

Analysis of Electromagnetic Compatibility Between Radar Stations and 4 GHz Fixed- Satellite Earth Stations

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Some measurement equipment is identified in this report by manufacturer name and model number for the purpose of adequately explaining measurement procedures. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that equipment so identified is necessarily the best available for these applications.

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ABSTRACT

The susceptibility of 3700- to 4200-MHz fixed-satellite service earth stations to interference from radar signals, and the mechanisms by which such interference can occur, are examined. It is shown that interference can occur even if all currently applicable NTIA and FCC spectrum engineering requirements for radar emissions and earth station receiver systems are satisfied. It is further shown that while most interference problems can be resolved by installing appropriate radio frequency (RF) filtering on either the radar transmitter RF output or the earth station RF input, determination of the system that requires filtering depends critically upon the interference coupling mechanism. Methods for determining the interference coupling mechanism are presented.

KEY WORDS

Audio Receive-Only (ARO) Terminals
Digital Audio Receiver Terminals (DART)
Electromagnetic Compatibility (EMC)
Interference Coupling Mechanisms
Fixed-Satellite Earth Stations
Front-End Overload
Interference Mitigation
Low-Noise Amplifier
Radar Interference
Radar Spurious Emissions
Radar Stations
Television Receive-Only (TVRO) Systems

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SECTION 1 INTRODUCTION

1.1 BACKGROUND

The National Telecommunications and Information Administration (NTIA) is responsible for managing the Federal Government's use, of the radio frequency spectrum. NTIA's responsibilities include establishing policies concerning spectrum assignment, allocation and use, and providing various departments and agencies with guidance to ensure that their conduct of telecommunication activities is consistent with these policies.¹ In discharging these responsibilities, NTIA assesses spectrum utilization, identifying existing and/or potential compatibility problems among the telecommunication systems that belong to various departments and agencies, provides recommendations for resolving any compatibility conflicts that may exist in the use of the radio frequency spectrum, and recommends changes to promote spectrum efficiency and improve spectrum management procedures.

This report addresses possible causes and solutions to reported cases of interference to earth stations from radar stations. (Radar stations include radiolocation, radionavigation and meteorological radar stations.) In recent years, NTIA has noted a significant increase in the number of reported cases of interference to 3700- to 4200-MHz (hereafter referred to in this report as "4-GHz band") fixed-satellite service earth stations from radar stations allocated in adjacent spectral bands between 2700 and 3700 MHz. Both the desired and interfering signal paths are shown schematically in Figure 1. The increase in interference has been largely attributed to the rapid growth of television receive-only (TVRO) and audio distribution earth stations. Because many of the radars that have been involved in these cases have been Federal Government systems, NTIA has had responsibility for investigating the causes of such interference, as well as for developing solutions to these problems.

1.2 OBJECTIVE

The objective of this task was to develop procedures to assess the potential for interference, and techniques to minimize electromagnetic compatibility (EMC) conflicts, between radar stations operating in the 2700- to 3700-MHz portion of the spectrum and fixed-satellite service (space-to-earth) earth stations operating in the 4-GHz band.

1.3 APPROACH

In order to accomplish the objective of this task, the following approach was taken:

- a) determine the mechanism(s) by which the interference from radars to fixed-satellite earth station receivers occurs, through measurements by NTIA at several earth station sites and laboratory testing at the NTIA Institute for Telecommunication Sciences (ITS) in Boulder, CO

¹ NTIA, "Manual of Regulations and Procedures for Federal Radio Frequency Management," U.S. Department of Commerce, National Telecommunications and Information Administration, May 1992 edition with revisions September 1993 and May 1994. (Hereafter referred to as the "NTIA Manual").

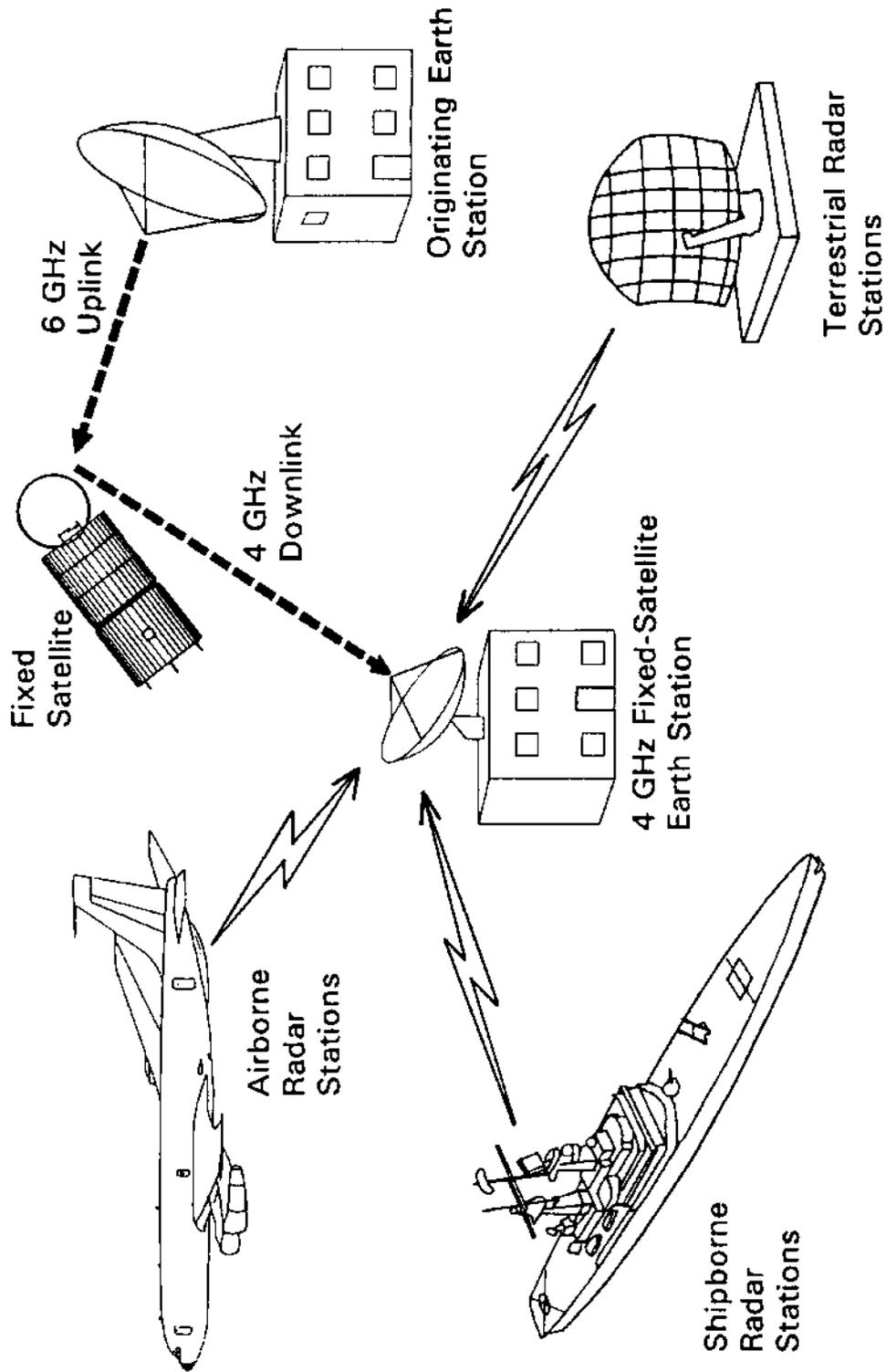


Figure 1. Fixed-satellite earth stations operating in the 3700- to 4200-MHz (4-GHz) band may experience interference from airborne, shipborne and terrestrial radar stations.

- b) identify various interference mitigation methods, applicable to both radar stations and fixed-satellite earth stations**
- c) determine the degradation criteria and susceptibility of 4-GHz fixed-satellite earth station receiver systems to interference from radar emissions**
- d) determine the emission characteristics (frequency domain and time domain) of interfering radars, using NTIA's Radio Spectrum Measurement System (RSMS) van and portable Compact Radio Spectrum Measurement Systems (CRSMS)**
- e) determine separation distances at which interference from radar stations to earth stations may occur for each identified interference coupling mechanism**
- f) determine measurement procedures to identify the interference coupling mechanism(s) at earth stations experiencing interference.**

SECTION 2 RULES AND REGULATIONS

2.1 INTRODUCTION

In the United States, the spectrum between 2700 -to 3700-MHz is mainly used by radar stations operating in the radiolocation, aeronautical and maritime radionavigation, and meteorological aids services. The bands included in this part of the spectrum are: 2700-2900, 2900-3100, 3100-3300, 3300-3500, 3500-3600, and 3600-3700 MHz. The band adjacent to these bands, 3700-4200 MHz, is used by fixed-satellite (space-to-earth) earth stations.

This section contains the rules and regulations applicable to systems in these bands. The National allocations, definitions, and applicable footnotes for these bands are discussed along with the applicable spectrum standards for Government and non-Government radar stations and earth stations.

2.2 NATIONAL ALLOCATION RULES

In the United States, the band 2700-2900 MHz is allocated for exclusive Government services (except as indicated in note US18), as listed in Table 1. The Government allocates this band to the aeronautical radionavigation and meteorological aids services on a primary basis, and to military radiolocation on a secondary basis.

The band 2900-3100 MHz is allocated on a shared basis for Government and non-Government maritime radionavigation services. Radiolocation services are secondary in this band. For cases in which the Government NEXRAD weather radar cannot be accommodated in the band 2700-2900 MHz, the band 2900-3000 MHz is allocated to radionavigation and meteorological aids services on a primary basis (see US316).

The bands 3100-3300 MHz and 3300-3500 are allocated on a primary basis to Government radiolocation service. These bands are allocated on a secondary basis to non-Government radiolocation and amateur services (see 664).

The bands 3500-3600 MHz and 3600-3700 MHz are allocated on a primary basis to Government ground-based aeronautical radionavigation services and radiolocation services, and on a secondary basis to the non-Government radiolocation service. The band 3600-3700 MHz is allocated on a primary basis to the non-Government fixed-satellite (space-to-earth) service.

The band 3700-4200 MHz is allocated exclusively to non-Government fixed and fixed-satellite (space-to-earth) services. These services share the band on a primary basis.

TABLE 1.
UNITED STATES FREQUENCY ALLOCATIONS 2700-4200 MHz.

Band (MHz)	PROVISIONS	GOVERNMENT	NON-GOVERNMENT
2700-2900	US18 717, 770 G2, G15	AERONAUTICAL RADIO NAVIGATION METEOROLOGICAL AIDS Radiolocation	
2900-3100	US44, US316 775A G56	MARITIME RADIONAVIGATION Radiolocation	MARITIME RADIO NAVIGATION Radiolocation
3100-3300	US110 713, 778 G59	RADIOLOCATION	Radiolocation
3300-3500	US108 664, 778 G31	RADIOLOCATION	Amateur Radiolocation
3500-3600	US110 G59, G110	AERONAUTICAL RADIONAVIGATION (Ground-based) RADIOLOCATION	Radiolocation
3600-3700	US110, US245 G59, G110	AERONAUTICAL RADIONAVIGATION (Ground-basad) RADIOLOCATION	FIXED-SATELLITE (apaca-to-Earth) Radiolocation
3700-4200	NG41		FIXED FIXED-SATELLITE (spaca-to-Earth)

US Footnotes

- US18** Navigation aids in the US and possessions in the bands 9-14 kHz, 90-110 kHz, 190-415 kHz, 510-535 kHz, and 2700-2900 MHz are normally operated by the US Government. However, authorizations may be made by the FCC for non-Government operation in these bands subject to the conclusion of appropriate arrangements between the FCC and the Government agencies concerned end upon special showing of need for service which the Government is not yet prepared to render.
- US44** The non-Government radiolocation service may be authorized in the band 2900-3100 MHz on the condition that no harmful interference is caused to Government services.
- US108** Within the bands 3300-3500 MHz and 10000-10500 MHz, survey operations, using transmitter with e peak power not to exceed five watts into the antenna, may be authorized for Government and non-Government use on a secondary basis to other Government radiolocation operations.
- US110** In the frequency bands 3100-3300 MHz, 3500-3700 MHz, 5250-5350 MHz, 8500-9000 MHz, 9200-9300 MHz, 9500-10000 MHz, 13.4-14.0 GHz, 15.7-17.3 GHz, 24.05-24.25 GHz and 33.4-36 GHz, the non-Government radiolocation service shall be secondary to the Government radiolocation service and to airborne doppler radars at 8800 MHz, and shall provide protection to airport surface detection equipment (ASDE) operating between 15.7-16.2 GHz.

Table 1. United States Frequency Allocations 2700-4200 MHz (continued)

US245 This Fixed-Satellite Service is limited to International inter-Continental systems and subject to case-by-case electromagnetic compatibility analysis.

US316 This band 2900-3000 MHz is also allocated on a primary basis to the Meteorological Aids Service. Operations in this service are limited to Government Next Generation Weather Radar (NEXRAD) systems where accommodation in the 2700-2900 MHz band is not technically practical and are subject to coordination with existing authorized stations.

International Footnotes

664 In the bands 435-438 MHz, 1260-1270 MHz, 2400-2450 MHz, 3400-3410 MHz (in Regions 2 and 3 only) and 5650-5670 MHz, the amateur-satellite service may operate subject to not causing harmful interference to other services operating in accordance with the Table (see No. 435). Administrations authorizing such use shall ensure that any harmful interference caused by emissions from a station in the amateur-satellite service is immediately eliminated in accordance with the provisions of No. 2741. The use of the bands 1260-1270 MHz and 5650-5670 MHz by the amateur-satellite service is limited to the Earth-to-space direction.

713 In the bands 1215-1300 MHz, 3100-3300 MHz, 5250-5350 MHz, 8550-8650 MHz, 9500-9800 MHz and 13.4-14.0 GHz, radiolocation stations installed on spacecraft may also be employed for the earth exploration-satellite and space research services on a secondary basis.

717 The use of the bands 1300-1350 MHz, 2700-2900 MHz and 9000-9200 MHz by the aeronautical radionavigation service is restricted to ground-based radars and to the associated airborne transponders which transmit only on frequencies in these bands and only when actuated by radars operating in the same band.

770 In the band 2700-2900 MHz, ground-based radars used for meteorological purposes are authorized to operate on a basis of equality with stations of the radionavigation service.

775A In the bands 2900-3100 MHz and 9300-9500 MHz, the response from radar transponders shall not be capable of being confused with the response from radar beacons (racons) and shall not cause interference to ship or aeronautical radars in the radionavigation service, having regard, however, to No. 347 of these Regulations.

778 In making assignments to stations of other services, administrations are urged to take all practicable steps to protect the spectral line observations of the radio astronomy service from harmful interference in the bands 3260-3267 MHz, 3332-3339 MHz, 3345.8-3352.5 MHz and 4825-4835 MHz. Emissions from space or airborne stations can be particularly serious sources of interference to the radio astronomy service (see Nos. 343 and 344 and Article 36).

Government Footnotes

G2 In the bands 216-225, 420-450 (except as provided by US217), 890-902, 928-942, 1300-1400, 2300-2450, 2700-2900, 5650-5925, and 9000-9200 MHz, the Government radiolocation is limited to the military services.

G15 Use of the band 2700-2900 MHz by military fixed and shipborne air defense radiolocation installations will be fully coordinated with the meteorological aids and aeronautical radionavigation services. The military air defense installations will be moved from the band 2700-2900 MHz at the earliest practicable date. Until such time as military air defense installations can be accommodated satisfactorily elsewhere in the spectrum, such operations will, insofar as practicable, be adjusted to meet the requirements of the aeronautical radionavigation service.

G31 In the bands 3300-3500 MHz, the Government radiolocation is limited to the military services, except as provided by footnote US 108.

G56 Government radiolocation in the bands 1215-1300, 2900-3100, 5350-5650 and 9300-9500 MHz is primarily for the military services; however, limited secondary use is permitted by other Government agencies in support of experimentation and research programs. In addition, limited secondary use is permitted for survey operations in the band 2900-3100 MHz.

Table 1. United States Frequency Allocations 2700-4200 MHz (continued)

G59	In the bands 902-928 MHz, 3100-3300 MHz, 3500-3700 MHz, 5250-5350 MHz, 8500-9000 MHz, 9200-9300 MHz, 13.4-14.0 GHz, 15.7-17.7 GHz and 24.04-24.25 GHz, all Government non-military radiolocation shall be secondary to military radiolocation, except in the subband 15.7-16.2 GHz airport surface detection equipment (ASDE) is permitted on a co-equal basis subject to coordination with the military departments.
G110	Government ground-based stations in the aeronautical radionavigation service may be authorized between 3500 and 3700 MHz where accommodation in the 2700-2900 MHz band is not technically and/or economically feasible.

Non-Government Footnotes

NG41	Frequencies in the bands 3700-4200 MHz, 5925-6425 MHz, and 10.7-11.7 GHz may also be assigned to stations in the international fixed public and international control services located in the U.S. Possessions in the Caribbean area.
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2.3 SPECTRUM STANDARDS (Government and Non-Government)

The following is a summary of spectrum standards pertaining to Government and Non-Government radar stations and non-Government 4-GHz earth stations. Only spectrum standard requirements that affect the electromagnetic compatibility between radar stations and earth stations are discussed in detail.

Government Spectrum Standards

Chapter 5 of the NTIA Manual contains the Radio Frequency Spectrum Standards that are applicable to Federal radio stations and systems. However, within the Federal Government, any Government agency may promulgate more stringent standards for its own use.

Radar Spectrum Engineering Criteria

The Radar Spectrum Engineering Criteria (RSEC) apply to all Government radar systems. RSEC specifications are contained in Section 5.3 of the NTIA Manual. The RSEC specifies certain equipment characteristics to ensure an acceptable degree of electromagnetic compatibility among radar systems, and between such systems and those of other radio services sharing the radio spectrum.

The complete RSEC description is omitted herein; the following list identifies the technical radar characteristics for which the RSEC specifies limits:

- 1) emission bandwidth
- 2) emission level relative to the level of the radar fundamental
- 3) antenna pattern
- 4) frequency tolerance
- 5) frequency tunability
- 6) image and spurious rejection
- 7) local oscillator radiation.

The emission level, which specifies spurious emission limits, is the only technical radar characteristic listed above that has any pertinence since the 4-GHz earth stations operate in bands adjacent to the 2700- to 3700-MHz radar stations. The RSEC spurious emission level requirement is specified in decibels, X, relative to the peak power radiated at the radar fundamental. Extended spectral emissions which are limited by this suppression level are called *spurious emissions*. Procedures for measurement of radar emission characteristics are documented in an NTIA report² and are described summarily in this report's appendix.

Since the initial adoption of the RSEC emission level specification (including spurious emission limits) by NTIA in 1973, there have been several revisions to the RSEC limits. The applicable limits on radar spurious emissions are determined by the procurement date of the radar system. The following is a summary, in chronological order, of spurious emission limits applicable to radar stations operating in the 2700- to 3700-MHz bands.

For all radars that were developed, and subsequent procurement contracts let, between 1 January 1973 and 1 October 1977, the RSEC spurious emission level limit is (IRAC Doc. #13898/2):

$$\begin{array}{l}
 X \text{ (dB)} = 40 \text{ dB, or} \\
 X \text{ (dB)} = P_t - 20 \log_{10}(F_0) + 100
 \end{array}
 \left. \begin{array}{l} \\ \\ \end{array} \right\} \text{whichever value is larger.} \quad (1)$$

Where:

- P_t = $P_p + 20 \log_{10}(DC) + 10 \log_{10}(1000/PRR)$
- $X(\text{dB})$ = spurious emission level relative to the peak power
- F_0 = fundamental operating frequency, MHz
- P_p = peak transmitted power, dBm
- DC = duty cycle = $t \times PRR \times 10^{-6}$
- PRR = pulse repetition rate, pulses per second
- t = pulse width at 50% amplitude (voltage) points, μs .

For all radars that were developed, and subsequent procurement contracts let, after 1 October 1977, the RSEC spurious emission level limit is:

$$\begin{array}{l}
 X \text{ (dB)} = 60 \text{ dB, or} \\
 X \text{ (dB)} = P_t + 30
 \end{array}
 \left. \begin{array}{l} \\ \\ \end{array} \right\} \text{whichever value is larger.} \quad (2)$$

Where:

- P_t = $P_p + 20 \log_{10}(Nt) + 10 \log_{10}(PRR) - PG - 90$
- N = total number of chips (sub-pulses) contained in a pulse ($N = 1$ for non-FM and FM pulse radars)

² J. Sell, "Measurement Procedures for the Radar Spectrum Engineering Criteria," NTIA Report 84-157, U.S. Department of Commerce, National Telecommunications and Information Administration, August 1984.

PG	=	processing gain, dB; = 0 for non-FM, non-coded pulse radars
	=	10 log ₁₀ (d) for FM pulse radars
	=	10 log ₁₀ (N) for coded pulse radars
t	=	pulse width (t = chip width for coded pulse radars), μs
d	=	pulse compression ratio = emitted pulse duration/compressed pulse duration (at 50% amplitude points).

For all fixed radars in the 2700- to 2900-MHz band which were developed and for which subsequent procurement contracts were let after 1 October 1982 (IRAC Dec. #22834), the RSEC spurious emission level, X(dB), is 80 dB below the maximum spectral power density. In addition, all harmonic frequencies shall be at a level that is at least 60 dB below the maximum spectral power density.

Non-Government Spectrum Standards

All technical standards pertaining to non-Government radiolocation and maritime radionavigation stations may be found in CFR Title 47, Part 90. For non-Government radar stations the spurious emission suppression limit, X decibels, is given by:

$$\begin{array}{l}
 X \text{ (dB)} = 43 + 10 \log_{10}(P_{\text{ave}}), \text{ or} \\
 X \text{ (dB)} = 80
 \end{array}
 \left. \begin{array}{l}
 \lrcorner \\
 \text{---} \\
 \llcorner
 \end{array} \right\} \text{whichever attenuation is less.} \quad (3)$$

Where: P_{ave} = mean output power, watts
 = peak power, watts, x duty cycle.

The FCC Part 90 regulation for non-Government radars is roughly comparable to the NTIA RSEC for Government radars. However, a direct comparison between these two standards is difficult to make, as these two standards specify different spectrum measurement procedures (e.g., average power measurements vs. peak power measurements).

Non-Government Fixed-Satellite Earth Station Standards

All technical standards pertaining to non-Government earth stations may be found in CFR Title 47, Part 25. The only standards applied to receive-only earth stations are for antenna characteristics (§ 25.209). The FCC generally declines to establish effective receiver system interference immunity standards and lets the marketplace reach a consensus on system design.

The antenna performance standard for receiving earth stations in directions other than the geostationary satellite plane and outside the main beam requires that the gain of the antenna patterns shall lie below the envelope specified by CFR Title 47, § 25.209 (c) as follows:

$$\begin{array}{ll}
 32-25 \log_{10}(\Theta) \text{ dBi} & 1^\circ \leq \Theta \leq 48^\circ \\
 -10 \text{ dBi} & 48^\circ < \Theta \leq 180^\circ
 \end{array}$$

where Θ is the angle in degrees from the axis of the main lobe, and dBi refers to decibels relative to an isotropic radiator.

2.4 POLICY REGARDING SPURIOUS EMISSION INTERFERENCE

The Government policy regarding interference due to spurious emissions is contained in the NTIA Manual, Chapter 2, Section 2.3.7 and states:

“In principle, spurious emissions from stations of one radio service shall not cause harmful interference to stations of the same or another radio service within the recognized service areas of the latter stations, whether operated in the same or different frequency bands.

Providing that appropriate spectrum standards in Chapter 5 of the NTIA Manual are met, an existing station is recognized as having priority over a new or modified station. Nevertheless, engineering solutions to mitigate interference may require the cooperation of all involved parties in the application of reasonable and practicable measures to avoid causing or being susceptible to harmful interference. ”

The non-Government policy regarding interference due to spurious emissions from radiolocation stations is contained in CFR Title 47, Part 90, § 90.209(e) and states:

“When radiation in excess of that specified in paragraphs (c) and (d) above of this section results in harmful interference, the Commission may require, among other available remedies, appropriate technical changes in equipment to alleviate the interference. ”

CFR Title 47 does not contain a policy regarding interference due to spurious emissions when the interfering system is in conformance with all applicable spectrum standards.

SECTION 3 INTERFERENCE COUPLING MECHANISMS AND MITIGATION OPTIONS

3.1 INTRODUCTION

This section describes how energy radiated from radar stations may cause degradation to earth station receiver performance (interference coupling mechanisms) and methods to enhance compatibility between radar stations and earth stations (interference mitigation options).

Investigations of several interference cases have identified two interference coupling mechanisms that have occurred between radar stations in the 2700-to 3700-MHz portion of the spectrum and 4-GHz fixed-satellite service earth stations. These interference coupling mechanisms are earth station receiver front-end overload and receiver in-band interference due to radar transmitter spurious emissions.

Separation distances at which interference from radar stations to earth stations may occur for each of the interference coupling mechanisms are discussed in Section 4. Measurement procedures to identify the interference coupling mechanisms are described in Section 5.

3.2 RECEIVER FRONT-END OVERLOAD

Receiver front-end overload coupling occurs when energy from the fundamental frequency of an undesired signal saturates the receiver front-end (e.g., low-noise amplifier, or LNA), resulting in gain compression (reduction in output signal level) of the desired signal sufficient to degrade performance. Receiver front-end overload generally occurs from high-power signals in adjacent bands.

The input threshold at which receiver front-end overload occurs is a function of the 1-dB output gain compression level (saturation level) and the gain of the front-end low-noise amplifier:

$$T = C - G \quad (4)$$

Where: T = input threshold at which receiver front-end overload occurs, dBm
 C = 1-dB gain compression level of the low-noise amplifier, dBm
 G = low-noise amplifier gain at the radar fundamental frequency, dB.

A typical 1 -dB output gain compression level for a low-noise amplifier is +10 dBm. Earth station receiver systems typically use low-noise amplifiers with 50 to 65 dB gain in the 4-GHz band, and varying (and sometimes even higher) gain outside that band. The input threshold at which receiver front-end overload may be expected to occur is approximately in the range of -55 to -40 dBm.

LNA/LNB/LNC Response

An earth station receiver system typically employs a low-noise, high-gain preamplifier at the antenna feed. The preamplifier may produce output at the same frequencies as are received in the 4-GHz band, in which case it is designated an LNA. Or, the preamplifier may incorporate a mixer which downconverts the signal to a lower frequency band near 1000 MHz (e.g., 950-1450 MHz), in which case it is designated an LNB. A third preamplifier type, designated LNC, downconverts frequencies from the 4-GHz band to a few hundred MHz (e.g., 270-770 MHz) output.

The purpose of a front-end preamplifier is to provide sensitivity to a weak input signal (which requires that the noise figure of the preamplifier be low) and to produce an output with enough gain to compensate for both the line loss between the antenna and the receiver and the noise figure of the receiver. To achieve this functionality, 4-GHz front-end preamplifiers are typically designed to operate with noise figures of about 0.4-0.7 dB (noise temperatures of about 30-50 K) and gain values of about 50-65 dB.

Ideally, the frequency response range of such a preamplifier would be the same as the assigned operational band of the receiver (i.e., 3700- to 4200-MHz). If the frequency response of an amplifier is wider than the allocated band of the receiver, then the likelihood of overloading an earth station preamplifier by emissions from transmitters outside the receiver band is increased.

As part of the effort to resolve occurrences of interference involving fixed 4-GHz satellite earth station receiver systems, the NTIA study sought to quantify the frequency response (gain and sensitivity) of LNAs and LNBs that are representative of devices currently in use at 4-GHz earth stations. For this purpose, one LNA model (designated LNA in this report) and two LNB models (designated LNB #1 and LNB #2 in this report), all of which are commercially available and are in use at earth stations, were purchased by NTIA from retail suppliers. LNB #2 was specified by the manufacturer as incorporating bandpass filtering in its design; the other two devices did not incorporate any built-in bandpass filtering in their designs. All three devices were tested at the NTIA/ITS laboratory in Boulder, CO.

Gain Response and Noise Figure

The gain and noise figure of the LNA and LNB devices were measured using a +18 dB excess noise ratio (ENR) noise diode. Standard Y-factor calibrations were performed to determine gain and sensitivity as a function of frequency.³ Gain and noise figure curves for

³Y-factor calibrations are performed by connecting a calibrated excess noise source to the input of the device under test, and comparing the output power levels when the noise source is turned on and off. The gain and noise figure that are measured are those of the entire system, which in this case consists of the preamplifier under test and a spectrum analyzer used to perform the power measurements. However, if the preamplifier sufficiently overdrives the spectrum analyzer noise figure (as these devices

these units are shown in Figures 2 through 4. The in-band gain of the devices was approximately 50-65 dB, and the in-band noise figures were typically found to be less than or equal to 1 dB. (The noise figures shown in Figures 2 through 4 are about 2 dB, due to the fact that the amplifiers were overdriving a 26-dB spectrum analyzer noise figure.) The LNA exhibited slightly more gain below the operational band than it did in its nominal operational band. LNB #2, which incorporates some bandpass filtering in its design, exhibits this feature as a somewhat sharper cut-off characteristic at about 3500 MHz.

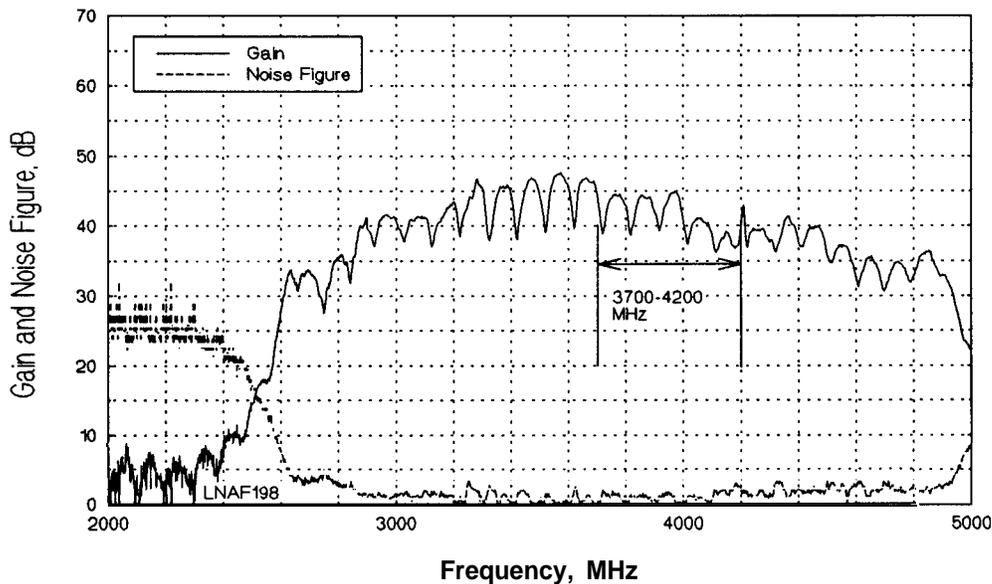


Figure 2. Gain and noise figure of a 4-GHz LNA. Same LNA model has been used in an earth station experiencing RF interference. Y-factor calibration performed with + 18 dB ENR noise diode.

did), then the characteristics measured are very nearly those of the amplifier alone. For these tests, the noise diode generated + 18 dB of noise in excess of the thermal background level, kTB . The quantity kTB is called thermal noise, where k = Boltzmann's constant ($1.38 \cdot 10^{-20}$ mW·s/K), T = system temperature (290 K for these tests), and B = measurement IF bandwidth, Hz, which was $1 \cdot 10^6$ Hz for these tests. kTB was thus -114 dBm for these tests. The complete equation for the system was:

$$G = 10 \log[(10^{P_{on}/10}) - (10^{P_{off}/10})] - ENR_d - kTB$$

where G = amplifier gain in decibels, P_{on} and P_{off} = output power in decibels measured with noise diode on and off, respectively, and ENR_d = excess noise ratio in decibels of the noise diode. The equation for noise figure was:

$$NF = ENR_d - 10 \log[10^{Y/10} - 1]$$

where NF = noise figure of the system in decibels and $Y = (P_{on} - P_{off})$, in decibels.

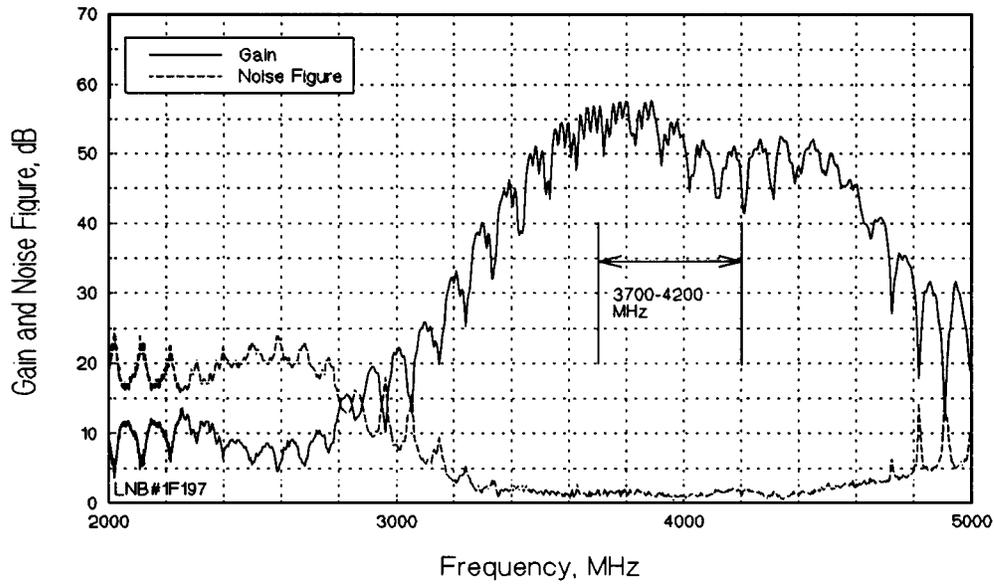


Figure 3. Gain and noise figure of a 4-GHz LNB. Output converted graphically ($f_{\text{graph}} = 5150 \text{ MHz} - f_{\text{output}}$) to show frequency response. Calibration with + 18 dB ENR noise diode.

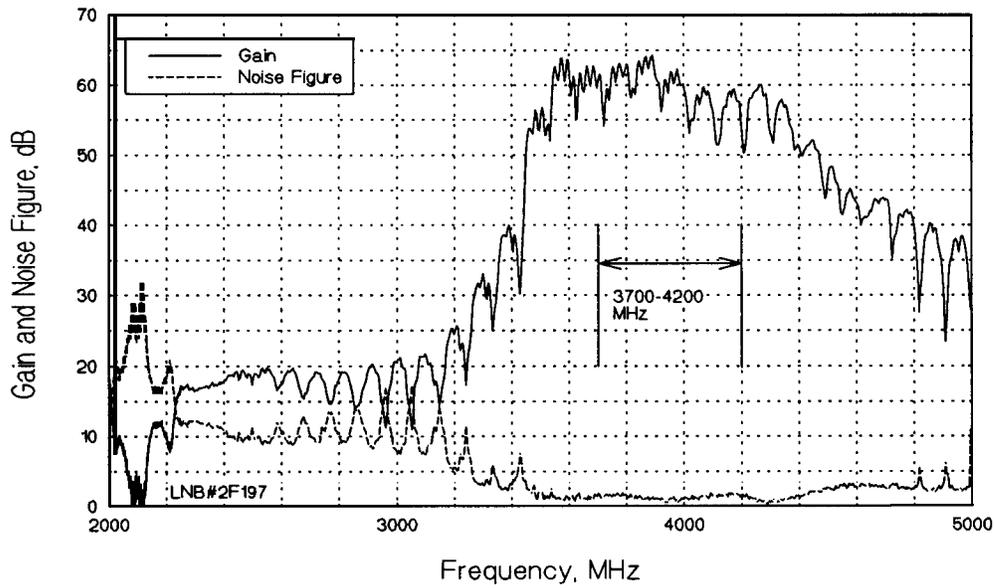


Figure 4. Gain and noise figure of a second 4-GHz LNB, specified by manufacturer as incorporating bandpass filtering. Y-factor calibration performed with + 18 dB ENR noise diode.

The LNA showed the widest frequency response range. This device's response band exhibited less than 10 dB noise figure and more than 35 dB gain between 2800 and 4800 MHz. This response range represents 40 percent of the spectrum below 5 GHz. The response ranges of all three devices include part or all of every radiolocation band between 2700 and 3700 MHz, as well as the 4200- to 4400-MHz aeronautical radionavigation band. This broadband frequency response of low-noise amplifiers used in 4-GHz earth stations makes these systems vulnerable to front-end overload by radars operating outside the 4-GHz band.

Gain Compression

If the input signal level at the amplifier does not exceed the threshold value (see Equation 4), then the output gain of the front-end preamplifier will remain at its nominal design value. However, if the input signal level to the device exceeds a critical threshold, then the gain characteristic of the amplifier will be reduced. A significant feature of this degradation is that gain will be reduced across the entire frequency response range of the amplifier (e.g., 2800-4800 MHz), even if the overload occurs at a single frequency (e.g., 3300 MHz). Figures 5 through 7 show measured gain characteristics of the previously characterized LNA and two LNBs in overload conditions.

One of the requirements of the NTIA tests on the LNA and LNB units was to determine input thresholds at which gain compression begins, and the rate at which gain compression increases with increasing overload. Tests were performed with both continuous wave (CW) overload inputs and with simulated radar inputs. Overload values were measured both with and without the presence of simulated in-band (desired) signals. The tests in which an out-of-band radar signal overloaded the LNA or LNB while a low-power signal was received in-band represented the closest simulation of actual operational conditions; those test results are presented in Figures 5 through 7. Radar signals were simulated with 1- μ s pulses at a rate of 1000 pulses per second. The measured overload characteristics were not found to vary as a function of modulation (CW vs. radar-like input) or as a function of the presence or absence of low-amplitude in-band (desired) signals, and the results of those tests duplicated the results shown in Figures 5 through 7.

Figures 5 through 7 show gain responses for each amplifier as measured with a spectrum analyzer. Each amplifier was tested for overload characteristics at three input power levels of a simulated radar signal. To achieve graphical clarity, the input frequencies at the three power levels were adjusted successively to 3300, 3400, and 3500 MHz. The in-band (desired) signals were similarly adjusted to 3900, 4000, and 4100 MHz. The desired input level in each figure is that of the desired signal at 3900 MHz; the decrease in desired signal levels at 4000 MHz and 4100 MHz is due to gain compression.

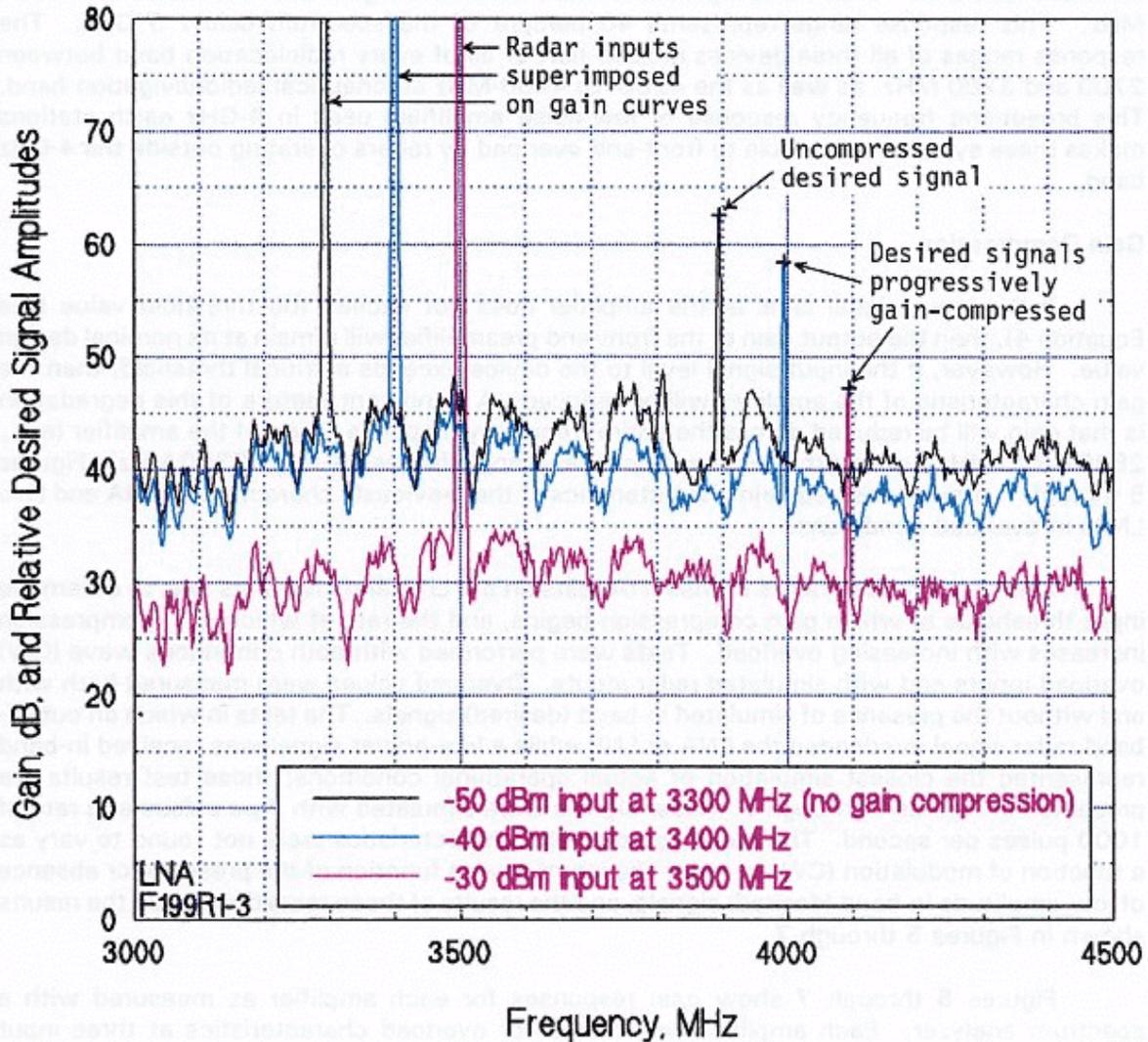


Figure 5. LNA response as a function of simulated radar inputs. Radar parameters: $1 \mu\text{s}$ pulses, 1000/sec, at 3300, 3400, 3500 MHz. Desired (in-band) signals are marked at 3900, 4000, 4100 MHz.

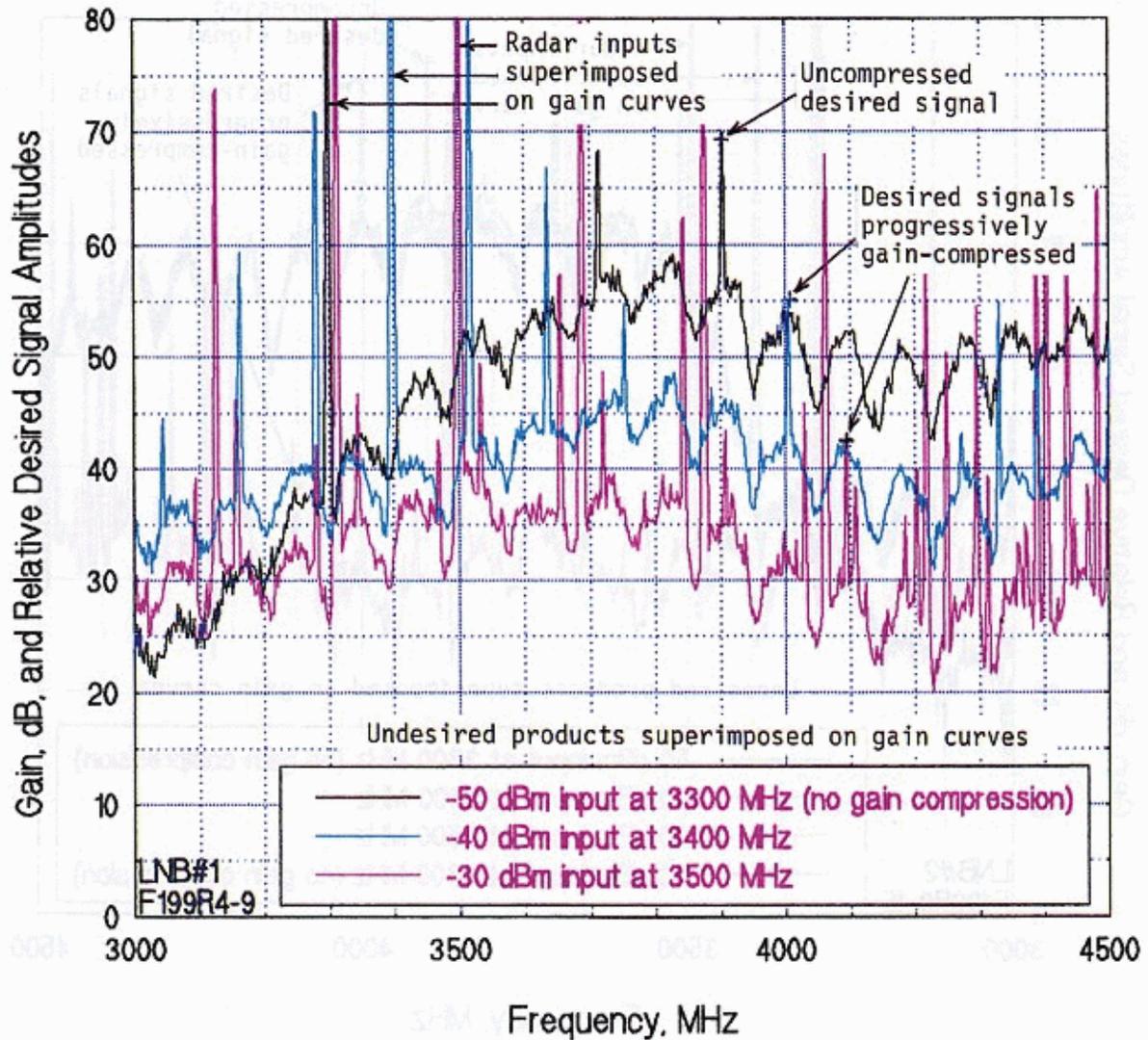


Figure 6. LNB #1 response as a function of simulated radar inputs. Radar inputs identical to Figure 4. Note products at -30 dBm and -40 dBm input amplitudes. Desired signals at 3900, 4000, 4100 MHz.

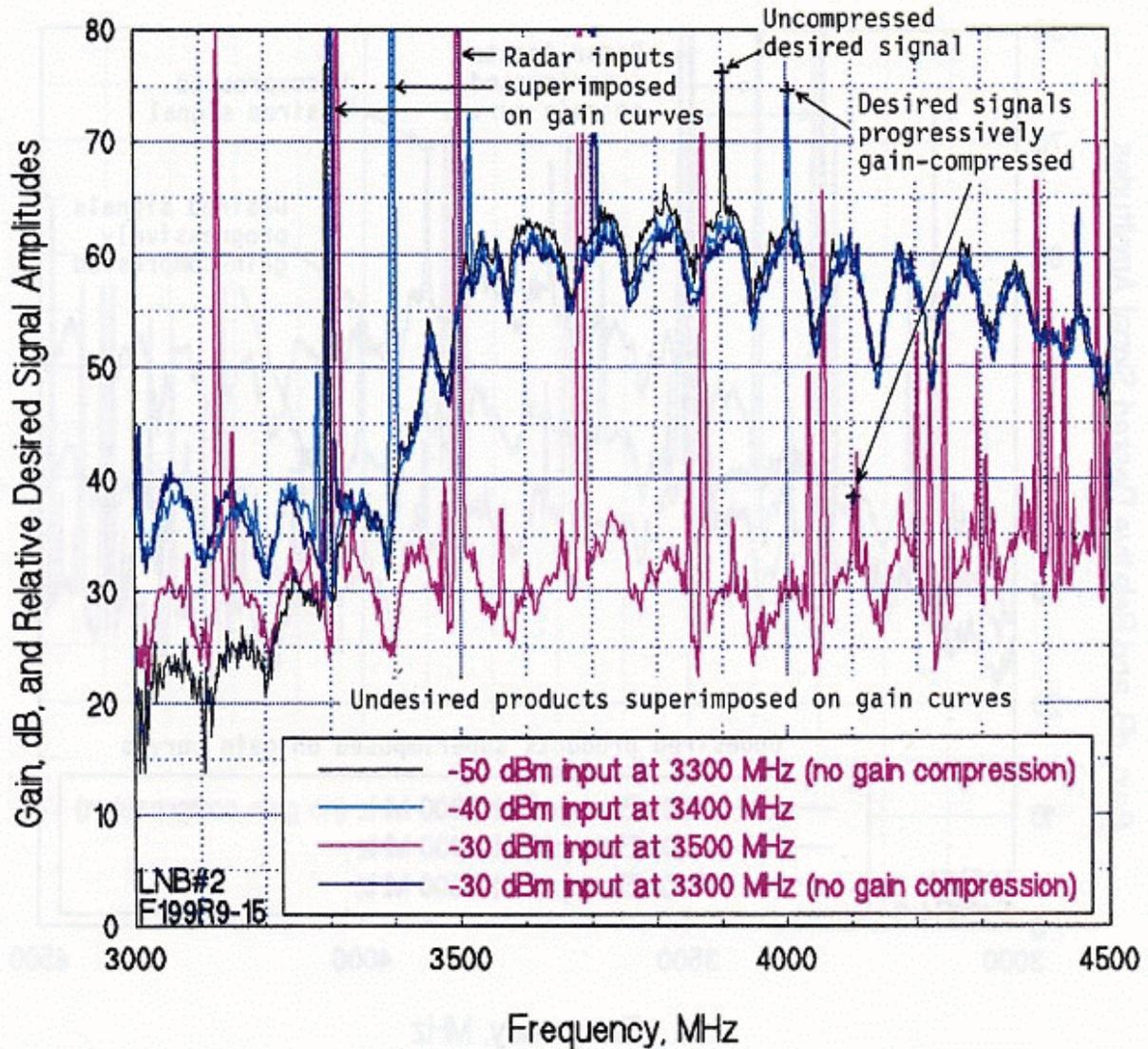


Figure 7. LNB #2 response as a function of simulated radar input. Radar inputs identical to Figures 5-6. Built-in bandpass has decreased susceptibility to overload at input frequencies below 3500 MHz.

At the lowest radar input level (-50 dBm peak power) in each of Figures 5 through 7, the amplifiers are not overloaded and the amplifier gain and the power level of the in-band (desired) signals are normal. We discovered during the tests that the gain of the LNA and of LNB #2 decreased by 1 dB (1 -dB compression point occurred) at a peak power input of about -40 dBm. LNB #1 gain was compressed by about 10 dB at that input level. When the input power of the out-of-band simulated radar signal at 3500 MHz was increased by another 10 dB, to -30 dBm peak, the gain was severely compressed in all three devices. In summary, the gain compression of the LNA/LNB is dependent upon the gain of the device at the frequency of the simulated radar signal.

Note that, although LNB #2 showed an overload response to a simulated radar signal at -30 dBm peak input and a frequency of 3500 MHz, the same device showed essentially no compression when the frequency of the input was shifted down to 3300 MHz. This finding is consistent with the earlier measurement of the 3500-MHz bandpass cutoff built into this device. This response makes this device more resistant to the phenomenon of front-end overload, but does not eliminate the problem for radars tuned above 3500 MHz.

Other Overload Responses

Gain compression may not be the only result of front-end overload; mixing products to the input signal can be generated as part of the device output. Such products are especially likely to occur if the device incorporates a mixing stage (downconversion), as is the case for an LNB or an LNC. A device lacking such stages, such as an LNA, would be expected to be less susceptible to this phenomenon.

During the NTIA tests, such mixing products were not observed for the LNA, but were observed for both LNB devices. In Figures 5 through 7, the only signals that should be seen are the simulated radar inputs at 3300, 3400, and 3500 MHz, and the simulated desired signals at 3900, 4000, and 4100 MHz. However, the LNB responses shown in Figures 6 and 7 exhibit a number of additional responses. Mixing products were produced at peak input power levels of -40 dBm and -30 dBm. For LNB #2, which incorporated bandpass filtering with a 3400-MHz cutoff, a peak input power level of -30 dBm at 3500 MHz (within the bandpass) resulted in generation of undesired products, but the same input power level at 3300 MHz (below the bandpass cutoff) did not produce such responses.

It is critical to note that some of the undesired products in the LNB devices occurred at frequencies within the 4-GHz band. Such responses could result in interference in a receiver system if they were to coincide with the frequencies of desired in-band signals. Also, such responses may easily be misinterpreted by measurement personnel as spurious signals generated by the radar, rather than being correctly identified as a response generated within the earth station's own RF front-end. (See Section 5 for methods of determining the difference.)

Gain Compression Interval

The interval of overload gain compression of an amplifier is finite. The length of the compression interval is one of the factors which determines the amount of data that a receiver system may lose as a result of overload. NTIA tests were conducted on the three devices previously described to determine their overload compression intervals. For each device, the overload signal was applied at four different peak power levels, which were adjusted to produce gain compressions of 10, 20, 30 and 40 dB in a simulated in-band (desired) signal at 4000 MHz. The input overload signal was pulsed to simulate an out-of-band radar, as had been done during the earlier gain compression tests, with a pulse width of 1 μs , pulse repetition rate of 1000/s, and radar fundamental frequency of 3500 MHz. The output power of the amplifier at the frequency of the simulated desired signal was recorded as a function of elapsed time on a digital oscilloscope, documenting the process of gain compression and the interval of that compression. The results of these tests are shown in Figures 8 through 10. The compression intervals are presented in Table 2.

The compression intervals for the LNA were found to be on the order of several hundred microseconds, whereas the compression intervals for the LNB devices were about two orders of magnitude shorter, on the order of a few microseconds. For the LNA, the interval resulting from a compression of 40 dB was 900 μs , which approached the 1000- μs interval between simulated radar pulses. For LNB #1, the 1- μs gain compression interval from 10-dB compression which is indicated in Figure 9 is probably longer than the device's inherent compression interval; the input pulse was itself 1 μs long. The reason for the difference in gain compression intervals between the LNA and the two LNB devices is not known, and was not pursued as part of this study.

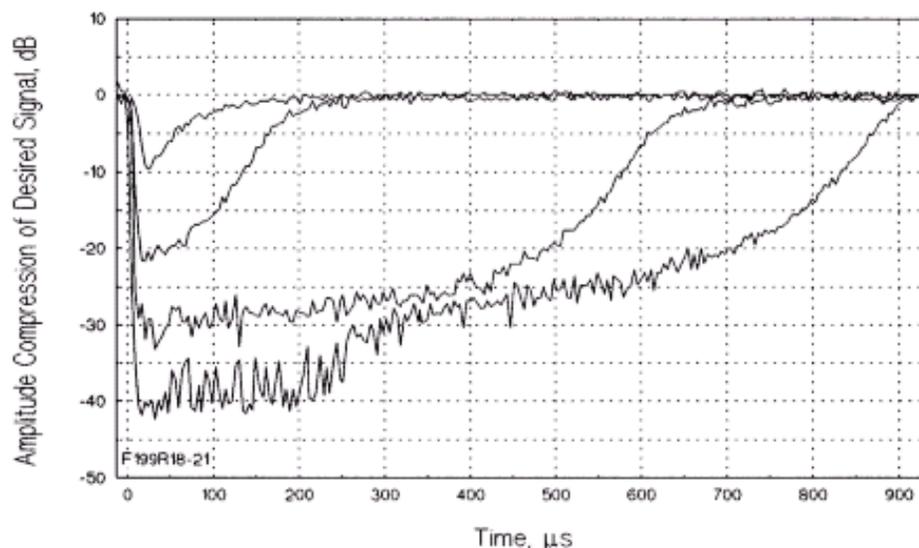


Figure 8. Time domain behavior of LNA at gain compression of 10, 20, 30 and 40 dB in desired signal at 4000 MHz. Compression created by out-of-band pulses (1- μs pulse width) at 3500 MHz.

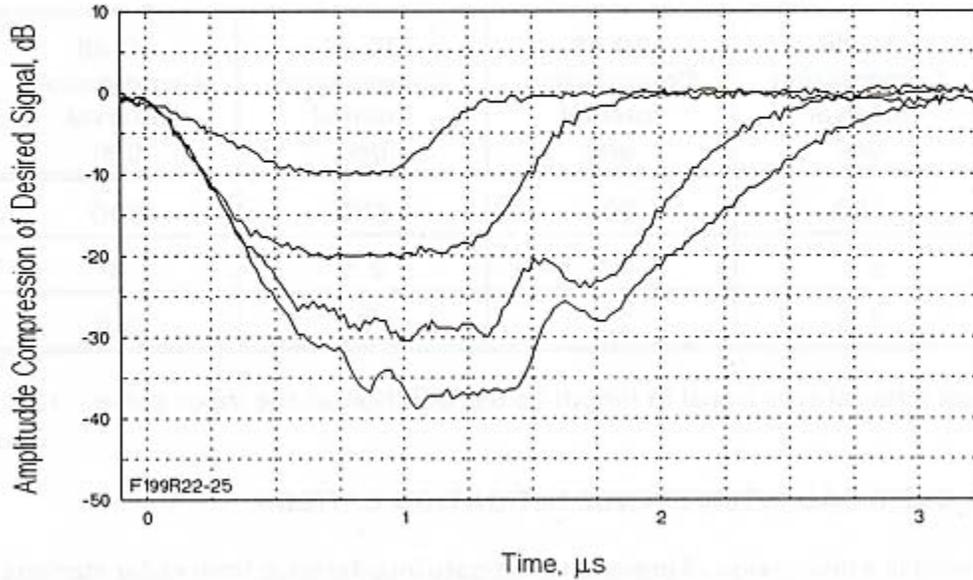


Figure 9. Time domain behavior of LNB #1 at gain compressions of 10, 20, 30 and 40 dB in desired signal at 4000 MHz. Compression created by out-of-band pulses (1- μ s pulse width) at 3500 MHz.

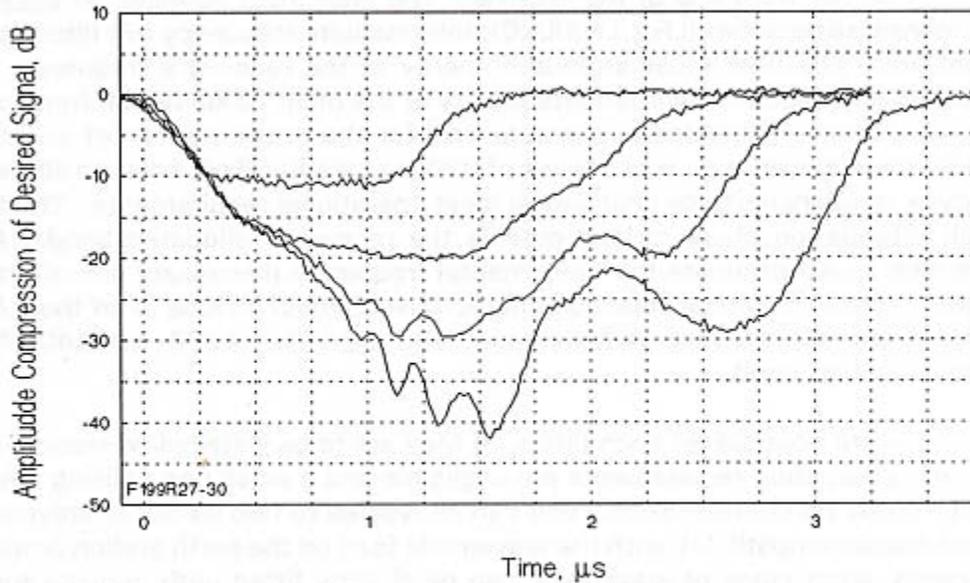


Figure 10. Time domain behavior of LNB #2 at gain compressions of 10, 20, 30 and 40 dB in desired signal at 4000 MHz. Compression created by out-of-band pulses (1- μ s pulse width) at 3500 MHz.

**TABLE 2.
GAIN COMPRESSION INTERVALS OF LNA AND LNB DEVICES**

	10 dB Compression Interval (μ s)	20 dB Compression Interval (μ s)	30 dB Compression Interval (μ s)	40 dB Compression Interval (μ s)
LNA	150	200	650	900
LNB #1	$\leq 1^*$	1.5	2.5	3
LNB #2	1.5	2.5	3	3.5

* The compression interval was equal in length to the duration of the input pulse: 1 μ s.

3.3 FRONT-END OVERLOAD INTERFERENCE MITIGATION OPTIONS

The following is a discussion of options to mitigate interference from radar stations due to emissions at the fundamental frequency (necessary emissions) of the radar causing front-end overload.

RF Filtering

A solution that mitigates interference caused by receiver front-end overload is installation of a filter on the front-end of the receiver. The filter must be installed ahead of the earth station low-noise amplifier (LNA/LNB/LNC); intermediate frequency (IF) filtering will not solve the problem. The filter must attenuate energy at the receiver's frequency to a minimal extent, but must substantially attenuate energy at the radar fundamental frequency. Ideally, the filter would have a bandpass characteristic for the entire portion of spectrum allocated for use by the receiver (e.g., a bandpass of 3700- to 4200-MHz), so as to allow the receiver frequency or frequencies to be changed to meet operational requirements. The filter must have a high attenuation characteristic outside the receiver's allocated band. At a minimum, such a filter must attenuate the fundamental frequency (necessary emissions) of the interfering radar. Ideally, the filter rejection characteristic would include all of the 2700- to 3700-MHz spectrum allocated to radiolocation, and also the 4200- to 4400-MHz aeronautical radionavigation band.

Several designs are possible for such filters. If they are to be installed on receive-only systems, then power dissipation requirements are negligible and a small box utilizing several tuning stubs can be easily fabricated. Such a unit can be welded to two pieces of waveguide to provide for mechanical compatibility with the waveguide feed on the earth station antenna. Alternatively, a single, short piece of waveguide can be directly fitted with in-guide tuning stubs to provide the same capability. Several companies in the United States and Canada supply both of these types of filters. The frequency response curve of one such filter is shown in Figure 11.

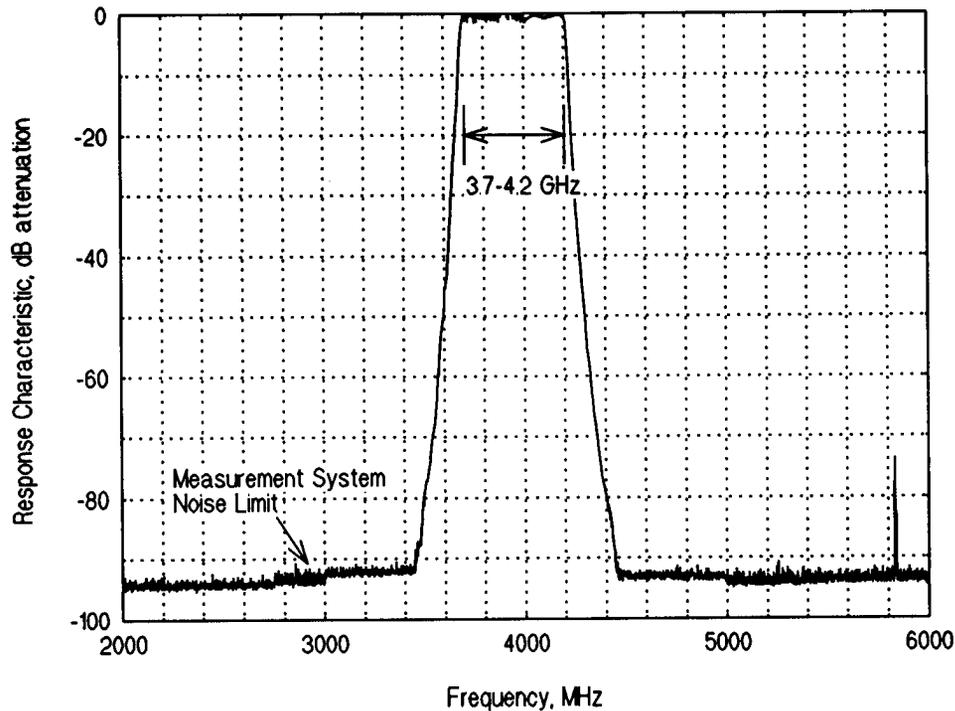


Figure 11. Frequency response curve of a commercially procured 3700-to 4200-MHz bandpass filter of same type as were used to mitigate out-of-band interference to 4-GHz TVRO receivers in south Florida.

The frequency response curve shown in Figure 11 was measured at the NTIA/ITS laboratory in Boulder, CO. The same filter type was used to mitigate interference from the south Florida airborne radar discussed in Section 3.4. The in-band (3700- to 4200-MHz) insertion loss ranges between 0 and 1 dB, and is typically about 0.5 dB. Out-of-band attenuation is approximately 25 dB within 50 MHz of the band edges, and is in excess of 45 dB within 100 MHz of the band edges. Suppression exceeds 90 dB within 300 MHz of the band edges. In cases in which a radar fundamental is so close to the band edge that the roll-off of the filter is not sufficient to prevent front-end overload, the filter can be re-tuned to shift the bandpass roll-off point to higher or lower frequencies.

3.4 FRONT-END OVERLOAD INTERFERENCE CASES

A case of interference to a 4-GHz earth station from a radar was jointly investigated by NTIA and the U.S. Naval Electronics Engineering Activity (NAVELEX), Charleston, SC, in

1992⁴. The earth station was a television receive only (TVRO) site on a hilltop overlooking the ocean in the San Diego, CA area. The interference coupling mechanism was identified as receiver front-end overload, and the problem was mitigated by installation of a front-end bandpass filter on the TVRO.

In response to complaints of interference to many 4-GHz earth stations in southern Florida from an airborne source, the NTIA Radio Spectrum Measurement System⁵ (RSMS) was positioned at two earth station sites during the period of April through June 1993. In April 1993, NTIA identified the source of interference as an airborne radar belonging to the Federal Government. The interfering platform was identified by using the RSMS to obtain the radar characteristics (center frequency, antenna rotation rate, pulse repetition rate, pulse width, and antenna pattern); the Federal Aviation Administration confirmed the identification of the platform. NTIA identified the interference coupling mechanism as receiver front-end overload⁶.

NTIA has also assisted in the resolution of other complaints of interference associated with this type of airborne radar platform. In all cases, the interference coupling mechanism has been identified as receiver front-end overload, and the insertion of an RF bandpass filter ahead of the LNA/LNB/LNC has mitigated the interference.^{7,8}

It is also known that non-Government marine surface search radars operating at 3050 MHz cause front-end overload in 4-GHz receive systems that are near marine waterways. Characteristics of such activity were documented by NTIA RSMS measurements at Norfolk, VA.⁹ Some manufacturers of 3700- to 4200-MHz bandpass filters primarily advertise these devices as being useful for elimination of this interference.

⁴ J.A. Lucas and B.J. Ramsey, "Daniel's CableVision Satellite Receiver Earth Station Interference Study," July 1990, E3 Task Number E90135-C093.

⁵ See Section 5, Identification of the Radar, and Appendix A.

⁶ F.H. Sanders and R.L. Hinkle, "Interference Resolution Report on Station WGUF Naples, Florida," letter report for NTIA, dated April 7, 1993, and F.H. Sanders and R.L. Hinkle, "Interference Resolution Report on Colony Cablevision of Florida," letter report for NTIA, dated July 6, 1993.

⁷ R.L. Hinkle and G. Hurt, "Interference Resolution Report on Time Warner Cable," letter report for NTIA, dated June 22, 1993.

⁸ Memo from William D. Gamble to Arlan K. van Doorn, "South Florida Radar Interference," dated October 5, 1993.

⁹ J.D. Smilley and F.H. Sanders, data and summary of RSMS "Norfolk, VA February 1988 Measurements Notebook. "

3.5 SUMMARY REMARKS ON RECEIVER FRONT-END OVERLOAD

Front-end overload is a phenomenon which occurs when a low-noise, high-gain preamplifier is located at the front-end of a radio receiver system and is subjected to a strong signal from an external source, as given by Equation 4. In this condition, the amplifier will not only gain-compress at the frequency of the overloading signal, but also at all other frequencies in the amplifier's gain response band. Thus, desired signals will be lost at frequencies which may be hundreds or even thousands of megahertz away from the frequency of the signal which is causing overload to occur. The majority of cases of interference to 4-GHz satellite earth stations that have been investigated by NTIA have been found to be due to the phenomenon of front-end overload.

It is important to note three aspects of receiver front-end overload interference which are not always appreciated. First, the filtering provided in a receiver IF stage is irrelevant to the problem of receiver front-end overload. The overload and loss of desired signal occur before the IF stage is reached.

Second, earth station front-end amplifiers may have a significantly wider frequency response range than is indicated by the manufacturer's specifications. Although an amplifier is specified for a given band by the information on its package case (e.g., "3.7-4.2 GHz"), this does not mean that it does not respond to (or filters out) signals outside that range. Quite to the contrary, it is highly likely, especially with current gallium-arsenide field-effect transistor (GaAsFET) technology, that the actual frequency response range of such amplifiers will typically be several gigahertz wide (e.g., 2800-4800 MHz). The actual response of an amplifier can be assessed by connecting the amplifier output to the input of a spectrum analyzer, and observing the frequency range over which the amplifier compensates for the spectrum analyzer noise (that is, the frequency range over which the amplifier excess noise is observed above the analyzer noise floor).

Third, in the presence of an overloading signal outside the 4-GHz band, undesired products may be generated in front-end amplifiers which incorporate mixer/downconverter stage(s) (i.e., LNB/LNC devices); such products may occur anywhere in the frequency response range of the amplifier, including the 3700- to 4200-MHz spectral range used by 4-GHz earth stations. If such products happen to occur at the same frequency or frequencies as desired signals, then interference with earth station operations could result. Also, if a spectrum analyzer is used to observe the spectrum through the earth station receiver, the products which occur in the 4-GHz band may easily be mistakenly identified as spurious radar emissions in this band. Thus, the observed presence of apparent interfering signals in the 3700- to 4200-MHz band does not necessarily mean that such signals are originating from an external source, such as a radar. (See Section 5 for methods of determining the difference between radar spurious emissions in the 4-GHz band and mixing products generated by the front-end LNB/LNC in that band.)

3.6 INTERFERENCE DUE TO RADAR SPURIOUS EMISSIONS IN THE 4-GHz BAND

Radar spurious emission coupling occurs when energy from the radar transmitter spurious emissions in the 3700- to 4200-MHz band causes degradation in the earth station receiver system performance. The predominant factor that governs the level of spurious emissions from radars is the transmitter output device¹⁰ (also referred to as an output tube).

It is important to know the inherent spurious emission levels and variances for the different types of transmitter output tubes in order to assess the potential for interference from radars utilizing these tubes. This information is important in identifying microwave radar tube types that promote efficient use of the spectrum and as a parameter in interference resolution prediction.

Microwave radar tubes inherently generate spurious emission noise that generally dominates spectral emissions at frequency separations greater than 50 MHz from the radar fundamental frequency. (Such emissions are often referred to as "transmitter noise.") Thus, at frequency separations of greater than 50 MHz, the radar emission spectrum is independent of radar system characteristics such as the pulse modulation parameters (e.g., pulse width, pulse modulation, and pulse rise/fall times). Based on measurements contained in studies conducted by NTIA¹¹ and a review of tube characteristics with major microwave radar tube manufacturers, the inherent spurious emission level for the various types of microwave tubes used in radars are shown in Table 3.

Additional attenuation of spurious emission levels can be achieved through the use of RF bandpass filters inserted in the radar after the output device. With the use of RF bandpass filters, the spurious emission levels of crossed-field amplifiers (CFAS), magnetrons, and coaxial magnetrons can be reduced below -100 dBc. Examples of such output filtering and the effect on a radar's emission spectrum are shown in Figures 12-13. However, in cases where radars use phased array antennas, RF waveguide filters cannot be installed.

Measurements conducted by NTIA (see footnotes 10 and 11) have shown that radars using magnetrons, coaxial magnetrons, and klystrons comply with the spurious emission limits imposed by the RSEC (see Section 2). Although it is not possible to make the power levels of spurious emissions in the 4-GHz band arbitrarily low, some limits, such as those defined by the RSEC, can reasonably be achieved. Measurable emissions may still occur in the 4-GHz band even when a radar meets the RSEC. These emissions may interfere with 4-GHz satellite earth stations by decreasing the carrier-to-interference (C/I) ratio to an unacceptably low level if the radar main beam aims at the earth station. Some examples of radar spurious emissions in the 4-GHz band are shown in Figures 13 through 15.

10 R.J. Matheson, J.D. Smalley, G.D. Falcon and V.S. Lawrence, "Output Tube Emission Characteristics of Operational Radars," NTIA Report 82-92, January 1982.

11 R.L. Hinkle, "Background Study on Efficient Use of the 2700-2900 MHz Band," NTIA Report 83-117, August 1983, NTIS # PB83-214288.

**TABLE 3.
RADAR OUTPUT DEVICE INHERENT SPURIOUS EMISSION LEVELS***

TUBE TYPE	SPURIOUS EMISSION LEVEL RELATIVE TO THE CARRIER MEASURED IN A 1 MHz REFERENCE BANDWIDTH (dBc)
CROSSED-FIELD DEVICES:	
Crossed-Field Amplifiers (CFAs)	-40 to -70
Magnetrons (unlocked)	-65 to -80
Magnetrons (locked)	-75 to -90
Coaxial Magnetrons	-60 to -75
LINEAR-BEAM DEVICES:	
Coupled-Cavity TWTs	-105 to -115
Klystrons	-110 to -120

“ As contained in Radiocommunications Bureau Report 914-2, “Efficient Use of the Radio Spectrum by Radar Stations in the Radiodetermination Service, ” International Radio Consultative Committee (CCIR) XVIIth Plenary Assembly, Dusseldorf, 1990.

3.7 RADAR SPURIOUS EMISSIONS INTERFERENCE MITIGATION OPTIONS

The following is a discussion of options to mitigate interference from radar stations due to radar transmitter spurious emissions in the 3700- to 4200-MHz band.

Radar Station RF Filtering

RF waveguide filters can be used in some radars stations to reduce interference to earth stations to acceptable levels. Measurements have shown (see Figures 12 and 13) that RF waveguide filters will suppress radar spurious emissions in the 4-GHz band by at least 40 to 50 dB. In Figure 12, note that the filter is characterized by attenuation in excess of 80 dB at frequencies immediately above the upper cutoff at 3700 MHz, but that this attenuation decreases to as little as 15 dB at frequencies above 4300 MHz. This demonstrates that, while filter installation on a radar station may reduce the potential for interference in one band, it may not provide a solution for other bands even farther removed in the spectrum.

When radar interference to 4-GHz earth stations is caused by spurious emissions from the radar transmitter, the installation of an RF filter for the appropriate band at the radar transmitter is considered a practicable solution provided that it is technically and/or economic-

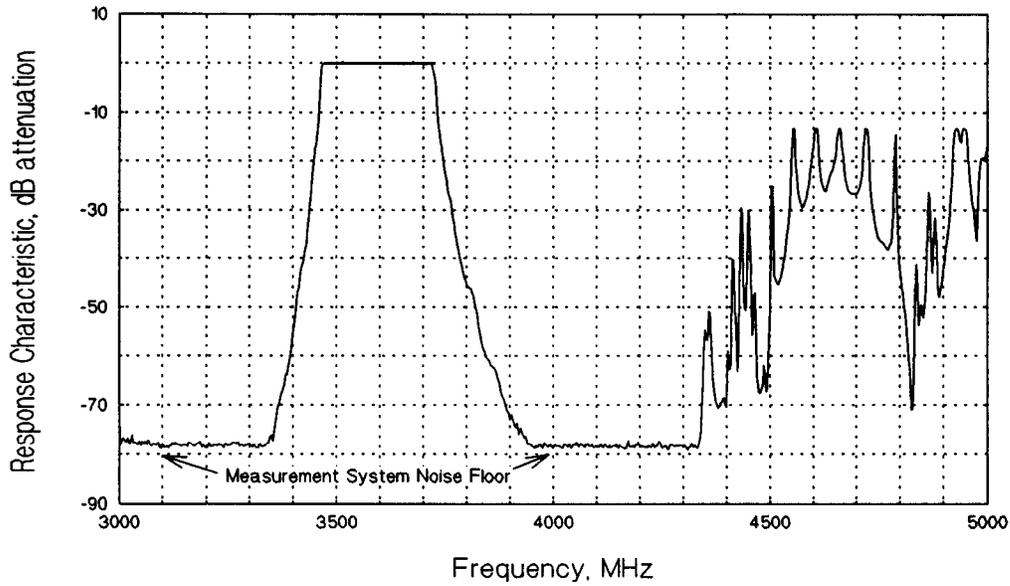


Figure 12. Measured frequency response curve of a bandpass filter installed on naval radar (Figure 13) to suppress spurious emissions and enhance electromagnetic compatibility with 4-GHz receivers.

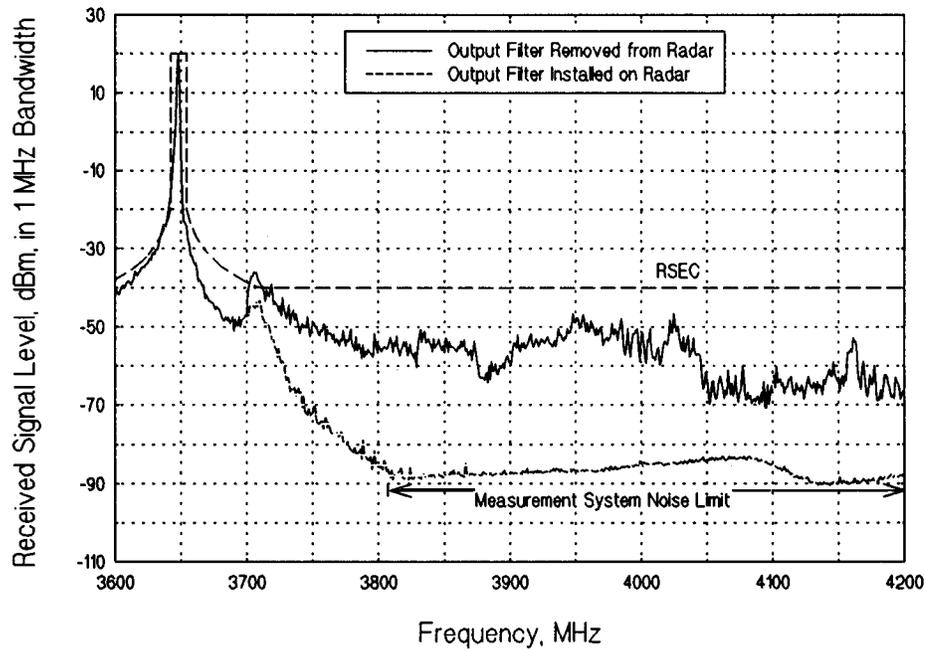


Figure 13. Spectrum of a naval radar showing effect on spectrum when bandpass filter is installed on radar output. Filtered radar output caused front-end overload interference to a TVRO at San Diego, CA.

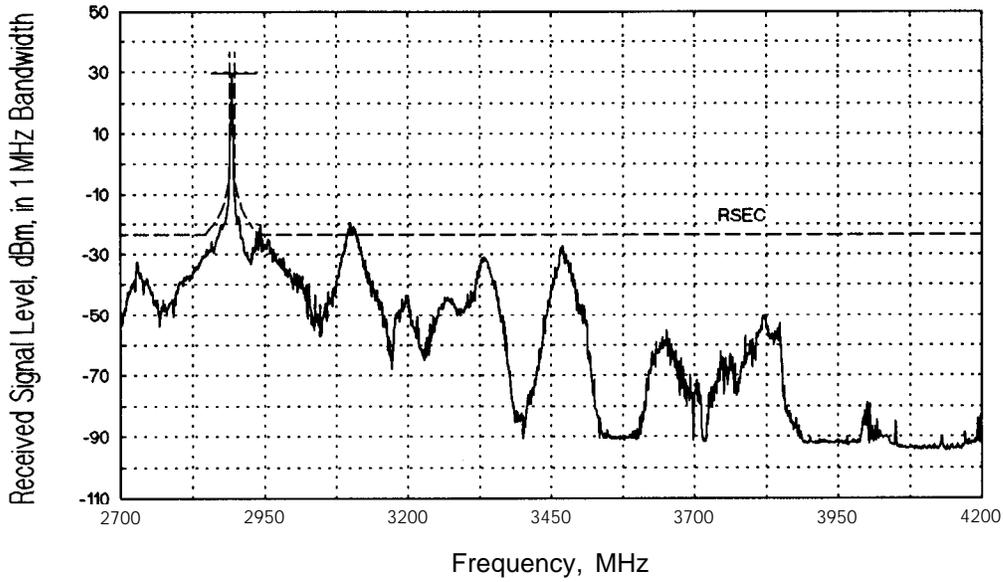


Figure 14. Spectrum of a WSR-74S weather radar, showing spurious emissions in the 3700- to 4200-MHz range. The spurious emissions from this radar caused interference to a 4-GHz terrestrial radio link.

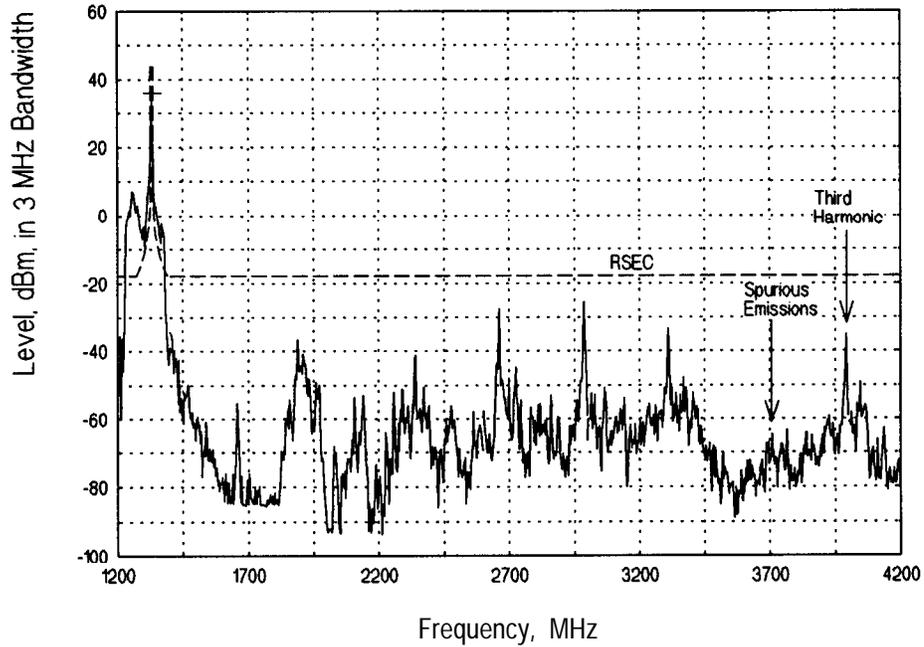


Figure 15. Emission spectrum of a long-range air search radar. Both spurious emissions and third harmonic occur in the 4-GHz band. Third harmonic produced interference to a terrestrial 4-GHz link.

ally possible. The policy and responsibility for dealing with the purchase and installation of an RF filter for a specific radar transmitter are discussed in Section 2 of this report.

3.8 EARTH STATION MITIGATION OPTIONS

Antenna Selection

Antenna discrimination, the response of an antenna to signals arriving from various azimuths, varies widely among antenna types. In some situations, it may be possible to take advantage of those characteristics to reduce the response of a system to interference arriving from a particular direction. Currently, the vast majority of earth stations use standard parabolic antennas with prime focus feeds. Other types of antennas used which have lower sidelobe levels include those incorporating cassegrain reflectors, offset-fed reflectors and horn reflectors. Antenna manufacturers have stated that shrouded parabolic antennas used for radio-relay systems can also be used in 4-GHz earth stations. Each type has a different response to off-axis signals; typical patterns for these general types of antennas are shown in Figure 16. At off-axis angles in excess of 10 degrees, shrouded parabolic and conical horn reflector antennas can provide 10 to 20 dB of additional suppression of an interfering signal and 20 to 50 dB of suppression for off-axis angles greater than 50 degrees.

Site Selection

Site selection can be used during the design phase of new earth stations to avoid potential interference exposures to operational radar stations. There are many factors that determine the site selection of earth stations. When possible, one of the factors should be the electromagnetic environment. For site selection to be successful as an interference mitigation option, knowledge of the location of radar stations is necessary. It should be recognized, however, that additional constraints on site selection may significantly impact the economics of the earth station construction. The key to mitigation of radar interference in selection of a site is electromagnetic shielding by surrounding terrain.

3.9 SPURIOUS EMISSION INTERFERENCE CASES

NTIA has not investigated any cases in which a 4-GHz satellite earth station has experienced interference due to radar transmitter spurious emissions in the 4-GHz band. Some such cases have been documented by NAVELEX Charleston, however. In one case, spurious emissions from a shore-based, long-range naval search radar located on Crown Mountain, St. Thomas, USVI, caused interference to two 4-GHz commercial earth stations on that island.¹² One was an analog TVRO, and the other was a digital telephone satellite earth station. In another set of cases, spurious emissions from high-power radars on ships have caused interference at earth stations located at sites that overlook the ocean.

12 J.A. Lucas, "Radar Interference Due to Receive System Susceptibility and Spurious Emissions," presentation to the Federal Communications Commission, Naval Electronic Systems Engineering Center (NAVELEX), Code 222, Charleston, SC, July 14, 1992.

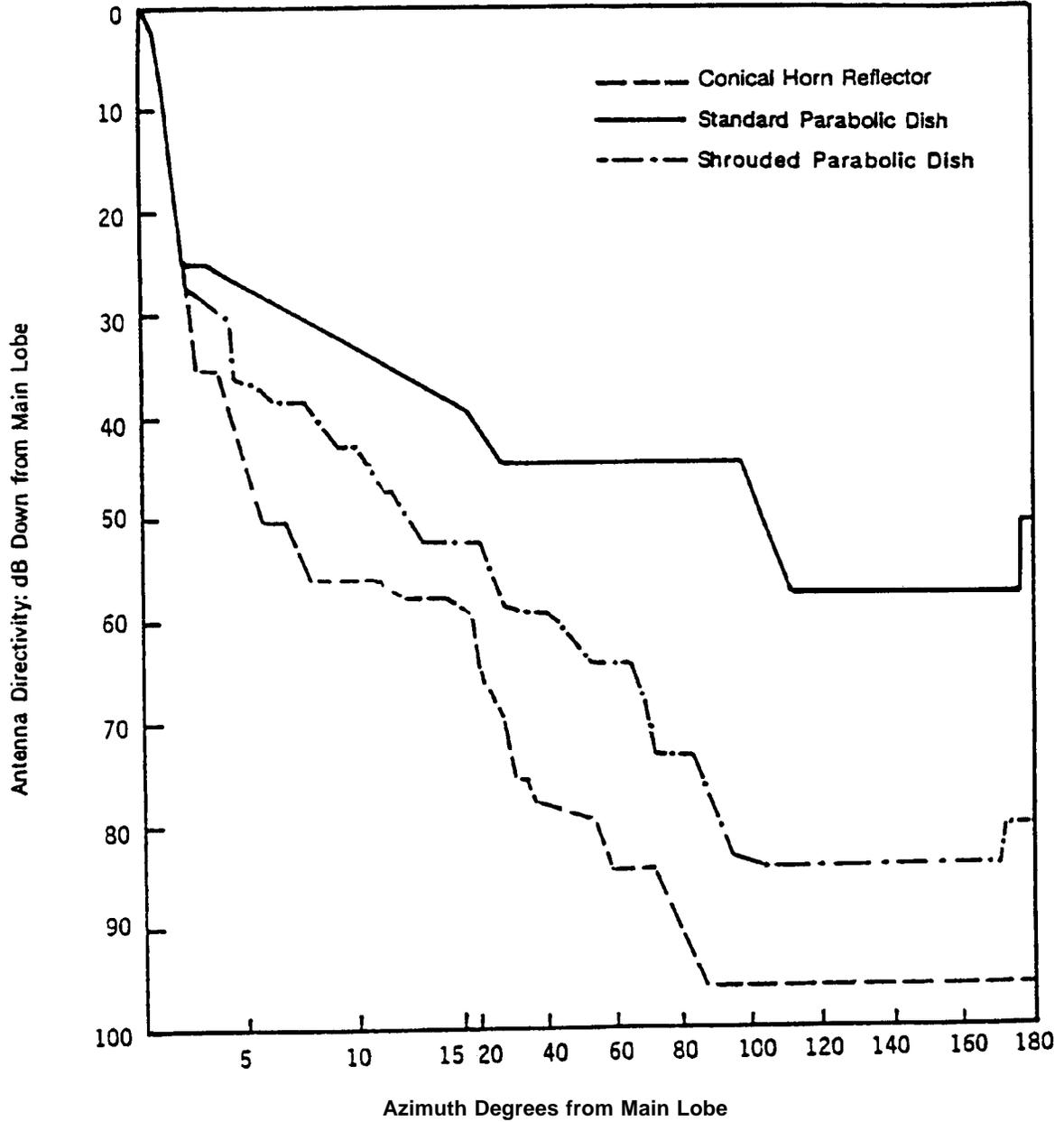


Figure 16. Comparison of directivities for three high-gain antenna types. Shrouded parabolas and conical horns can exhibit higher directivities than ordinary parabolic. Note scale change at 15 degrees.

There have been no substantiated cases of airborne radars causing interference due to spurious emissions in the 3700- to 4200-MHz band. All high-power airborne radars in the 2700- to 3700-MHz band use linear beam output devices which have spurious emissions down at least 100 dB from the fundamental.

SECTION 4 ELECTROMAGNETIC COMPATIBILITY ANALYSIS

4.1 INTRODUCTION

This section contains analysis procedures for determining the separation distances between radar stations and earth stations necessary to mitigate interference due to receiver front-end overload and radar transmitter spurious emissions. The separation distances are based on radar station and earth station characteristics associated with regulatory standards contained in Section 2 and 3. Since nominal radar and earth station system characteristics and typical antenna heights are used in these calculations, the separation distance calculations presented in this section are to assess the potential for interference and to provide an estimate of when a detailed electromagnetic compatibility (EMC) analysis may be required.

A smooth-earth propagation model, NLAMDA¹³ ($N\lambda$), was used to calculate the required separation distances presented in this section. For detailed EMC analyses, a propagation model that takes into consideration the terrain (such as TIREM¹⁴) between the radar station and earth station should be used in determining the propagation loss. Also, building attenuation, foliage attenuation, and ducting should be considered in determining the propagation loss.

In addition when performing a detailed EMC analysis, it is also necessary to perform an analysis for indirect path coupling (multiple path scattering). When the direct path between a transmitter and a receiver contains propagation obstacles, multiple path scattering caused by terrain or building reflections can result in significantly less propagation loss than along the direct path. Such multiple path propagation can also cause an apparent stretching of radar pulses. The effect of such stretching is to increase the time interval of the interference, thus increasing the potential degradation to an earth station.

4.2 RADAR STATION CHARACTERISTICS

The following are nominal characteristics of radar stations operating in the 2700- to 3700-MHz bands. These characteristics are identified for the purpose of EMC analysis.

Peak Transmit Power (P_T)	=	0.86 to 4.0 MW (+89 to +96 dBm), nominal +90 dBm
Main Beam Gain (G_T)	=	30 to 34 dBi, nominal 32 dBi
Pulse Width	=	1 to 60 μ s
Pulse Repetition Rate	=	100 to 27,000 pps
Duty Cycle	=	0.1 to 6 percent

¹³M.A. Maiuzzo and W.E. Frazier, "A Theoretical Groundwave Propagation Model - $N\lambda$ Model," DOD Electromagnetic Compatibility Analysis Center (ECAC), December 1968.

¹⁴G. Benoit, "Terrain-Integrated Rough-Earth Model (TIREM) Handbook, ECAC-HDBK-86-076, DOD Electromagnetic Compatibility Analysis Center, September 1986.

4.3 EARTH STATION CHARACTERISTICS

Table 4 summarizes the nominal characteristics of earth stations in the 4-GHz band associated with TVRO and audio receive only (ARO) terminals. Currently there is a mix of analog and digital earth station systems in the 4-GHz band with a majority of the TVRO earth stations using analog frequency modulation (FM). However, there is a trend toward use of digital modulations. The susceptibility of these digital modulations to pulsed emissions is a function of the order of digital modulation used (i.e., BPSK, QPSK, etc.). Manufacturers of 4-GHz earth stations have indicated that digital modulation systems are more susceptible to interference than analog systems.

TABLE 4.
CHARACTERISTICS OF 4-GHz EARTH STATION RECEIVER SYSTEMS

	Analog Television Receive-Only (TVRO) Systems	Digital Television Receive-Only (TVRO) Systems	Digital Audio Receiver Terminals (DART)
Modulation	FM	QPSK	BPSK
Receive Frequency, MHz	3700-4200	3700-4200	3700-4200
Antenna Main Beam Gain, dBi	40 to 44 @ 4.0 GHz, nominal 42	40 to 44 @ 4.0 GHz, nominal 42	40 to 44 @ 4.0 GHz, nominal 42
Antenna Output Level, dBm	-105 to -95, nominal -100	-105 to -95, nominal -100	-105 to -95, nominal -100
Receiver Input Frequency, MHz	270 to 770 (LNC) 950 to 1450 (LNB)	950-1450 (LNB)	270
Number of Channels	24*	24*	20 @ 384 kbps****
Receiver Input Level, dBm	-70 to -30	-65 to -25	-65 to -45
IF Bandwidth, MHz	30**	15 to 31***	20
Maximum Receiver Noise Figure, dB	12	12	12
Maximum Bit Error Rate (BER)	N/A	10 ⁻⁶	10 ⁻³
Error Correction	N/A	Yes	Yes, 7/8 code rate
Minimum Carrier-to-Noise Ratio (C/N), dB	N/A	7.5	6
Protection Ratio (C/I), dB	10	12	12

- * 12 channels on vertical feed and 12 channels on horizontal feed
- ** Adjacent channel rejection achieved by polarization discrimination
- *** Depending upon receiver mode
- **** Time-division multiplexed (TDM)

4.4 RECEIVER FRONT-END OVERLOAD INTERFERENCE

Due to the high power levels required to cause receiver front-end overload in a 4-GHz earth station, it is likely that radar interference will occur only when the main beam of a radar is directed at the earth station site. Also, based on the results of NTIA front-end recovery tests (Figures 8 through 10), gain compression will occur in coincidence with each pulse in the radar main beam, with a finite recovery time that varies with the amount of gain compression and type of LNA/LNB amplifier. As shown in Figures 8 through 10, the gain compression from each pulse may last as little as about 1 μ s (the pulse width of the radar) or may approach the entire interval between pulses (see the 40-dB gain compression curve in Figure 8). In summary, the effects of earth station front-end overload interference will be a function of the degree of gain compression and the radar pulse repetition rate.

As a radar antenna main beam scans across an earth station, approximately 20 pulses will typically be directed at that station. The operational characteristics of 2700- to 3700-MHz radars are such that each pulse will be about 1-60 μ s long, and the spacing between pulses will usually be about 1-3 ms, although much shorter intervals, on the order of tens of microseconds, are possible for some radars. If the radar main beam is utilized in a mechanically scanned rotation, then it will sweep across the earth station site at very precise and regular intervals of typically 5-15 s. (Some radars scan electronically in elevation while rotating mechanically, and thus the interval for such radars may appear slightly irregular.) If the radar utilizes a phased array antenna, then the main beam will still probably be directed at the earth station every few seconds, but the exact interval between visitations will be irregular.

For analog TVRO systems, these interference bursts may be observed on a television screen as a pattern of black or white spots. For earth stations using digital systems (television or audio), the performance degradation will be manifested as an increase in bit error rate (BER) for slight gain compression, to loss of sync (out-of-frame) for severe (long recovery time) gain compression. Because of the potential for loss of sync, the potential performance degradation of digital systems may be more catastrophic than for analog systems, thus increasing the susceptibility of digital systems to pulse-type emissions and reported interference cases.

4.5 SEPARATION DISTANCE REQUIRED TO PRECLUDE OVERLOAD INTERFERENCE

The following is a discussion of the procedure to determine separation distance between radar stations and earth stations to ensure compatibility for receiver front-end overload coupling. To determine the separation distance it is necessary to calculate the propagation loss required to preclude interference to an earth station receiver system. For direct path coupling, the required propagation loss is given by

$$L_p = P_T + G_T + G_R(O) - L_T - L_R - I_{MAX} \quad (5)$$

Where:

L_p	=	Median propagation path loss between the transmitting and receiving antennas, in dB.
P_T	=	Peak transmitted power of radar station, nominal +90 dBm.
G_T	=	Radar station main beam antenna gain, nominal +32 dBi.
$G_R(\Theta)$	=	Earth station antenna gain in the direction of the radar station, nominal $32 - 25 \log_{10}(\Theta)$ dBi for $1^\circ \leq \Theta \leq 48^\circ$ and -10 dBi for $48^\circ < \Theta \leq 180^\circ$ (CFR Title 47, § 25.209).
L_T	=	Insertion loss in the radar station transmitter, in dB (assumed 2 dB).
L_R	=	Insertion loss in the earth station receiver system, in dB (assumed 0 dB)
I_{MAX}	=	Maximum radar signal level at the antenna output which precludes receiver front-end overload (See Equation 4), nominal -50 to -40 dBm.

When the required propagation loss is determined, an appropriate propagation model must be applied to determine the nominal separation distance between radar stations and earth stations at which it may be necessary to perform a detailed analysis. For this analysis, the NLAMDA (Nλ) propagation model was used to estimate the distance for the required basic transmission loss.

The required separation distance between a radar station and earth station to preclude interference due to receiver front-end overload for an airborne radar platform and a surface radar station is shown in Figure 17. The separation distance is shown as a function of off-axis angle of the earth station antenna. The altitude, H_a , of the airborne radar was set at 10,000 m, and the antenna height used for the surface radar was 25 m. The earth station antenna height, H_e , was set at 4 m. The separation distance to preclude receiver front-end overload from airborne radars is several hundred kilometers even at off-axis angles greater than 10 degrees. For surface radars, front-end overload interference may occur at ranges of 60 km for a few degrees off-axis to less than 40 km for off-axis angles greater than 30 degrees. Note that, with RF filter installation ahead of the LNA as described in Sections 3.3 and 3.5, the separation distance required to preclude front-end overload would become negligible.

4.6 RADAR TRANSMITTER SPURIOUS EMISSIONS INTERFERENCE

Due to the relative level of radar spurious emissions to the radar fundamental emissions, it is likely that radar interference due to spurious emissions will occur only when the main beam of a radar is directed at the earth station site. As previously discussed, approximately 20 pulses will typically be directed at the earth station as the radar antenna main beam scans across the earth station. To determine the effect of this pulse train

associated with spurious emissions from radar stations on earth station receiver system performance, it is necessary to characterize the pulse time waveform responses in the receiver IF passband.

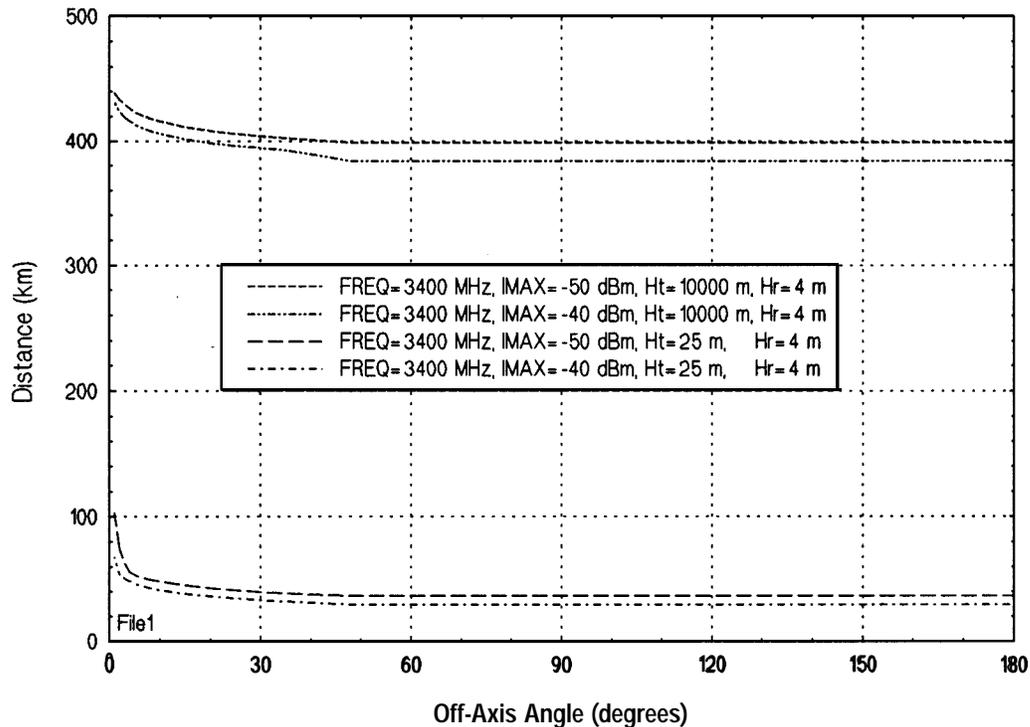


Figure 17. Separation distances required to preclude earth station front-end overload by radar fundamental, as a function of I_{\max} and antenna height. See text for station parameters.

Figures 18-19 show pulse time waveform measurements at the radar fundamental frequency (reference pulse width) as well as at other frequencies in the 4-GHz band. These measurements were made with the RSMS front-end (RF preselector through IF output) and a digital oscilloscope. The time waveforms indicate that the radar spurious emissions in the 4-GHz band produce two types of time waveform response at the receiver IF output:

- 1) spurious emissions produced from the pulse modulation leading edge and trailing edge
- 2) spurious emissions produced by the radar output device inherent noise during the pulse interval.

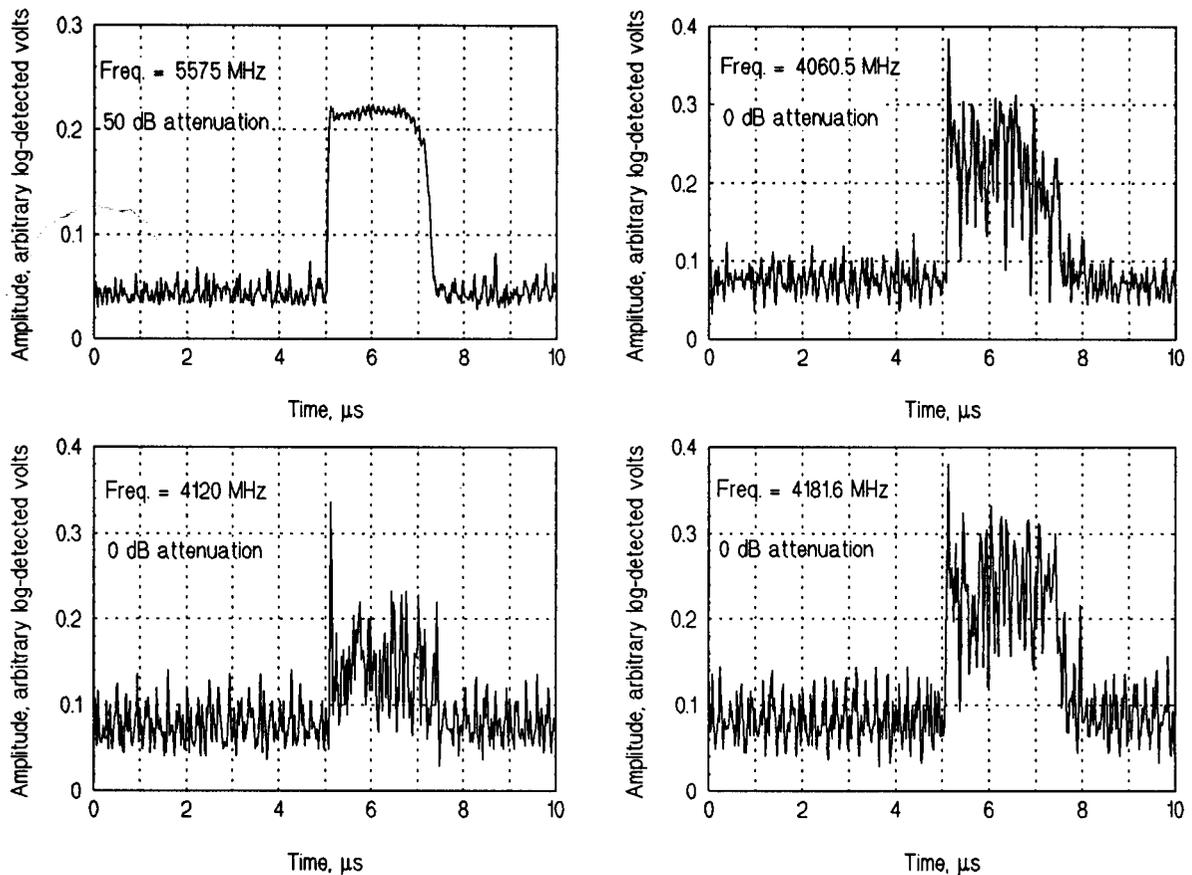


Figure 18. Time waveforms of a weather radar at center frequency (5575 MHz) and at three frequencies in the 3700- to 4200-MHz band. Radiated measurement in 3-MHz bandwidth.

Effects of Radar Spurious Emissions

The spurious emissions occurring during the leading and trailing edges of the pulses are broadband in nature, thus producing an impulse response in the earth station receiver IF output. The amplitudes of the leading and trailing edge impulse responses are not always equal, and some received pulses may lack a leading or trailing edge altogether. Because the actual widths of the leading and trailing edge features are often only a few nanoseconds, the apparent widths of these impulse responses in the receiver are a function of the reciprocal of the receiver IF bandwidth (that is, they are bandwidth-limited in the receiver). Therefore, leading and trailing edge impulse responses will appear to be approximately 30 to 50 ns for nominal IF bandwidths used by 4-GHz earth stations. Thus, the leading and trailing edge impulse responses appear as short pulses approximately equal to a baud interval of a digital system. The effect of these receiver impulses on digital systems is to cause background or residual error rates.

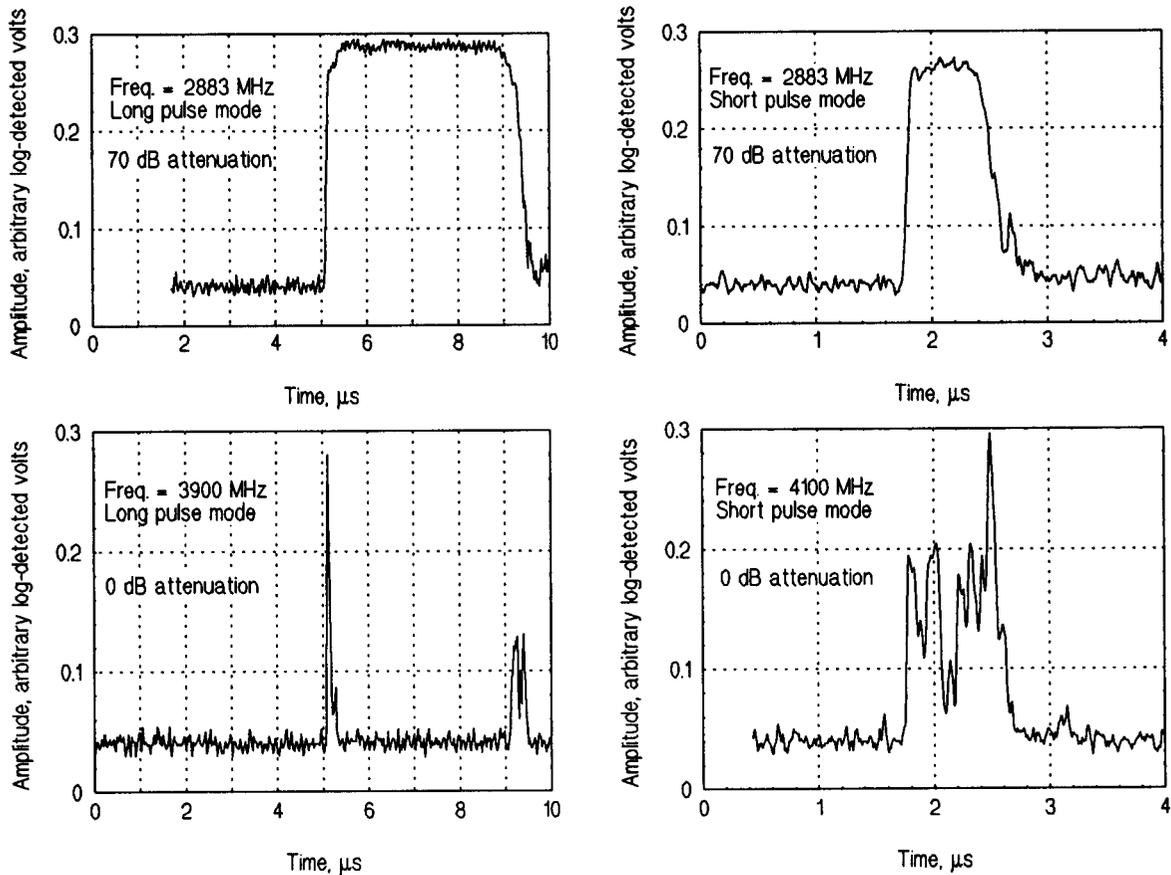


Figure 19. Time waveforms of radar in two pulse modes (long and short) at center frequency (2883 MHz), and at two frequencies in the 3700- to 4200-MHz band. Radiated measurement in 3-MHz bandwidth.

Radar spurious emissions occurring between the leading and trailing edges of the pulses will appear at the receiver IF output as non-coherent noise. The duration of such noise in a pulse may be equal to or shorter than the nominal pulse width. If the noise pulses are approximately equal in length to the nominal radar pulse width (which may be at least several microseconds), and are at amplitudes that exceed the earth station C/I protection ratio, then error rates momentarily above the earth station maximum bit error rate (BER) may occur. Also, when the full noise pulse duration exceeds the required protection ratio, the noise may defeat the receiver error correction function and result in a block of errors for each incoming pulse.

If the radar spurious emissions produce pulses at the receiver if output for several framing pulses in digital systems, system out-of-frame condition will occur. The reframe interval may last for tens of milliseconds and will inevitably cause a severely errored second. Error correction provides no advantage when out-of-frame condition occurs. Generally, for

radar spurious emissions to cause out-of-frame in digital systems, multipath scattering (pulse stretching) must occur, so as to stretch the received pulse length to exceed several framing intervals.

4.7 SEPARATION DISTANCE REQUIRED TO PRECLUDE SPURIOUS EMISSIONS INTERFERENCE

As mentioned earlier, the level of radar spurious emissions is a function of the type of radar transmitter output device (see Table 3). The first step in assessing the potential for interference due to radar spurious emissions should be to identify the type of output device used in the radar of concern. The separation distances presented in this section are only applicable to radars using magnetrons or coaxial magnetron output devices.

The following is a discussion of the procedure to determine the separation distance between radar stations and earth stations to ensure compatible operation of the radar and earth station systems. To determine the distance from a radar station at which it may be necessary to perform such an analysis, it is necessary to determine the required propagation loss that will ensure compatibility. For direct path coupling, the required propagation loss is given by

$$L_p = (C/I) - C + P_T + G_T + G_R - L_T - L_R - FDR \quad (6)$$

Where:

- L_p = Median propagation path loss between the transmitting and receiving antennas, in dB.
- C/I = Carrier-to-interference ratio at the predetector input (IF output) necessary to maintain acceptable performance criteria, nominal + 12 dB.
- C = Received carrier level at earth station antenna output, nominal -100 dBm.
- P_T = Peak transmitted power of interfering radar station, nominal + 90 dBm.
- G_T = Interfering radar station main beam antenna gain, nominal + 32 dBi.
- $G_R(\theta)$ = Earth station antenna gain in the direction of the interfering radar station, nominal $32 - 25 \log_{10}(\theta)$ dBi for $1^\circ \leq \theta \leq 48^\circ$ and -10 dBi for $48^\circ < \theta \leq 180^\circ$ (CFR Title 47, § 25.209).
- L_T = Insertion loss in the radar station transmitter, in dB (assumed 2 dB).
- L_R = Insertion loss in the earth station receiver system, in dB (assumed 0 dB).

- FDR =** Frequency-dependent rejection of spurious emissions between the radar transmitter and the earth station receiver system, in dBc. Nominal +60 to +80 dB -10 log(BWIF(MHz)/(1 MHz)). (60 to 80 dBc represents worst-case RSEC and nominal magnetron/coaxial magnetron spurious emission levels in a 1-MHz bandwidth; see Table 3.)
- BWIF =** Earth station receiver intermediate frequency (IF) bandwidth, nominal 30 MHz.

After the required propagation loss was determined, the NLAMDA propagation model was applied to determine the nominal separation distance between radar stations and earth stations at which radar transmitter spurious emission interference would be precluded. At separations less than that distance, it may be necessary to perform a detailed analysis.

The required separation distances between a radar station and an earth station to preclude interference due to radar transmitter spurious emissions for surface radar stations are shown in Figure 20. The separation distance is shown as a function of off-axis angle of the earth station antenna. The radar antenna heights, H_r , used were 25 m and 9 m. (There have been no substantiated cases of radar spurious emission interference from airborne radars to 4-GHz earth stations; therefore, an antenna height of 10,000 m was not used.) The earth station antenna height, H_e , was set at 4 m. The separation distance required to preclude radar transmitter spurious emission interference ranges from several hundred kilometers at off-axis angles of less than 5 degrees to less than 50 km for off-axis angles greater than 30 degrees.

4.8 SUMMARY OF ELECTROMAGNETIC COMPATIBILITY ANALYSIS

In summary, there are many radar station, earth station, and environmental factors that influence the effects of pulsed radar emissions on earth station receiver system performance and the resulting separation distance required to preclude interference. The analytical determination of these effects is very complex. Because of this complexity, every effort should be made to ensure compatibility. Methods of mitigating interference between radars and earth stations are discussed in Section 3. The EMC analysis showed that interference from radar stations to 4-GHz earth stations can occur even if all current Federal standards for radars and earth stations are satisfied.

The separation distance to preclude front-end overload from airborne radars is several hundred kilometers even at off-axis angles greater than 10 degrees. For surface radars, front-end overload interference may occur at ranges of 60 km for a few degrees off-axis to less than 40 km for off-axis angles greater than 30 degrees. The separation distance required to preclude radar transmitter spurious emission interference ranges from several hundred kilometers at off-axis angles of less than 5 degrees to less than 50 km for off-axis angles greater than 30 degrees.

Although most radar types can accept the installation of an output filter to reduce spurious emissions, some radar systems utilize distributed, phased-array transmitters and thus cannot be effectively output filtered. Therefore, the required spurious emission attenuation

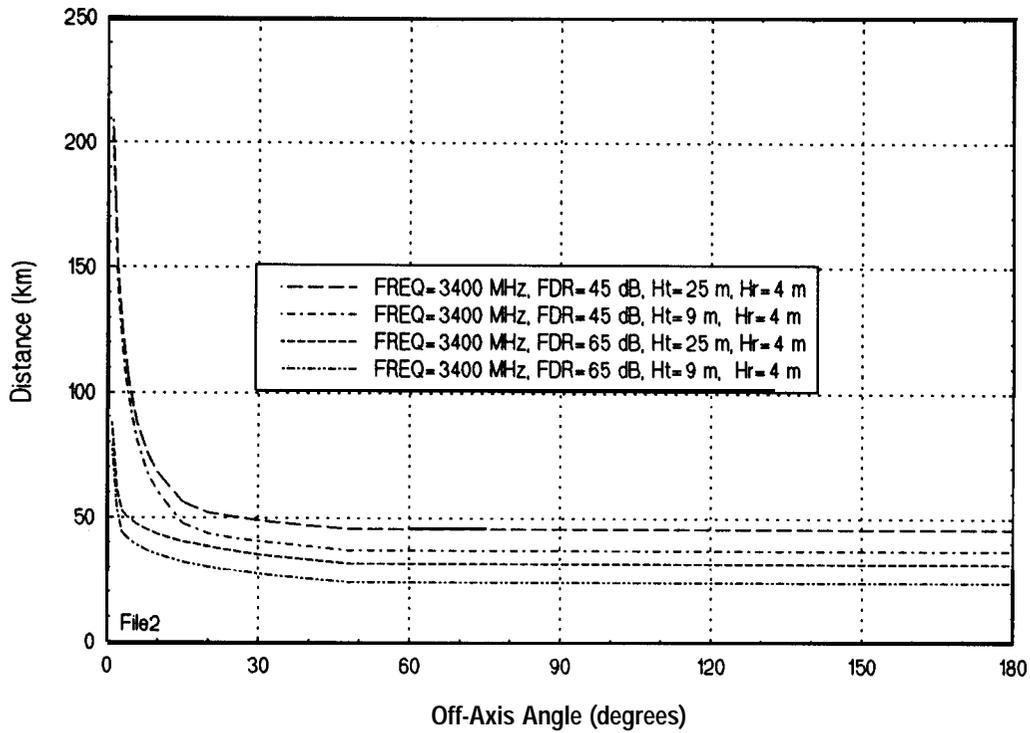


Figure 20. Separation distance required to preclude earth station interference by radar spurious emissions, as a function of FDR and antenna height. Nominal station parameters used (see text).

must be provided by one or more of these mitigation measures: improved earth station sidelobe suppression levels, or improved earth station antenna site selection.

SECTION 5 DETERMINATION OF COUPLING MECHANISM

5.1 INTRODUCTION

With reference to Section 4, interference mitigation measures will be ineffective unless the correct interference coupling mechanism (radar transmitter spurious emissions or earth station front-end overload) is identified. This section describes methods by which the interference mechanism may be determined, so that appropriate mitigation measures may be implemented as reliably as possible. It should be noted that the tests and measurements required to determine the interference mechanism are not necessarily easy to perform, even if the earth station facility has access to the necessary test equipment (a spectrum analyzer and digital oscilloscope are recommended, at a minimum).

Commercially available RF front-end bandpass filters (passband of 3700-4200 MHz) for earth stations typically cost a few hundred dollars and can be installed relatively quickly. Installation of such a filter ahead of the first LNA/LNB/LNC in the earth station RF front-end is recommended as a first step at an earth station which is experiencing interference. If the only interference mechanism is front-end overload which is occurring outside the 3700- to 4200-MHz band, then the filter should mitigate the problem. (It should be noted that the presence of front-end overload does not necessarily mean that the overloading signal is outside the earth station's band, but under United States spectrum allocations (see Section 2) it would not be expected that a sufficiently strong signal, and particularly not a radar fundamental, would occur in the 3700-to 4200-MHz portion of the spectrum. No case of in-band front-end overload is known.)

It is also possible for front-end overload interference and radar spurious emission interference to occur simultaneously. In that case, installation of a bandpass filter on the earth station will only eliminate the front-end overload interference component; the station will still experience interference effects due to the radar spurious emissions in the 3700-to 4200-MHz band. Because of this possibility, the installation of a bandpass filter on the earth station ahead of the LNA/LNB/LNC is recommended before tests for radar spurious emission interference are attempted. If no such filter is installed, then the absence of earth station front-end overload must be verified through tests described below.

Finally, it should be noted that an earth station front-end amplifier which also incorporates a mixer/downconverter (LNB or LNC) may generate undesired products in the 3700- to 4200-MHz band when it is in an overload condition, as shown in Section 3. These products may be easily mistaken for radar spurious emissions in the earth station band. Thus, it is critical that the possibility of front-end overload be eliminated by installation of a front-end bandpass filter before tests for spurious emissions are performed.

5.2 MEASUREMENT PROCEDURES

Determination of Front-End Overload in an Earth Station

There are several steps in the process of determining whether or not front-end overload is occurring in an earth station. The first and most obvious step is to physically examine the

RF front-end of the system, usually at the antenna, and determine if any preselection already exists. It is important not to be misled by schematic diagrams, which may indicate the presence of filters which may not have actually been installed, or by narrow frequency ranges which are specified on an amplifier case (e.g., “3.7-4.2 GHz”); the actual amplifier response may be much wider than the label indicates. If RF bandpass filtering ahead of the first preamplifier is verified as being present, then it is very unlikely that the coupling mechanism is front-end overload. If no such filtering is present, then such a filter should be installed. If the installation results in elimination of the problem, then the mechanism is probably front-end overload.

If a bandpass filter for the earth station is unavailable, or for any other reason the presence of front-end overload must be independently verified, then the following measurement procedure can be performed through the front-end of the earth station during an interference event. The goal of this measurement is to determine the extent, if any, to which the amplifier is gain-compressing when energy from the radar is received. In order to document this effect clearly, it is necessary to simultaneously monitor the radar energy at the radar fundamental frequency, as well as the response of the earth station to that energy. A block diagram for the hardware arrangement to used in this test is shown in Figure 21.

With reference to Figure 21, this test is performed with the antenna feed horn connected directly into the earth station’s front-end amplifier (LNA/LNB/LNC). **THERE SHOULD NOT BE ANY BANDPASS FILTER AHEAD OF THE LNA/LNB/LNC DURING THIS TEST.** The signal out of the amplifier is then split into two paths. One side of the split is sent to a spectrum analyzer, and the analyzer video output is in turn routed to one channel of an oscilloscope,¹⁵ The analyzer should be tuned to the equivalent preamplifier output of the radar fundamental frequency (see Identification of the Radar, below), and the analyzer frequency span should be set to 0 Hz. (If two or more radar fundamentals are produced, any one of them will suffice.) The analyzer IF bandwidth should be set to 1 MHz, and analyzer trace sweeping should be suspended.

The other side of the split is routed to the earth station receiver, and the receiver’s IF output is routed to a second channel of the oscilloscope. The oscilloscope should be triggered from the radar pulse train coming out of the spectrum analyzer. Thus, both the radar pulse train and the earth station response to that pulse train maybe simultaneously observed on the oscilloscope. If the radar is overloading the earth station front-end, then gain compression should be observed on the IF trace when pulses from the radar are observed on the other oscilloscope trace. Examples of such responses are shown for an LNA and an LNB in Figures 22-25.

A variation on this technique can be implemented on an antenna that incorporates two cross-polarized feeds: install a bandpass filter ahead of the preamplifier on one feed. If

¹⁵ Documentation of these measurements is important. Either a digital oscilloscope that can transfer data to a magnetic medium or an analog oscilloscope with a camera can be used for this purpose.

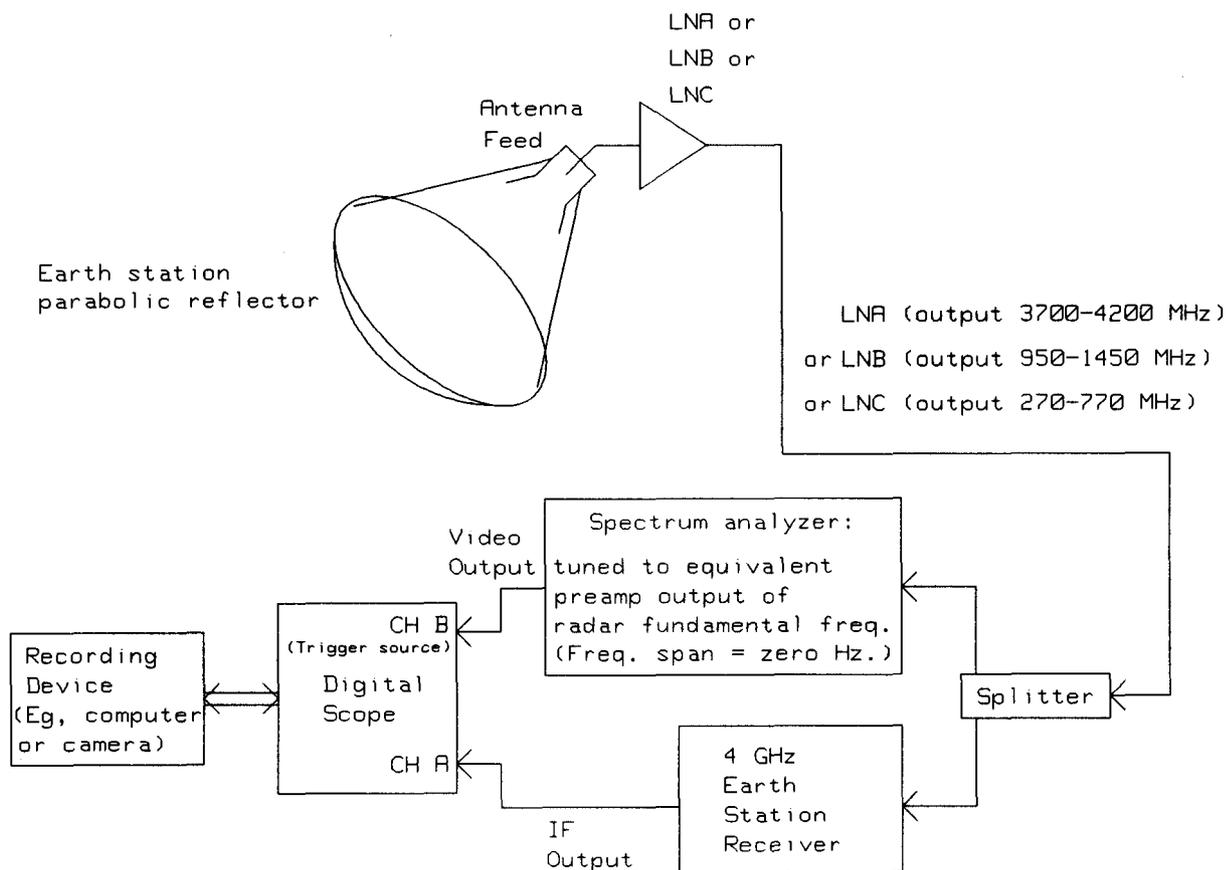


Figure 21. Block diagram for determination of interference coupling mechanism. Characteristics of either front-end overload or radar spurious emissions are observed in coincidence with radar pulses.

interference subsequently occurs on the unfiltered feed but not on the filtered feed, then the problem is earth station front-end overload. As a caveat, however, it should be noted that interference may be polarization-dependent, and the cross polarization between feeds can unintentionally produce a filtering effect of its own. So it is critical, if this technique is attempted, that both feeds are known to have previously been affected by the interference simultaneously.

Simultaneous Occurrence of Front-End Overload and Spurious Emission Interference

As stated at the beginning of this section, it is entirely possible for both earth station front-end overload and radar spurious emission interference to occur simultaneously. This would be the case if a radar produced strong spurious emissions at the earth station's center frequency, while the earth station was being operated with an unpreselected front-end. However, before the spurious emission interference problem can be addressed, the possibility of front-end overload must first be eliminated by installing an RF filter on the earth station.

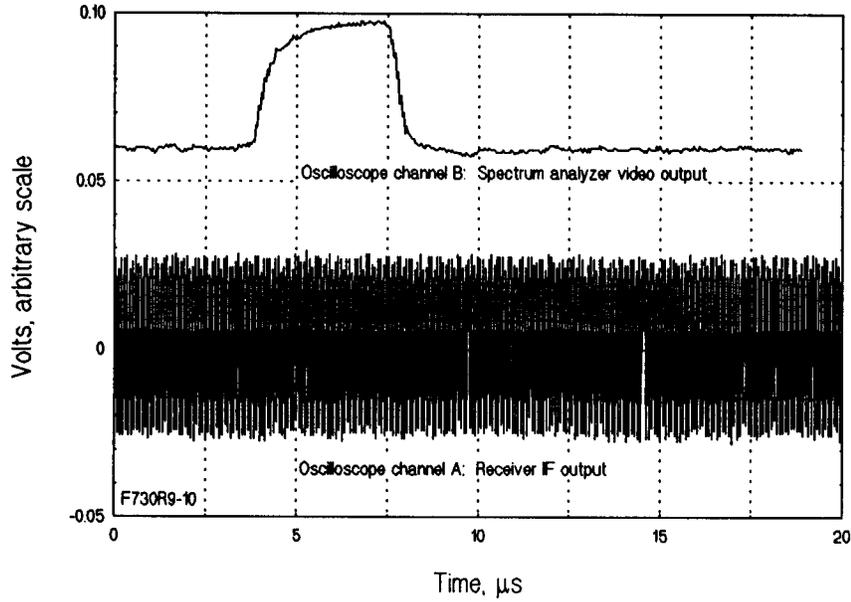


Figure 22. Channels A and B of oscilloscope when test arrangement of Figure 21 is used and LNB front-end is not overloaded. Note that time axis is much faster, due to faster expected recovery time of LNB.

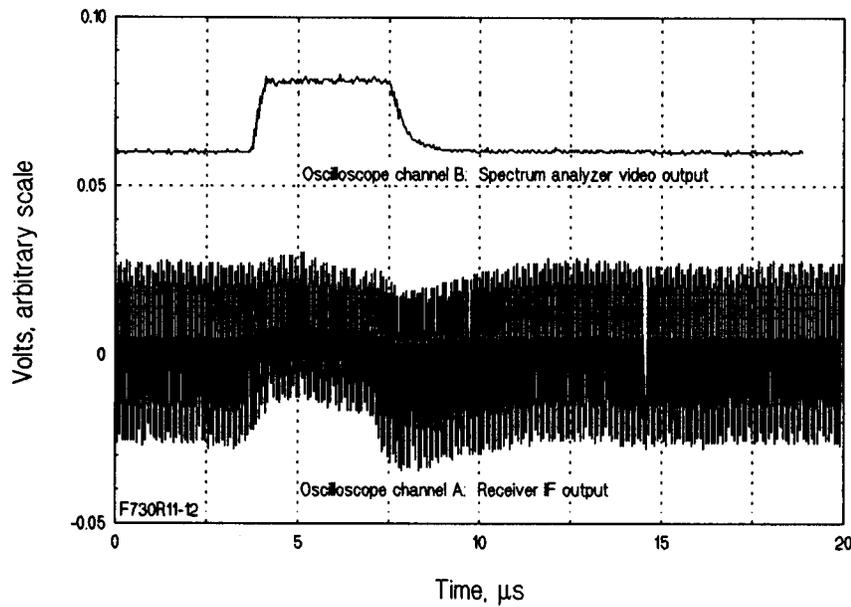


Figure 23. Channels A and B of oscilloscope when test arrangement of Figure 21 is used and LNB front-end is overloading. Note faster recovery time of LNB than of LNA, (interval the same as pulse width).

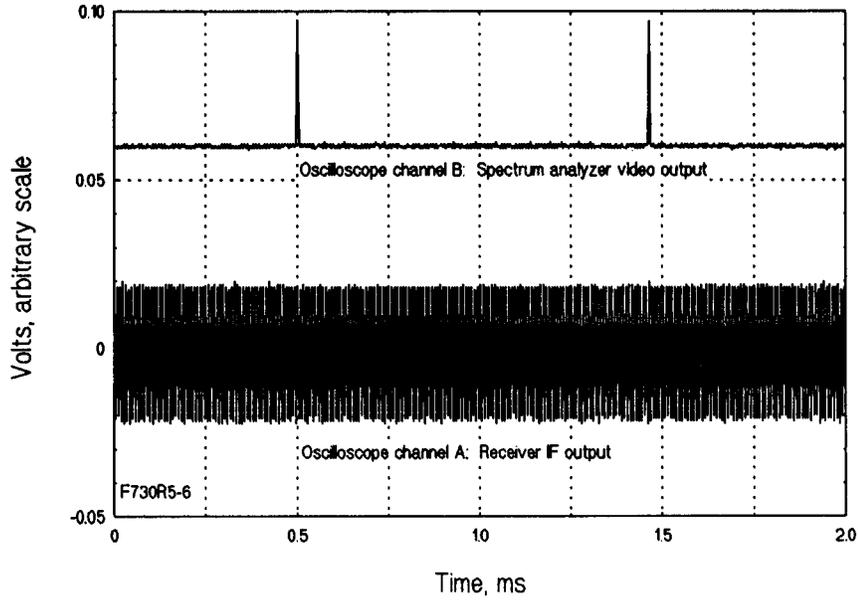


Figure 24. Channels A and B of oscilloscope when test arrangement of Figure 21 is used and radar pulses are not overloading LNA front-end.

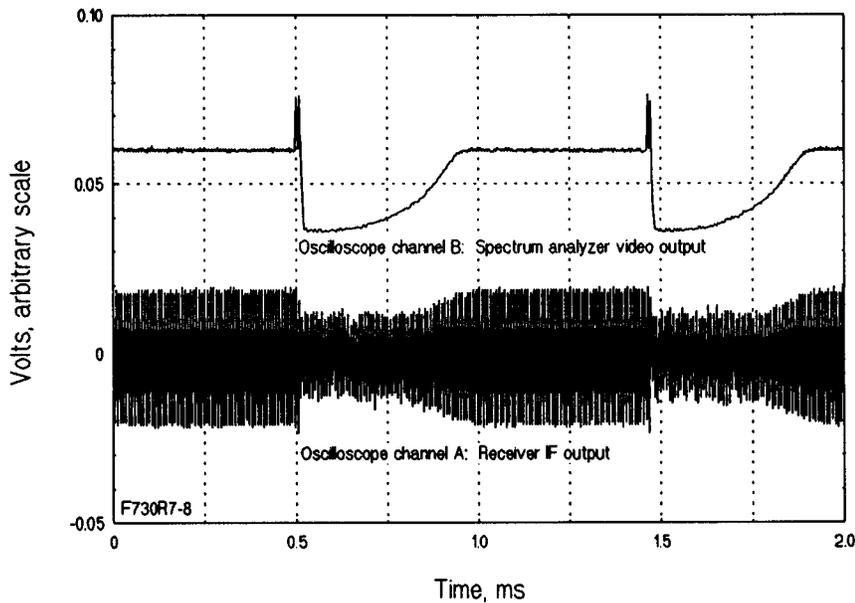


Figure 25. Channels A and B of oscilloscope when test arrangement of Figure 21 is used and front-end LNA is overloading. Note long LNA recovery interval relative to the radar pulse width.

Determination of Radar Spurious Emissions in an Earth Station

If tests for front-end overload are negative or interference persists when a 3700- to 4200-MHz bandpass filter has been installed ahead of the first RF amplifier in the earth station, then the interference is probably occurring as a result of spurious emissions in the earth station band.

It must be emphasized that, if the tests for radar spurious emission interference are to utilize unpreselected earth station RF front-ends, as shown in Figure 21, then the possibility that interference is caused by front-end overload must be eliminated before these tests are conducted. While the use of a bandpass filter on the earth station front-end is not absolutely required under these circumstances, the presence of such a filter during the tests increases the confidence that no front-end overload is occurring.

The observations may be accomplished in two ways. One method uses the same block diagram arrangement as shown in Figure 21 (but preferably with a bandpass filter inserted ahead of the LNA/LNB/LNC). The result will be to observe the radar spurious emission pulses superimposed on the desired signal, as shown in Figure 26. The spurious emission radar pulses will usually be observed as pairs of high leading and trailing edges (“rabbit ears”); the time-domain spacing will be the same as the nominal pulse width. It is also possible for spurious emissions to appear as noise-like pulses. A disadvantage to this method is that the presence of the desired earth station signal may have the effect of masking the radar spurious emissions.

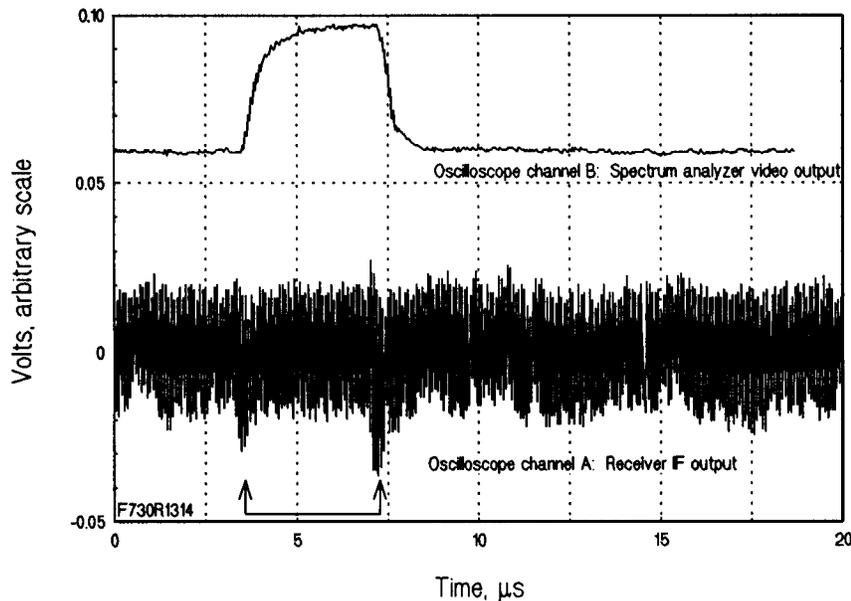


Figure 26. Channels A and B of oscilloscope when test arrangement of Figure 21 is used and spurious emissions occur at received frequency. Desired signal must be eliminated to perform this test.

The second observation technique eliminates the desired signal, thus reducing possible masking of the radar spurious emission pulses. With reference to Figure 21, this is accomplished by substituting an omnidirectional antenna for the earth station parabolic antenna (and again, preferably with a bandpass filter inserted ahead of the LNA/LNB/LNC). The omnidirectional antenna must have a frequency response of at least 2700- to 4400-MHz. This method may be most practical if the earth station has a spare receiver system already available, to which the omni antenna can be attached.

If radar spurious emissions are established as causing interference to an earth station, then the radar that is involved must be identified. The radar spurious emission levels must be quantified so that steps can be taken to resolve the problem.

Identification of the Radar

Identification of the radar can be achieved most easily if the parameters of pulse width, pulse repetition rate, fundamental frequency or frequencies, beam scanning technique, and beam scanning interval are obtained. (Direction finding is desirable but is often difficult for personnel who are unfamiliar with such techniques.) Measurements of radar emission parameters can be performed with a spectrum analyzer and an oscilloscope attached to the analyzer's video output. It is critical that the measurement system be deselected, so that front-end overload does not affect the measurements. An omnidirectional antenna should be used, because it will probably provide more gain in the direction of the radar than the earth station's dish antenna will provide.

The radar's fundamental frequency may be determined by sweeping the analyzer as rapidly as possible across the 2700- to 4400-MHz portion of the spectrum, using the widest possible IF bandwidth and positive peak detection with a maximum hold trace mode. The fundamental frequency of the radar should become roughly defined after a few rotations of the radar's main beam. The analyzer should then be tuned to the measured fundamental frequency and a narrow frequency span (about 50 MHz) should be selected. After a few more rotations, the center frequency should be well-defined. The analyzer should then be re-tuned to the radar center frequency again, and the frequency span should be adjusted to 0 Hz. In this mode, the spectrum analyzer becomes a slow-motion oscilloscope.

The sweep time should be set to about 60 s, and then the time trace of the radar's beam scanning will become visible. If the radar is rotating mechanically, the time trace will be repetitive and the rotation interval can be read directly off the analyzer screen using a delta marker function. If the radar is a phased array system, or if it is a three-dimensional system that scans elevation as well as azimuth, the time trace will be irregular but a typical time interval between visitations of the main beam may be estimated. In any event, at this point the radar's fundamental frequency or frequencies, beam scanning technique, and rotation interval, if any, should have been acquired.

Next, a storage oscilloscope should be attached to the analyzer's video output. A time scale of several microseconds per division and a voltage scale appropriate to the analyzer's video output level should be selected. With the analyzer still running in the 60-s time trace

mode, the oscilloscope triggering level should be adjusted high enough that a trace will be triggered just at the point that the radar's main beam swings past the measurement site. The radar pulse train will now be captured every time the radar aims at the measurement site. The pulse width, pulse repetition rate, stagger, and phase coding of the pulses (if any) can be read directly from the oscilloscope display.

It must be emphasized that it is very important to acquire as many of the radar emission parameters as possible, as these parameters are the only reliable electronic means by which a radar may be identified, and by which other radars may be eliminated from consideration.

When the radar is identified, it may be necessary to measure the radar spurious emissions to determine whether or not the radar spurious emissions comply with the RSEC (see Section 2). Such measurements and analysis may require the resources of a spectrum-management agency. Procedures for such measurements and the application of the RSEC are described in the Appendix.

When a reliable measurement of radar spurious emissions has been performed, another measurement of the extended radar spectrum should be performed through the antenna and RF front-end of the earth station that is experiencing interference. If the interference is occurring as a result of in-band spurious emissions from the radar, then the exact amplitude of the spurious emissions in the earth station system can be unambiguously determined. This measurement of spurious emission amplitude in the earth station can then be used to determine the minimum amount of attenuation that must be provided by one or more of these mitigation measures: RF filtering installed on the radar transmitter output, earth station antenna sidelobe suppression, or earth station site selection.

There is no fixed process for coordination of radar spurious emission interference mitigation. The contingencies that arise in the coordination process must be accommodated on a case-by-case basis. If the radar involved is a Government installation, agencies such as NTIA, the FCC, and the spectrum management section of the agency operating the radar may assist the process.

SECTION 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

The use of the 4-GHz (3700- to 4200-MHz) band by earth stations in the fixed-satellite service has increased rapidly in recent years due to the growth in the number of earth stations associated with broadcasting, such as television receive-only (TVRO) and audio distribution systems. As the transition to earth stations associated with broadcasting has evolved, there have been several reported cases of interference to 4-GHz earth stations caused by radar stations operating in the bands below 3700 MHz. The potential for interference from high-power radars could escalate as broadcasting systems continue to proliferate and to rapidly migrate towards digital-type systems. The following are conclusions and recommendations based on findings contained in this report.

6.2 GENERAL CONCLUSIONS

1. Interference from both Government and non-Government radars to 4-GHz earth stations has been documented.
2. Interference from radar stations to 4-GHz earth stations can occur even if all current NTIA standards applicable to radar transmitters and FCC standards applicable to earth station receiver systems are satisfied.
3. NTIA measurements and tests have shown that the interference from radars to 4-GHz receive-only earth stations can occur as a result of two interference coupling mechanisms:
 - a) receiver front-end overload from the radar center-frequency (fundamental) emissions causing gain compression (reduction in desired signal level) in the earth station front-end low-noise amplifier; the compression occurs not just at the radar fundamental frequency, but also across the entire response band of the earth station front-end
 - b) radar transmitter spurious emissions in the 3700- to 4200-MHz band, which cause degradation by increasing the C/I ratio at the frequency or frequencies used by the earth station.
4. Resolution and mitigation of interference from radars to 4-GHz fixed-satellite earth stations depends upon the ability to determine the interference coupling mechanism. The interference coupling mechanism can generally be substantiated by installing a 3700- to 4200-MHz bandpass filter ahead of the low-noise amplifier. If interference continues, the test and measurement procedures contained in Section 5 of this report should be used to determine the interference coupling mechanism.

6.3 SPECIFIC CONCLUSIONS

Spectrum Policy and Regulations

The following are conclusions related to spectrum policy and regulations associated with compatibility between stations.

1. There are no interference immunity standards pertaining to non-Government 4-GHz earth stations. The FCC generally declines to establish effective receiver system spectrum standards and lets the marketplace reach a consensus on receiver design.
2. For Federal radar stations, the responsibility for mitigating interference due to radar transmitter spurious emissions is dependent upon radar station compliance with appropriate spectrum standards and which system (radar or earth station) existed first. (NTIA Manual Section 2.3.7).

Earth Station Receiver Front-end Overload

The following are conclusions related to radar interference cause by earth station receiver front-end overload.

1. The desired signal level received by earth stations is very low, thus requiring low-noise amplifiers (LNA/LNB/LNC) of 50-65 dB gain in the earth station RF front-ends.
2. Low-noise amplifiers (LNA/LNB/LNC) used in some earth stations produce gain over 40 percent of the spectrum below 5 GHz (2.8-4.8 GHz). This makes the receiver systems extremely susceptible to interference from high-powered radar systems operating in adjacent bands and in accordance with regulations.
3. Radar signal peak power levels at which receiver front-end overload occurs are a function of the gain of the low-noise preamplifier (LNA/LNB/LNC) used in the earth station. Since the gain of preamplifiers used by earth stations in this band range between 50-65 dB, the gain compression threshold may occur at radar signal levels at the input to the LNA/LNB/LNC of -55 to -40 dBm.
4. Radar interference due to earth station receiver front-end overload can be mitigated by inserting an RF bandpass (preselector) filter ahead of the low-noise amplifier. Measured in-band insertion losses of RF preselector filters are typically 0.5 dB.
5. Earth station receiver front-end preamplifiers that incorporate mixer/downconverters (LNB and LNC devices) are more likely to generate undesired product responses than low-noise preamplifiers which do not incorporate downconversion. Such responses may cause interference with the desired signal, and may also be mistaken for radar spurious emissions.

6. Earth station receiver front-end preamplifiers that incorporate built-in preselection showed reduced susceptibility to front-end overload from radar-like signals in the 2700-3500 MHz portion of the spectrum, but were still susceptible to overload by strong signals in the frequency range of 3500-3700 MHz. Because some radar systems operate in the 3500-3700 MHz portion of the spectrum, the use of such preamplifiers reduces but does not eliminate the possibility of front-end overload in such devices.
7. The gain compression interval of front-end preamplifiers ranges from less than 1 μ s to approximately 900 μ s. The compression interval depends upon the characteristics of the preamplifier and the amount of gain compression which has occurred. Devices incorporating mixer/downconverters (LNB/LNC) exhibited recovery intervals that were about two orders of magnitude shorter than the LNA recovery intervals.
8. The separation distance required to preclude receiver front-end overload from airborne radars in bands adjacent to the 4-GHz band is several hundred km even at off-axis angles greater than 10 degrees. For surface radars, receiver front-end overload interference may occur at ranges of 60 km for a few degrees off-axis to less than 40 km for off-axis angles greater than 30 degrees.

Radar Transmitter Spurious Emissions

The following are conclusions related to interference to earth stations caused by radar transmitter spurious emissions.

1. The predominant factor that governs the level of spurious emissions from radars is the transmitter output device.
2. When radar transmitter spurious emissions are identified as the interference source, then the additional task of identification of the radar must be performed. Measurement procedures for obtaining radar transmitter characteristics that will assist in such identification are contained in Section 5.
3. Interference mitigation options for radars to reduce radar transmitter spurious emission coupling include inserting an RF filter after the radar output device. However, in cases where radars use antenna phased array techniques, such filters cannot be installed.
4. Interference mitigation options for earth stations to reduce radar transmitter spurious emissions coupling include the use of shrouded antenna dishes and careful site selection.
5. There have been no substantiated cases of radar spurious emission interference from airborne radars to 4-GHz earth stations. All airborne radars in the 2700-3700 MHz range use klystron output tubes which have very low spurious emission levels (approximately -110 to -120 dBc).

6. The separation distance required to preclude radar transmitter spurious emission interference ranges from several hundred km at off-axis angles of less than 5 degrees to less than 50 km for off-axis angles greater than 30 degrees.

6.4 RECOMMENDATIONS

1. NTIA should hold discussions with major earth station manufacturers and system integrators to recommend that RF front-end preselection filters be included as a standard part of new 4-GHz earth station installations; the purpose of the preselectors would be to preclude receiver front-end overload due to strong adjacent-band radar signals. This practice would enhance compatibility between radars in the 2700- to 3700-MHz portion of the spectrum and fixed-satellite earth stations in the 3700- to 4200-MHz portion of the spectrum.
2. NTIA should hold discussions with manufacturers of LNAs, LNBs and LNCS to recommend that they incorporate very sharp preselector filters (similar to preselector filter characteristics shown in Figure 11) in those devices.
3. In response to reported cases of radar interference to 4-GHz earth stations, NTIA recommends that the following action(s) be taken:
 - a) install a 3700- to 4200-MHz bandpass filter (preselector) ahead of the low-noise preamplifier
 - b) if the interference continues, use the procedures described in Section 5 to identify the interference coupling mechanism and, if the interference is identified as radar transmitter spurious emissions in the 4-GHz band, identify the radar emission parameters (i.e., center frequency, scan pattern, scan rate, pulse repetition rate, pulse width).
4. NTIA should inform appropriate industry associations and service providers of the findings of this report to work towards the development of possible solutions to the interference problem.
5. NTIA should submit the measurement procedures described in Section 5 to the International Telecommunication Union, Radiocommunication Sector (ITU-R), to aid administrations in determining the interference coupling mechanism(s) when radar interference to fixed-satellite earth stations occurs.

APPENDIX
MEASUREMENT OF RADAR SPURIOUS EMISSIONS AND APPLICATION OF THE RSEC

A.1 MEASUREMENT OF RADAR SPURIOUS EMISSIONS

This appendix outlines procedures for the measurement of radar spurious emissions. Such measurements can be used to determine compliance of the radar with the RSEC (see Section 2). Such a measurement may require the resources of a frequency management agency. The measurement may be used to determine the radar's compliance with the RSEC or other applicable emission criteria. Measurement of the extended radar spectrum will indicate the power density at the frequency of the earth station, and hence the likelihood that sufficient power exists at the earth station's frequency and in the earth station's bandwidth to cause in-band interference.

A broadband radar emission spectrum will typically have to be measured across a frequency range of at least 1 GHz, and possibly much more. The dynamic range required of the measurement system will typically be at least 100 dB, so that both the power at the center frequency of the radar and in the spurious emission spectrum can be observed. To achieve this dynamic range, a variable RF attenuator should be installed at the front-end of the measurement system. If, for example, the attenuator is 0-70 dB and the measurement system has an instantaneous dynamic range of at least 50 dB, then 120 dB of total dynamic range can be achieved.

It is important that the measurement system not experience front-end overload while the measurement is in progress. Therefore, tunable front-end preselection is required. Current technology provides yttrium-iron-garnet (YIG) preselectors which can be used for this function in the range of 500 MHz to 18 GHz. Varactor preselection may be used below 500 MHz.

High sensitivity is required for the portion of the measurement that includes the spurious emissions in the extended radar spectrum. Low-noise amplifiers following the preselector can compensate for line loss and other components of measurement system noise figure. The NTIA Radio Spectrum Measurement System (RSMS), shown as a block diagram in Figure A-1, incorporates all of the features described here: Variable RF attenuation for wide dynamic range, automatic tracking preselection to prevent front-end overload from strong out-of-band signals, and low-noise preamplification to provide maximum measurement system sensitivity. A subset of the equipment shown in Figure A-1, called the Component Radio Spectrum Measurement System (CRSMS), can also be used for measurements of radar spurious emissions, and incorporates the same features of wide dynamic range, preselection, and sensitivity.

The most efficient way to measure an extended radar emission spectrum is stepping across the spectrum in the frequency domain rather than sweeping across in the more conventional manner. Stepping means tuning the measurement system to a single frequency in a measurement (IF) bandwidth and using a fast-running positive peak detector to capture the highest emission received from the radar at that frequency during one full rotation of the radar beam. (Video bandwidth, which is post-detected lowpass filtering, should be as wide or wider than the measurement bandwidth.) That highest emission received during the radar rotation is then retrieved by a controller computer, corrected for calibration factors, and stored

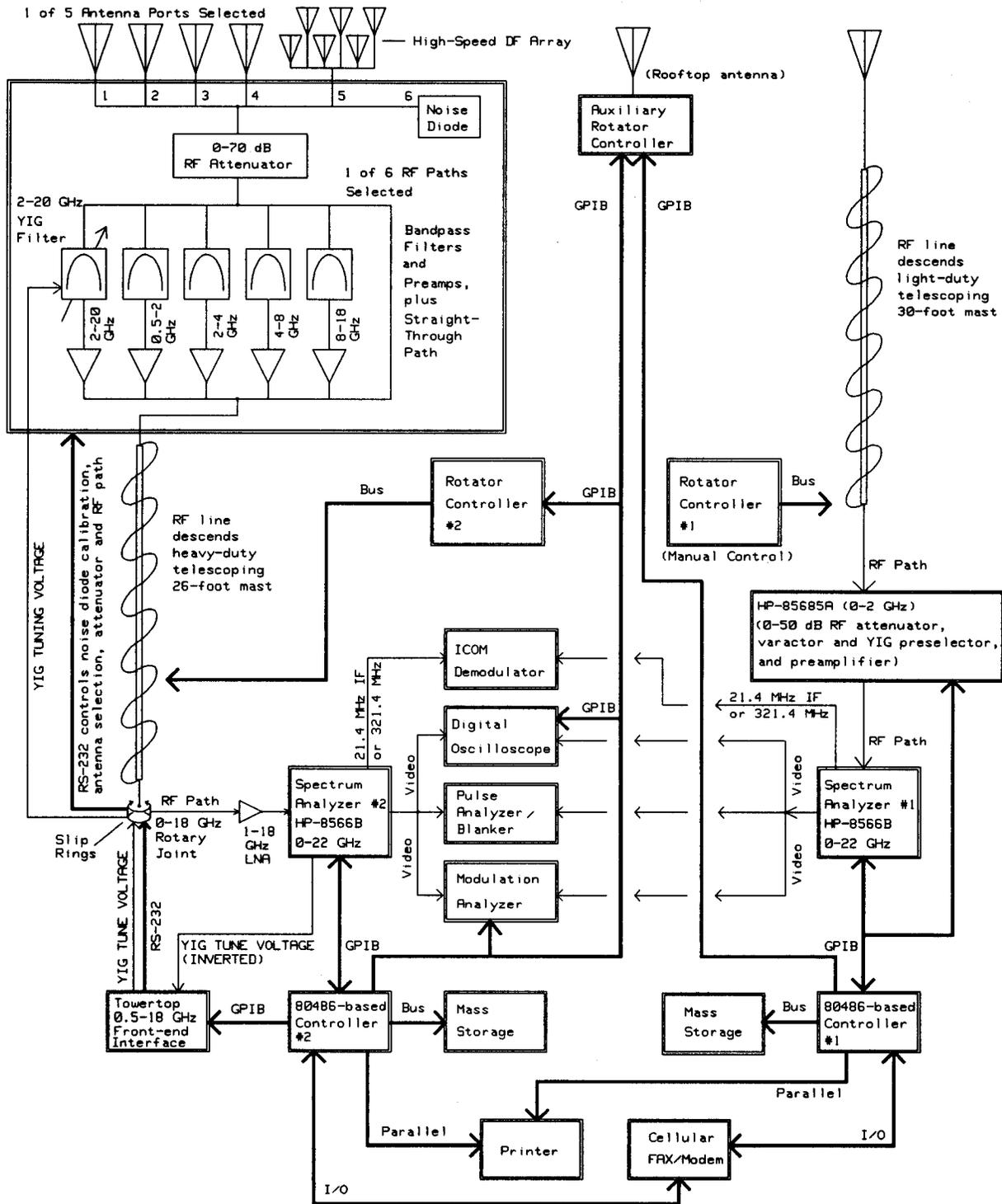


Figure A-1. Block diagram of the NTIA/ITS Radio Spectrum Measurement System (RSMS). The RSMS is a Department of Commerce asset used to assess and resolve radio spectrum occupancy questions and problems.

in memory. Then, the measurement system is tuned in frequency by an amount approximately equal to the measurement bandwidth (e.g., the measurement frequency is tuned 1 MHz higher if the measurement bandwidth is 1 MHz), and the process is repeated for the new frequency during the next rotation of the radar. Thus, one measured frequency step occurs with each rotation of the radar. The stepping process is continued until the entire measurable spectrum has been acquired. All radar spectra presented in this report (e.g., Figures 13-1 5) were made using the stepped technique. The stepped technique has several advantages over the conventional swept technique for spurious radar emission measurements:

- 1) Stepping is at least twice as fast at filling in the spectrum as sweeping in a maximum hold mode
- 2) Stepping allows for greater dynamic range than sweeping, because attenuation can be increased and decreased as a function of measurement frequency and as required by the rise and fall of the measured spectrum across that frequency range
- 3) Stepping creates a deterministic, rather than a probabilistic, spectral envelope. That is, a dip in a swept spectrum may be the result of not having sampled adequately at those frequencies where the dip occurred, and verification of whether or not the dip is real is difficult, whereas a dip in a stepped spectrum measurement must represent a real dip in the emission spectrum.

A.2 APPLICATION OF THE RSEC

Application of the RSEC to the measured spectrum of a radar is complicated by the fact that the measured peak power of the spurious emissions relative to the measured peak power of the radar fundamental frequency may be dependent upon the selection of the measurement (IF) bandwidth. Such dependence will occur if the measurement is peak-detected and utilizes a video bandwidth (post-detected low-pass filtering) which is as wide as or wider than the IF bandwidth, as is usually true for radar spectrum measurements. Such a case is shown in Figure A-2.

In Figure A-2, the radar spectrum has been measured in IF bandwidths of 300 kHz and 1 MHz. While the center frequency power levels are unchanged when measured in these two bandwidths, the spurious emission levels change by anywhere from 5 to 15 dB, with a typical difference of about 10 dB. This 10 dB difference is consistent with the theoretically expected change of $20 \log(\text{measurement bandwidth ratio})$. (In this example, $20 \log(1 \text{ MHz}/300 \text{ kHz}) = 10.5 \text{ dB}$ expected difference between the two spurious emission measurements.)

This phenomenon (a bandwidth-independent power measurement at center frequency with a bandwidth-dependent power measurement in the spurious emission spectrum) will occur in peak-detected measurements utilizing wide video bandwidths and measurement (IF) bandwidths which are wider than approximately (1 /radar pulse width). If the measurement bandwidths are equal to or less than (1 /radar pulse width), then the power measurement at the center frequency will also be bandwidth-dependent and will go as $20 \log(\text{measurement bandwidth ratio})$, and the ratio between power levels at the center frequency and in the

spurious emissions will be constant. Table A-1 summarizes the relationship between the measurement bandwidth, the radar pulse width, and the correction which NTIA applies to measured radar emission spectra.

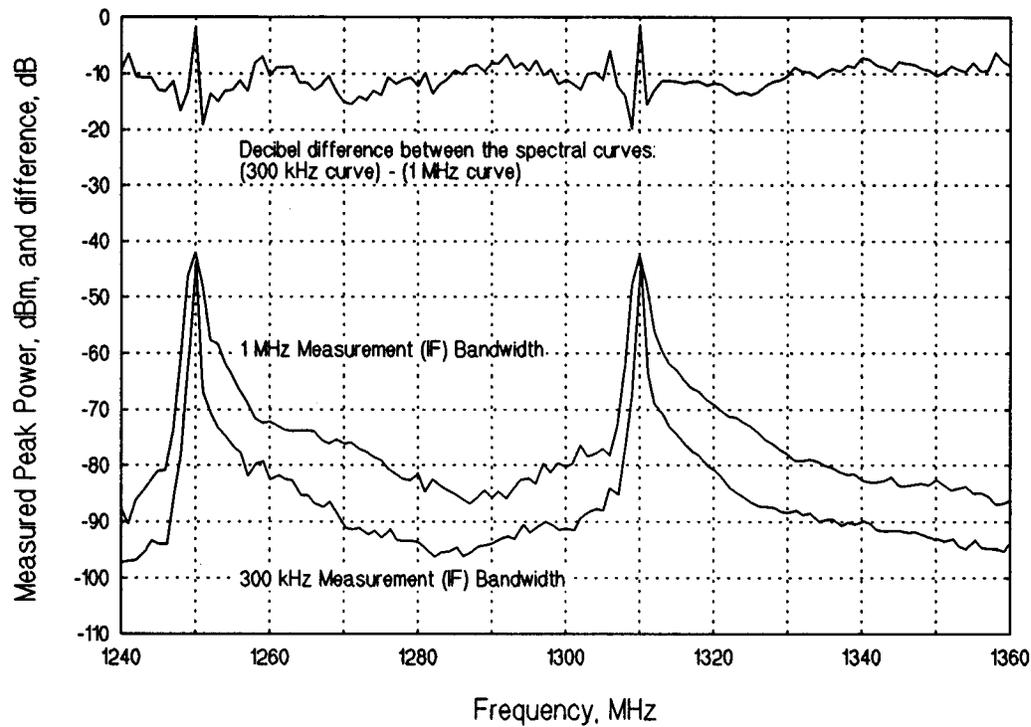


Figure A-2. Measured emission spectra of a radar in two different measurement bandwidths. The center frequency power level does not change, but the spurious emissions change by about $20 \log(\text{bandwidth ratio}) = 10 \text{ dB}$.

**TABLE A-1 .
RELATION BETWEEN MEASUREMENT BANDWIDTH, RADAR PULSE WIDTH AND NTIA
CORRECTION FOR WIDE-BANDWIDTH MEASUREMENTS***

Width of Measurement (IF) Bandwidth Relative to Radar Pulse Width	NTIA Correction for Application of the RSEC
Measurement Bandwidth > (1/radar pulse width)	Correct either by graphically/numerically reducing the measured spurious emission levels or by raising the RSEC envelope. Correction value is $20 \log(\text{measurementbandwidth/radar pulse width})$
Measurement Bandwidth \leq (1/radar pulse width)	No correction necessary.

* These corrections are appropriate for cases in which the measurement is performed using peak detection and a video bandwidth (post-detected lowpass filtering) which is as wide or wider than the measurement (IF) bandwidth.