to 364 pps
Pulse duration	2 μS
Transmitter bandwidth	14.4 MHz

The product of the radiometer bandwidth and the pulse width is approximately 200 which is much greater than 1. It is thus possible to estimate the out-of-band rejection by treating the pulsed signal as a CW signal with an effective power equal to the peak power reduced by the duty cycle. Using a pulse repetition rate of 333 pps, the out-of-band rejection is estimated to be about 5 dB at a normalized frequency separation of 1. The effective transmitted power is 35.2 dBW.

The maximum interference level occurs when the radiometer is located in the main beam of the interference source. This occurs at low elevation angles as seen from the radar station. The interference level as received by the radiometer can be calculated as follows:

Effective transmitted power	35.2 dBW
Transmitter antenna gain	34.5 dBi
Spreading loss (0° elevation angle)	-139.0 dB/m^2
Radiometer effective area (side lobe)	-38.0 dB·m^2
Out-of-band rejection (B_N = 0.1)	-5.0 dB
Received interference level	-112.3 dBW

The received interference level would exceed the allowable level by as much as 52.7 dB. To avoid interference, a frequency separation of 270 MHz or more is needed.

3.0 Near 4 GHz

The sensor interference threshold is -158 dBW for this frequency. The corresponding sensor bandwidth is 200 MHz. The transmitters in the Radionavigation Service near this frequency are primarily used for world-wide radar altimetry measurements. These altimeters can be a CW system or a pulsed system.

Technical characteristics of the pulsed system are as follows:

Transmitter peak power	23 dBW
Antenna gain	11 dBi
Pulse duration	0.05 to 0.1 μS
Pulse repetition rate	10 K pps

Technical characteristics of the CW system are as follows:

Transmitter power	- 6 dBW
Antenna gain	11 dBi

For the pulsed system, the maximum effective transmitter power is -7 dBW which is only 1 dB below the transmitter power of a CW system. For the purpose of this analysis, it is adequate to combine the CW system and the pulsed system into one and assume that the effective transmitter power is -6 dBW. The interference level can be calculated as follows:

Effective transmitter power	-6 dBW
Antenna gain (back lobe)	-5 dBi
Spreading loss (altimeter to sensor [1])	-134 dB/m^2
Effective area of the radiometer antenna (side lobe)	-38 $dB \cdot m^2$
Out-of-band rejection ($B_N = 0.1$)	-5 dB
Received interference level	-188 dBW

The interference level is -188 dBW from a single interference source. Since there are a large number of altimeters in operation today, a large number of them can be simultaneously in view of a radiometer. It is estimated in Report 694 that at most 750 altimeters can be simultaneously in view of a radiometer near the coastal and ocean areas. The total interference level from 750 interferers is -159 dBW which exceeds the allowable level by only 1 dB.

4. Near 15 GHz

Microwave landing systems are being planned in the vicinity of 15 GHz. The technical characteristics of these systems are:

Transmitter power	7 dBW
Antenna gain	20 dBi

Microwave sensors operating near this frequency require a 200-MHz bandwidth, and the acceptable interference level is -160 dBW or less. The received interference level can be estimated as follows:

Transmitter power	7 dBW
Antenna gain (back lobe)	-10 dBi
Spreading loss	-134 dB/m^2
Effective radiometer antenna area (side lobe)	-59 dB·m^2
Out-of-band rejection (B_N = 0.1)	-5 dB
Received interference level	-201 dBW

The received interference level from a single source is 41 dB below the sensor interference threshold. It would take almost 12,500 interferers to be simultaneously in view of a radiometer in order for the received interference level to exceed the sensor threshold. The probability for this to occur is believed to be very small.

5. Conclusion

Potential adjacent band interference between passive microwave sensors and the Radiolocation and Aeronautical Radionavigation Services has been analyzed for systems near 1.4 GHz, 4 GHz, and 15 GHz. It is concluded that it is feasible to operate passive microwave sensors in bands adjacent to the frequency bands of Radiolocation and Aeronautical Radionavigation Services for the 4-GHz and 15-GHz bands. For the 1.4-GHz band, it is feasible only if the frequency separation between the microwave sensors and the transmitters in the Radiolocation and Aeronautical Radionavigation Services is more than 270 MHz.

ANNEX 8

Analysis of the Potential Adjacent Band Interference Between Passive Microwave Sensors and the Broadcasting Satellite Service

1. Introduction

Advances in satellite technology have made it economically feasible to broadcast TV signals from satellites directly to users. In direct TV broadcasting, the earth receive terminals are much smaller than the receive terminals in other services, such as the Fixed Satellite Service. Consequently, a higher downlink e.i.r.p. is necessary to maintain a good picture quality. This Annex examines the potential interference to passive microwave sensors due to the high downlink e.i.r.p. of the satellite in the Broadcasting Satellite Service.

2. Near 12 GHz

Direct broadcasting satellite systems have not yet been fully developed. For the purpose of this analysis, it is assumed that a direct broadcasting satellite in the 12-GHz band would have the following characteristics.

Downlink e.i.r.p.	60 dBW
Antenna Gain	37 dBi
TWT Output Power	200 Watt
Bandwidth	35 MHz

The assumed characteristics are similar to the system characteristics of the Japan Broadcasting Satellite.

These are two potential interference paths:

- o Coupling of the downlink signal through the backlobe of the radiometer antenna,
- o Coupling of the isotropically backscattered downlink signal through the mainlobe of the radiometer antenna.

The interference level will be calculated for each of these two possible interference paths.

2.1 Interference level due to the back lobe coupling of the downlink signal

Transmitter e.i.r.p	60 dBW
Spreading loss	-162 dB/m^2
Effective area of the radiometer antenna(back lobe)	-60 dB·m^2
Out-of-band rejection (B_N = 0.2)	-7 dB
Received interference level	-169 dBW

The sensor interference threshold for sensors operating near 11 GHz is -156 dBW. It thus appears that this interference path would not cause interference to sensor operations.

2.2 Interference due to main lobe coupling of the backscattered signal

Transmitter e.i.r.p.	60 dBW
Spreading loss (from satellite to earth)	-162 dB/m^2
Reflectivity (50% loss)	-3 dB
Surface area within main lobe of radiometer antenna	+67 dB·m^2
Spreading loss (from earth to radiometer)	-125 dB/m^2
Radiometer effective antenna area (main lobe)	+13 dB·m^2
Out-of-band rejection (B_N = 0.2)	-7 dB
Received interference level	-157 dBW

The received interference level due to the backscattered signal is 12 dB stronger than the level due to direct coupling through the back lobe of the radiometer antenna. Even though neither one is strong enough to exceed the sensor threshold, the second interference path represents a potential interference source.

3.0 Conclusion

The potential interference between passive microwave sensors and the Broadcasting Satellite Service has been examined for systems operating near 12 GHz. It appears that it is feasible to simultaneously operate the passive microwave sensors and the space-to-earth links of the Broadcasting Satellite in adjacent bands if care is taken to ensure that the signal from the Broadcasting Satellite, backscattered from the surface of earth, would not exceed sensor threshold. The simultaneous operation of the passive microwave sensor and the earth-to-space link of the Broadcasting Satellite is feasible if the earth station e.i.r.p. is limited to 36.0 dBW. (Annex 4). If the earth station e.i.r.p. exceeds 36.0 dBW, frequency spacing between the sensor and the transmitter must be increased to avoid interference.

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