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ASSESSMENT OF NARROWBAND MODULATION TECHNOLOGIES FOR GOVERNMENT LAND MOBILE OPERATIONS

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ABSTRACT

This report examines the use of Amplitude Compandored Single Sideband (ACSB) and/or 12.5 kHz FM (NBFM) as possible solutions to the spectrum congestion in the Government Land Mobile Service in the VHF bands. These narrowband modulation techniques are investigated by looking into three different aspects of the problem. These are: operation and use, spectrum efficiency and implementation. In the operation and use area, the different capabilities and deficiencies of the NBFM and ACSB are identified and compared with the conventional 25 kHz FM presently used in the VHF band. Also, a review is made of both U.S. and foreign operational experience in these narrowband techniques. In the spectrum efficiency area, a definition is given for technical spectrum efficiency factor (spectrum resource used by reference system relative to spectrum resource used by evaluated system). Using this definition, the technical spectrum efficiency factor of both NBFM and ACSB relative to a reference 25 kHz FM is calculated for several different operational scenarios. Also, a discussion is made of the laboratory and field measurements on the ACSB and NBFM radios. These measurements were made by the Department of Defense Electromagnetic Compatibility Analysis Center, the Department of Agriculture, the FCC, and the Department of Commerce NTIA. In the implementation area, a rather comprehensive list of factors comparing the NBFM and ACSB to the 25 kHz FM is given. Also, a discussion is made of several implementation schemes and spectrum management strategies that the Government agencies might adopt in order to implement these narrowband modulation techniques. The conclusions from this study along with a number of definite recommendations for Government action are also included.

KEY WORDS

Amplitude Compandored Single Sideband (ACSB)
Land Mobile Radio
12.5 kHz FM (NBFM)
25 kHz FM

SECTION 1

INTRODUCTION

BACKGROUND

The National Telecommunications and Information Administration (NTIA) is responsible for managing the radio spectrum allocated to the U.S. Federal Government. Part of NTIA's responsibility is to: "...establish policies concerning spectrum assignment, allocation and use, and provide the various Departments and agencies with guidance to assure that their conduct of telecommunications activities is consistent with these policies" (Department of Commerce, 1983). In support of these requirements, NTIA has undertaken a number of spectrum resource assessments. The objectives of these studies are to: assess spectrum utilization, identify existing and/or potential compatibility problems between systems of various departments and agencies, provide recommendations for resolving any compatibility conflicts, and recommend changes to promote efficient use of the radio spectrum and to improve spectrum management procedures. This spectrum resource assessment (SRA) documents a follow-on study of an assessment of the 162-174 MHz band and addresses the feasibility of implementing narrowband techniques for Government fixed and land mobile operations in this band.

Land mobile radio (LMR) is used extensively by many Government agencies to assist in accomplishing a variety of missions. The 162-174 MHz band contains approximately 25 percent of all Government Master File (GMF) records. The vast majority of these assignments are for land mobile operations and associated fixed links with necessary bandwidths of 16 kHz. The use of this spectrum is such that it is often difficult to find spectrum space for new systems, especially in the larger metropolitan areas.

Over the past several years, extensive investigations of the feasibility of narrowband modulation techniques for land mobile application has been documented. Experimental usage of modified Single Sideband (SSB) techniques have been underway in England since 1979 (United Kingdom, 1980). The test results are not conclusive, but they support the feasibility of Amplitude Compandored Single Sideband (ACSB) usage for VHF land mobile operations. In the United States, the FCC sponsored an investigation of ACSB conducted by Stanford University (Lusignan, 1980). These tests also substantiate the feasibility of using ACSB for VHF land mobile operations. Both studies point out the potential for more efficient use of the VHF land mobile spectrum using ACSB technology.

Not everyone agrees with the findings of the studies described above. Studies conducted in England contend that when all operational factors are considered, more operational channels can be obtained through the use of narrowband FM (NBFM) with 12.5 kHz channel spacing. In the United States, similar conclusions have been arrived at by General Electric (GE) and the Electronic Industries Association (EIA).

At the time of this report, ACSB radios are being produced by two manufacturers: Sideband Technology, Inc., and Stevens Engineering Associates, Inc., for marketing within the United States. However, present product lines and production capabilities are somewhat limited. NBFM equipment is currently available to foreign markets from several manufacturers who also produce conventional FM equipment. For these overseas markets, a diversity of product lines and extensive production capability has been reported, but plans for marketing these NBFM equipments within the United States were not determined. For both ACSB and NBFM, increasing demand by users in conjunction with rule changes to allow for regular operations of these narrowband technologies should encourage more widespread availability and diversity in the United States.

The FCC issued a Notice of Inquiry (NOI) on September 9, 1980, in the matter of: Amendment to the Commission's Rules governing land mobile radio stations to provide for additional technologies which can improve the efficiency of radio spectrum use (PR Docket 80-440). The most widely held view of those who commented was that the Commission should continue the practice of letting the marketplace influence introduction of new technology as it is warranted, after thorough testing in the rigorous "real world" of land mobile communications. Subsequently, the FCC issued a Notice of Proposed Rulemaking (NPRM) on April 4, 1984, to authorize narrowband technologies in the 150-172 MHz frequency band (PR Docket 84-279). The deadline for comments on this NPRM was August 10, 1984, with reply comments due by September 11, 1984.

OBJECTIVE

The objective of this task was to examine the use of Amplitude Compandored Single Sideband (ACSB) and/or narrowband FM (NBFM) technologies as possible solutions to spectrum congestion in the Government Land Mobile Service in the VHF bands.

APPROACH

The following are specific tasks that were performed to determine the potential use of narrowband mobile radios.

1. Determine the compatibility (interference/susceptibility potential) of ACSB and NBFM technologies by performing laboratory and field measurements on commercially available radios.

    a. Technical specification validation (laboratory tests),

    b. Cochannel and adjacent channel protection ratios (laboratory tests),

    c. Communication range (field tests),

    d. Voice quality comparison (field tests), and

    e. Adjacent channel performance (field tests).

2. Determine the present and future operation and use of land mobile technology by:

    a. Discussing present usage,

b. Exploring spectrum efficient trends, and

c. Relating narrowband land mobile operational experience.

3. Evaluate the technical spectrum efficiency factor of narrowband land mobile technologies all of which perform the same misson as a reference system by:

a. Defining the technical spectrum efficiency factor (TSEF),

b. Discussing measurements of ACSB, NBFM, and 25 kHz FM, and

c. Calculating the technical spectrum efficiency factor of ACSB and NBFM utilizing as a reference a 25 kHz FM.

4. Explore the implementation aspects of narrowband land mobile by:

a. Making a general comparison of narrowband and wideband systems,

b. Discussing possible implementation schemes, and

c. Determining the impact on spectrum management policies.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

GENERAL CONCLUSIONS

Two narrowband modulation techniques, amplitude compandored single sideband (ACSB) and 12.5 kHz narrowband FM (NBFM) have been investigated and found to be effective spectrum efficient modulation methods that can be implemented by Federal Government agencies in the VHF bands allocated to the Fixed and Mobile Services. In an overall comparison of ACSB and NBFM technologies for analog voice applications, each provided advantages and limitations. ACSB was found to be as high as 2.5 times as spectrum efficient as 25 kHz FM and NBFM as high as 1.8 times as spectrum efficient (see summary in Section 4). The current availability of the ACSB equipment offers an advantage over the NBFM which is not presently marketed in the United States. NBFM, however, offers expected advantages over ACSB in such factors as interoperability with the existing FM equipment, common acceptance testing procedures and test equipment, maintenance, and lower cost. Additionally, in congested environments where a large adjacent signal protection ratio is required, the spectrum efficiency of NBFM is commensurate with that of ACSB. The channel spacing associated with both techniques limits the data rate handling capability to values less than that of current 25 kHz FM. In addition, neither can accommodate currently available digital voice techniques. Both provided a communication range commensurate with current 25 kHz FM, but with slightly lower voice quality at the fringe of the communication range. In other areas of comparison, neither technique showed a clear advantage. NBFM appears to offer more advantages for Federal Government land mobile applications considering the overall requirements of the Government agencies.

Various alternative spectrum management policies towards narrowband land mobile technologies were explored including adoption of strong regulatory requirements and a "marketplace" approach, as well as options in between. An overall NTIA policy which endorses and actively encourages the continued development and use by Federal agencies of narrowband technology is considered the most effective approach to stimulate its implementation. Specific conclusions based on measurements and analysis follow.

SPECIFIC CONCLUSIONS

Operational Considerations

As a result of limited field tests conducted by NTIA, as well as review of reports from other independent users of commercially available equipment, both ACSB and NBFM were found to be effective means of voice communication for the Government Land Mobile and Fixed Services in the VHF band. Specific results are as follows:

1. The use of average power for FM and peak envelope power for ACSB was considered the most appropriate method for specifying transmitter output power.

2. Using equal transmitter power rating (peak envelope power for ACSB and average power for FM), the communication range for both ACSB and NBFM was commensurate with current 25 kHz FM.

3. The voice quality of both ACSB and NBFM was similar to 25 kHz FM in a high signal environment. In a low signal environment, the voice quality of both narrowband techniques is not as good as that of the 25 kHz FM; the voice quality of the NBFM being slightly better than that of the ACSB. Under this condition, the NBFM voice signal is subject to distortion probably due to noise pops and capture, while the ACSB voice signal is subject to distortion probably due to the companding, pilot tone circuitry, and/or reduced audio bandpass.

4. The dominant factor affecting the adjacent signal performance of 25 kHz FM was considered to be the receiver selectivity characteristics.

5. The dominant factor affecting the adjacent signal performance of ACSB was found by measurement and analysis to be the transmitter out-of-band emissions (sideband spectrum).

6. Measurements and/or analysis of the cochannel and adjacent signal performance of ACSB and NBFM, as well as conventional 25 kHz FM, give the results indicated in TABLE 1. (See Section 4).

Spectrum Efficiency

1. For purposes of this analysis the spectrum efficiencies of the two narrowband modulation techniques were calculated using the Technical Spectrum Efficiency Factor (TSEF) as defined by the Technical Subcommittee (TSC) of the Interdepartment Radio Advisory Committee (IRAC). Mathematically this factor can be expressed using terms of the following type:

$$TSEF = \frac{B_r \times T_r \times S_r}{B_s \times T_s \times S_s} \qquad (1)$$

where:

B_r is the bandwidth the reference system denies to others,

T_r is the time the reference system denies to others,

S_r is the physical space (e.g., area) the reference system denies to others,

B_s is the bandwidth denied by the evaluated system,

T_s is the time denied by the evaluated system, and

TABLE 1

COCHANNEL AND ADJACENT SIGNAL PROTECTION RATIOS
(SIGNAL-TO-INTERFERENCE (S/I) RATIO IN dB)

INTERACTION		FREQUENCY SEPARATION (kHz)				
XMTR	RCVR	0	5	6.25	12.5	25
ACSB	ACSB	8	-47	-58	-70	<-80
25 kHz FM	ACSB	15	--	--	-70	<-80
NBFM	ACSB	15	--	--	-70	<-80
ACSB	25 kHz FM	9	--	--	-35	<-80
25 kHz FM	25 kHz FM	5	--	--	-25	<-80
NBFM	25 kHz FM	5	--	--	-35	<-80
ACSB	NBFM	9	--	--	-70	<-80
25 kHz FM	NBFM	9	--	--	-70	<-80
NBFM	NBFM	9	--	--	-80	<-80

S/I at Input Required to Reduce SINAD from 18 dB (without interference) to 12 dB (with interference).

-- not available

These S/I values represent the best available information. Additional measurements are needed to verify some of the values given.

S_s is the physical space denied by the evaluated system.

Both the reference and evaluated system accomplish the same mission, with equal quality of analog voice communication.

2. The reference system chosen for this analysis was a high-quality state-of-the-art conventional 25 kHz FM system. Using the above definition, ACSB was found to have a TSEF as high as 2.5 for a reference 25 kHz FM. Again, using the 25 kHz FM as the reference system the TSEF of NBFM was found to be 1.8.

Implementation

Means of accommodating and encouraging the implementation of narrowband technologies into the bands allocated to the Government fixed and mobile bands were examined. It was not appropriate to identify a single technique because of the diverse and varying requirements of Government agencies. Specific conclusions are as follows.

1. An overall comparison of the competing narrowband technologies, ACSB and NBFM, in fifteen key technical and operational factors was completed. A summary of the comparison is given in TABLE 2. (This is further described in detail in Section 5.)

2. Three methods of accommodating narrowband technologies into the present Government VHF fixed and mobile spectrum were examined. The first approach examined was the interleaving of narrowband assignment ACSB or NBFM, between existing 25 kHz FM channels. Interleaving is defined for the purpose of this discussion, as using a 12.5 kHz frequency offset between existing assignable Government channels in the 162-174 MHz band with 25 kHz channel spacings. Use of interleaved frequencies by narrowband technologies could also be employed on a case-by-case basis. A second option—to consider planning of the 216-225 MHz band jointly with the FCC for exclusive use by narrowband technologies—offers clear advantages. Chief among these are the interoperability between Federal Government and non-Government users, the reduced competition with the existing FM-using community, and the encouragement provided to equipment manufacturers. A disadvantage is the limitations imposed by sharing among the Government and non-Government Fixed, Mobile and Amateur Services in a portion of this band. Exercising a third option would be to designate certain channels for exclusive use by narrowband assignments as discussed in Section 5. This method would involve developing assignable channels in the radio spectrum allocated to the Fixed and Mobile Services with 6.25 kHz channel spacings and multiples thereof. Center frequencies with 6.25 kHz channel spacings could accommodate ACSB applications, and center frequencies with 12.5 kHz channel spacings could accommodate NBFM equipment. Portions of the spectrum should be designated for narrowband technologies such as to allow maximum flexibility for complementing the various narrowband techniques. By exercising this option, various additional options become available as to the location of the designated spectrum space. Channels or groups of channels in the fixed and mobile channeling plan for the

TABLE 2

COMPARATIVE FACTORS FOR NARROWBAND LAND MOBILE TECHNOLOGIES
(SUMMARY CHART)

Comparative Factors	Evaluation Factors: 25 kHz FM	ACSB	NBFM
1.[a] Channel Spacing (kHz)	25	5-6.25	12.5
2. Spectrum Efficiency (Relative to 25 kHz FM)	1.0	2.5	1.8
3.[b] Adjacent Channel Protection Ratio provided (dB)	-80	[c] -47 to -58	-80
4. Communication Range	Approximately the same for all sets		
5. Interoperability with existing equipment (25 kHz FM)	Yes	No	Yes, with minor performance degradation
6. Equipment Availability	Widespread	Limited	Not marketed in United States (Available in Europe)
7. Availability of Convenience Circuits	Yes	Yes	Yes
8. Maintenance/Testing Procedures compared to existing environ. (25 kHz FM)	Same	Modified	Same
9. Standardized equipment design	Yes	No	Yes
10. Maximum Data Handling Capability of Audio Bandpass (Kilobauds)	1.2-1.8	1.2-1.8	1.2-1.8
11. Maximum Data Handling Capability Using Full Channel Spacing (Kilobauds)	10-12	1.2-1.8	5-6
12. Channel spacing compatible with current digital voice techniques	Yes	No	No
13. Channel spacing compatible with current analog encryption techniques	Yes	Yes	Yes
14. Compatability with trunking techniques	Yes	Yes	Yes
15. Voice Quality compared to existing environment (25 kHz FM)	Same	[d] Good	[d] Good
16. Cost compared to existing equipments	Same	See Table 11	5% to 10% increase

a/ Values in this Table are based on these channel separations.

b/ 25 kHz FM vs 25 kHz FM, ACSB vs ACSB and NBFM vs NBFM, respectively.

c/ -47 dB for 5 kHz channel spacing
-58 dB for 6.25 kHz channel spacing

d/ See Section 5 for further discussion

162-174 MHz band can be set aside for narrowband applications. The military departments could investigate this option for relieving channel congestion problems in the 138-150.8 MHz band.

3. Chapter 2 of the NTIA Manual (1983) states a policy that "the Government shall exercise leadership in application of technological advances of operational procedures that will result in more efficient and effective use of the radio spectrum." Pursuant to this policy, effective spectrum management options available to NTIA include: (a) establishing a clear and positive position in support of suitable narrowband technologies; (b) committing NTIA funds towards furthering the technology; (c) continuing to provide information, test results and/or application results to potential Federal agency users; (d) introduce regulations and procedures which promote the use of narrowband technologies; (e) encouraging Federal agency development funding of narrowband technologies; and (f) identifying a lead Federal agency in implementation of narrowband technologies.

RECOMMENDATIONS

The following are NTIA staff recommendations based on the technical findings contained in this report. Any action to implement these recommendations will be accomplished under separate correspondence by modification of established rules, regulations or procedures.

In support of NTIA's goal of efficient use of the radio spectrum by the Federal agencies, NTIA should adopt a policy of full support and endorsement of the use of narrowband technologies for land mobile applications when compatible with agency mission requirements. Specific courses of action which should be considered are:

1. NTIA should issue a public news release which notes the completion of measurements and analysis on the subject and states NTIA's full support and endorsement of the concepts.

2. NTIA should develop, in coordination with the IRAC, a policy statement for inclusion into Chapter 4 of the NTIA Manual (1983) which encourages Federal agencies to use spectrum efficient technologies for land mobile communication when its use is compatible with the agencies mission requirement.

3. In coordination with other Government agencies, NTIA should take the following action to encourage the use of narrowband technologies:

   a. Fund a joint effort with another Federal agency to obtain a commercially available land mobile communication system which employs spectrum efficient technology. The system would serve both operational needs of that agency as well as being available to NTIA for demonstration purposes.

   b. Encourage an IRAC agency to become the lead Federal agency in funding continued development of narrowband modulation techniques.

c. Initiate discussions with Department of Commerce (DOC) spectrum management and administrative personnel to explore the possibility of DOC assuming the lead role in the Federal Government in implementing narrowband technologies for fixed and land mobile applications.

4. NTIA should pursue discussions with the FCC to consider planning of the 216-225 MHz band for shared Government and non-Government use of narrowband technologies by the Mobile and Fixed Services.

5. NTIA, in coordination with the IRAC, should develop a means to help identify proposed Federal agency spectrum requirements which are cost-effective candidates for using narrowband technologies and which are compatible with agency mission requirements.

6. Government technical standards specifically applicable to narrowband techniques should be developed to allow maximum flexibility within authorized channels, while minimizing the interference potential to the existing FM environment.

7. For Government applications, NTIA should develop procedures and policies to accommodate these narrowband technologies to encourage their further development and deployment. The recommended methods of accommodating narrowband modulation techniques are: (a) designate existing channels for exclusive use by narrowband assignments in the 162-174 MHz frequency band; Government use of ACSB radios should be assigned with 6.25 kHz spaced channels, and use of NBFM radios should be assigned with 12.5 kHz spaced channels, (b) use of 216-225 MHz band for narrowband techniques, and (c) interleaving narrowband assignments, ACSB or NBFM, between existing 25 kHz FM channels on a case-by-case basis taking into account that geographic separation may be required.

8. NTIA should conduct further investigations of these narrowband technologies to determine the sharing potential, especially the interactions between ACSB and NBFM, and further define the performance criteria for these narrowband technologies.

9. NTIA and the FCC should develop channeling schemes for narrowband technologies which support interoperability between the Federal Government and non-Government users to the maximum extent possible.

SECTION 3

OPERATION AND USE

INTRODUCTION

Land mobile radio (LMR) is used extensively by many Government agencies to assist in accomplishing a variety of missions. Government non-military and military non-tactical land mobile spectrum requirements are accommodated on a primary basis in three radio frequency ranges: the 29.89-50 MHz, 162.0125-174 MHz, and 406.1-420 MHz frequency bands. In the parlance of the land mobile user, these three bands are also known as the "Low-Band," "High-Band" and "UHF Band", respectively. In terms of number of frequency assignments in the Government Master File (GMF), the number of assignments contained in these three bands (most of which are for LMR operations) represents approximately 30 percent of that file. The total spectrum width of these three bands occupy a little less than 46 MHz. High-Band frequency assignments, alone, account for about 25 percent of the total number in a range of the spectrum just 12 MHz wide. In addition to this proportionate number, the demand for future use of these bands is expected to increase. The growth trend for the High-Band, over the last ten years, has been on the order of five percent per year. Correspondingly, the growth trend for the UHF Band, for the same time frame, has been about 14 percent per year. The greater growth trend in the UHF Band is due in part to the congestion and lack of available spectrum in the High-Band, particularly in the major metropolitan areas. Assignment trend data also indicate that these two bands are used by the majority of Government departments and agencies. Presently, there are 43 Government departments and agencies with frequency assignments in both the High and UHF Bands. However, more than 90 percent of the assignments in these bands are divided between nine agencies and over half of the total number belong to only three agencies: the Departments of Justice, Agriculture, and Interior. Other major users of these frequencies include the Departments of Air Force, Army, Energy and Treasury. The dominant usage of these bands are for FM land mobile operations and associated single channel fixed operations. The vast majority of the assignments in the GMF for these bands list necessary bandwidths of 16 kHz. The agencies in general use conventional off-the-shelf FM land mobile radios for these operations.

Government requirements for radio spectrum to support respective agency missions differ from non-Government requirements with respect to the need for nationwide coverage areas, and missions are mandated by Congress and the President. The relationship between the basic mission of a given agency, the facilities needed to fulfill this mission, and the requirement for corresponding radio frequency spectrum space must be recognized, for these three are inseparable if the mission is to be accomplished. For example, the firefighting responsibilities of the Departments of Agriculture and Interior, established by Acts of Congress, cannot be accomplished without mobile communications for those actually fighting the fires; and the Federal law-enforcement activities of the Departments of Justice and Treasury, as well as many other agencies, require radio channels dedicated nationwide to perform their national functions.

As previously stated, the demand for land mobile communications is increasing. Since the portions of available spectrum have not expanded in proportion to the number of users, methods of providing additional channels are needed for future expansion of mobile radio. There are a number of ways to provide for additional users in a limited amount of spectrum. One approach is to re-use channels by reassigning them on demand, as is done in systems that employ "trunking" or to limit coverage areas such that the same frequency could be re-used at closer distances. Another approach is to provide more channels by reducing channel spacing. Historically, the latter approach has been used to provide more channels. Channels 100 kHz wide in the 1950's have systematically been reduced to the present 25 kHz in the High-Band and UHF Band as demand increased. Channel bandwidth requirements, however, depend on current technology. The transmitted bandwidth and acceptance bandwidth of receivers have steadily decreased as techniques have improved. Further channel reduction will depend on the verification of new technologies. The following paragraphs examine some of these techniques to be used in reducing channel bandwidths.

NARROWBAND TECHNOLOGY

In the LMR environment, the use of FM has proven successful in providing good quality communication service. Conventional FM produces excellent voice quality, freedom from many types of noise interference, a useful phenomenon called "capture effect," and other desirable features which together are responsible for its universal acceptance. Unfortunately, however, conventional FM requires a considerable amount of bandwidth relative to the bandwidth of information to achieve its goal. The necessary bandwidth of an FM transmitted signal is approximately twice the sum of the peak frequency deviation and the highest modulation frequency as follows:

$$Bn = 2(Dp + fm) \qquad (2)$$

where

Bn = necessary bandwidth of the transmitted signal in Hz.

Dp = peak frequency deviation in Hz.

fm = highest modulation frequency in Hz.

or alternately in terms of the peak modulation index (βp):

$$Bn = 2\ (\beta p + 1)\ fm \qquad (3)$$

where

$$\beta p = Dp/fm \qquad (4)$$

Conventional off-the-shelf 25 kHz FM radios used for LMR operations typically have peak deviations of 5 kHz and highest modulation frequencies of 3 kHz. Therefore using conventional 25 kHz FM radios, a 16 kHz bandwidth is needed to transmit a little more than 3 kHz of audio information. In addition, if the frequency stability of the FM equipment and the acceptance bandwidth of the receiver are taken into account, the conventional FM radio operation requires the present 25 kHz channel spacing. Clearly, the present conventional FM radio operation could not be accommodated in a reduced channel bandwidth scheme.

Numerous techniques have been proposed to provide equivalent quality with less spectrum space. Among these techniques are 12.5 kHz FM channel spacing, single sideband (SSB) and amplitude compandored single sideband (ACSB).

12.5 kHz FM Channel Spacing

As in the past, when channel bandwidths were split from 50 kHz to the present 25 kHz, the FM standards for maximum permissible frequency deviation, frequency tolerance, and adjacent channel selectivity were correspondingly tightened. Further reduction of the channel bandwidth to 12.5 kHz will require further operational constraints. With FM, the deviation permissible with any system bandwidth is proportional to the channeling employed; and, therefore, halving the channels necessarily requires that the deviation be reduced by at least a factor of two. This will result in an FM signal with an 11 kHz necessary bandwidth (substitute Dp = 2.5 kHz in Equation 2) operating in a channel bandwidth scheme of 12.5 kHz channel spacings. Smaller guard band operations, such as this, will require tighter equipment frequency stability and receiver selectivity characteristics. Improved receiver selectivity and equipment frequency stability requirements also increase the cost of the equipment. However, halving the channels also doubles the amount of channels available for increased spectrum usage.

Several investigations of 12.5 kHz FM have been made. An investigation by Japan [CCIR Doc. 8/29-E] deals with 12.5 kHz channel spacing in the 400 MHz band, which was considered as a replacement for the present 25 kHz channel spacing. These investigations started in 1976, and various problems in regard to achieving a 12.5 kHz channel spacing were surveyed. Equipment was built and a series of laboratory experiments were performed to measure the characteristics of the equipment under various conditions. Field tests were also carried out in the Tokyo metropolitan area in order to confirm the effectiveness of the 12.5 kHz channel spacing. From these considerations, it is concluded that a 12.5 kHz channel spacing is practicable using equipment meeting the technical characteristics of CCIR Recommendation 478-2. TABLE 3 indicates the final values of the transmitter and receiver characteristics achieved and which satisfy CCIR Recommendation 478-2.

Single Sideband (SSB)

SSB is presently the standard mode of voice modulation for HF communications in the 2-30 MHz shortwave bands. One major advantage of using SSB is that it occupies a much smaller bandwidth than an amplitude modulated (AM) voice signal or conventional FM. A typical spectral representation of these three signals are

TABLE 3

TRANSMITTER AND RECEIVER CHARACTERISTICS FOR 12.5 kHz CHANNEL SPACING IN FM MOBILE COMMUNICATION SYSTEM

	Item	Tentative Value	Final Value
Transmitter	Frequency Tolerance	* $\pm 3 \times 10^{-6}$ Hz	* $\pm 3 \times 10^{-6}$ Hz
	Maximum permissible frequency deviation		2.5 kHz
	Maximum modulating frequency		3 kHz
	Necessary bandwidth	*, ** 8.5 kHz	*, ** 8.5 kHz
	Conducted spurious emission: (1) for transmitter powers up to 25W (2) otherwise	* (1) less than 2.5 μW * (2) 70 dB below the carrier power	* (1) less than 2.5 μW * (2) 70 dB below the carrier power
Receiver	Local frequency tolerance		$\pm 3 \times 10^{-6}$ Hz
	Reference sensitivity	* less than 2 μV	* less than 2 μV
	Bandwidth	more than 8 kHz	more than 8 kHz
	Adjacent channel selectivity	* 60 dB below the carrier power	* 60 dB below the carrier power
	Radio-frequency intermodulation	* more than 70 dB	* more than 70 dB
	Spurious response	* more than 70 dB	* more than 70 dB
	Conducted spurious emission	less than 4 nW	* less than 2 nW

*Denotes the value in Rec. 478-2.

**This value should be 11 kHz, as stated in this report.

illustrated on Figure 1. On the FM signal, the single lines represent sidebands generated by a single tone. The carrier occupies the center of the bandwidth and one tone creates a sideband on each side of the carrier and many additional sidebands spaced at the tone frequency from each other. Since voice varies in amplitude and frequency, this illustration is of an FM voice signal averaged over a period of time. The AM voice signal differs from the FM by the fact that a transmitted single tone generates only one sideband tone on each side of the carrier. Therefore, typical AM voice is substantially narrower in bandwidth than conventional FM. AM systems are routinely transmitted in 10 kHz channels. The SSB signal shown next is basically the same as the AM signal, except that the redundant parts of the signal are removed. The lower sideband is a mirror image of the upper sideband and so it is not necessary to convey information. The carrier wave does not relay information so it too can be eliminated; therefore, the SSB signal bandwidth is much narrower than that of the AM signal.

Conventional SSB has several drawbacks that have prevented universal acceptance by the LMR community; therefore, it has been rejected as a more spectrum efficient replacement for conventional FM in the past. One of these drawbacks is that SSB modulation is very intolerant of tuning errors. The frequencies are all translated by the tuning error. A tuning error of 100 Hz at HF will result in a voice signal that makes the speaker sound like Donald Duck. All high frequency SSB radios have a "clarifier" control to fine tune the oscillator and clear up the sound. The problem, however, is worse at VHF because a tuning error of only a few parts per million results in the same effect. Another problem is that in SSB modulation, unlike AM and FM, the carrier wave is suppressed. This means that power is transmitted only when modulation takes place, and has the following effect on the SSB. When the speaker pauses, the power output of the transmitter goes to zero. The receiver circuitry has no way of knowing whether this is the end of a transmission, there was a signal fade, or there was actually a pause. In any case, the gain of the receiver will increase. When the speaker resumes, the gain would again reduce. As a result, in typical SSB systems the gain varies up and down rapidly and the resulting sound quality is reduced. The lack of an exact tuning reference that makes it very difficult to design an effective automatic gain control (AGC) also prevents effective use of squelch, tone-coded squelch, and other signaling systems. One other important disadvantage is that SSB systems do not exhibit the "capture effect" that is inherent in FM systems. The FM capture effect causes the desired signal to completely eliminate interference from the undesired one if it is more than 8 dB stronger. With conventional SSB, both signals would be heard although the undesired signal would be much weaker. This is important when two or more systems use the same frequency in nearby cities which would be likely to occur in a crowded land mobile environment.

Research, however, has been accomplished to uncover ways to circumvent these technical difficulties of conventional SSB which would make it more acceptable to LMR applications. One innovation was the addition of a low-level pilot tone (-5 to -20 dB with respect to peak envelope power) to the audio band. The pilot tone provides a reference for automatic tuning and AGC, positive squelch action, and allows tone squelch and tone signaling. The greater part of research of pilot tone SSB has concentrated upon three systems which differ in the positioning of the pilot within the audio band. These systems are: (a) pilot carrier SSB

FM

AM

SSB

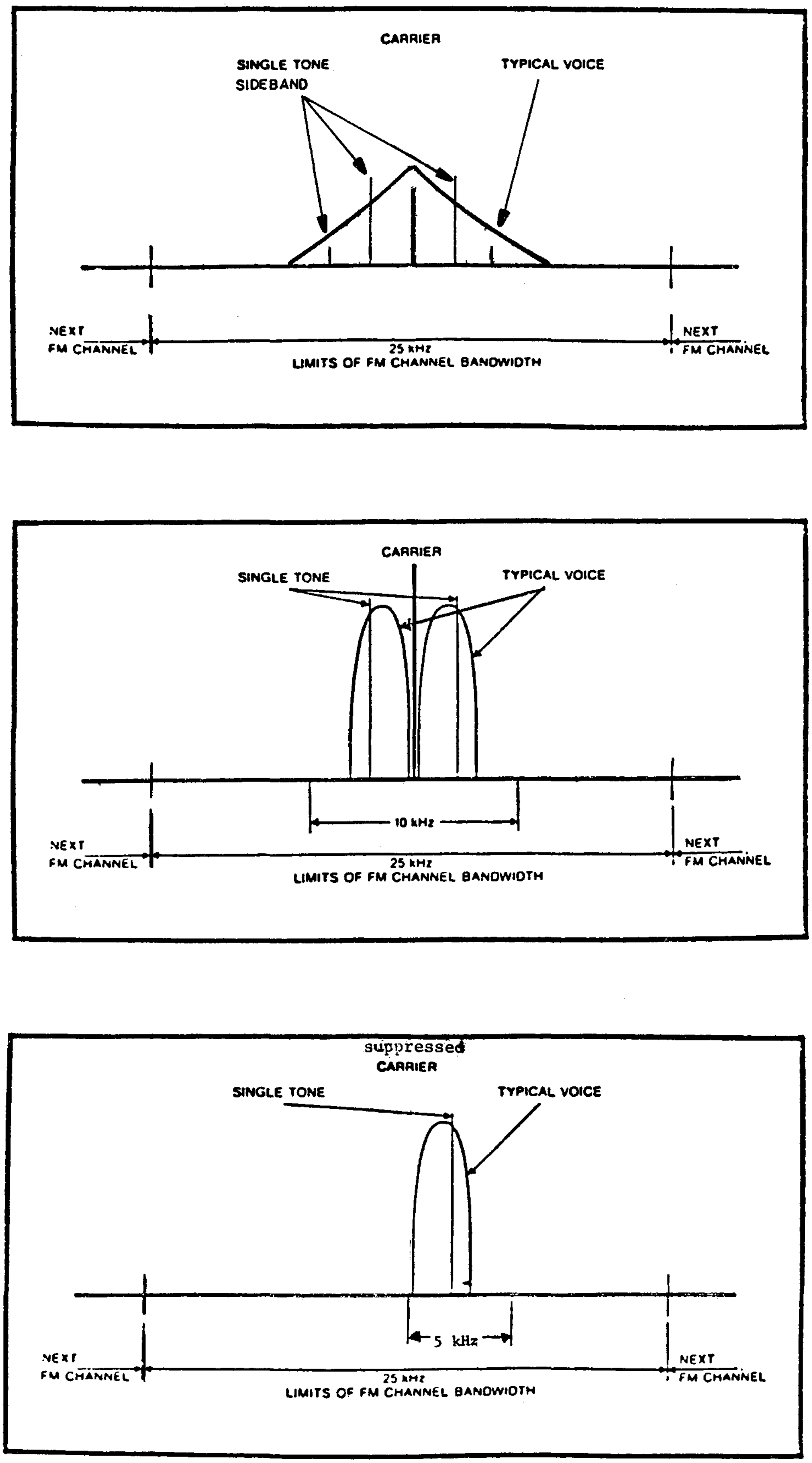

Figure 1. Comparison of Voice Spectrum Shapes Using FM, AM and SSB Modulations.

developed by Philips Research, (b) pilot tone-in-band (TIB) SSB researched at the University of Bath, and (c) pilot tone-above-band (TAB) SSB investigated at Stanford University.

At VHF, no one system has clearly emerged as superior. Philips Research Laboratories in the United Kingdom (UK) has been working on SSB land mobile radio for five years. The need for these investigations arose because, even though the UK has successfully used 12.5 kHz channeling at VHF for over a decade, the shortage of capacity in urban areas was threatening to restrict further expansion. Some experiments were carried out using AM and FM in 6.25 kHz channels. The SSB work at the Philips Research Laboratories has included the design and testing of equipment at 88, 170, 450 and 960 MHz. These experiments indicated that SSB with the addition of a low-level pilot carrier can give a performance suitable for land mobile purposes.

The research at the University of Bath centered around tone-in-band SSB for more extended applications to the 450 and 900 MHz band. The original aim at Bath was to achieve a spectrum efficient speech system which would offer: (1) the greatest degree of adjacent channel protection, (2) a good correlation between fades on the pilot tone and fades on the audio signal, and (3) a large symmetrical pull-in range for frequency control circuitry to operate. These three points were felt to be particularly important if SSB were to be eventually extended in its VHF form to the higher bands and are basically the disadvantages of placing the reference pilot to one side of the audio spectrum (i.e., the other two systems being researched). Tone-in-band SSB, in which part of the audio spectrum is removed and tone is inserted, has proven to be satisfactory for speech. The main disadvantage is that the tone is not transparent with all data systems. The tone-above-band (TAB) SSB investigated at Stanford has been received favorably at VHF, and TAB SSB is produced commercially by two companies. Many of the technical problems of conventional SSB in LMR operations were solved by the use of a low-level pilot signal. One other problem remains to be addressed: a capture effect similar to that of FM. The Stanford group, in addition to their development of TAB SSB, offered two other innovations not previously used in land mobile radio: frequency companding and amplitude companding. Frequency companding was subsequently dropped because of unfavorable acceptance of voice quality but amplitude companding was retained. Thus, the label Amplitude Compandored Side Band or ACSB came into being.

Amplitude Compandored Single Sideband (ACSB)

The UHF Task Force, Office of Plans and Policy, Federal Communications Commission, sponsored work in spectrum-efficient technology carried out by the Communication Satellite Planning Center at Stanford University. The results of the work, presented to the Commission in February 1978, indicated that use of Single Sideband Radio (SSB) with amplitude compandors could provide major improvements to spectrum efficiency in mobile radio.

Subsequent work, also sponsored by the FCC, has confirmed the original conclusions and refined the design of Amplitude Compandored Sideband Radios (ACSB). A final report (Lusignan, 1980) summarizes work on the use of ACSB in the mobile radio bands.

For SSB, the noise level that is heard at the speaker is the same as that received by the radio receiver; there is no signal-to-noise improvement in SSB equivalent to the FM capture effect. The noise problem is solved by the use of compandors. The compandors are similar to the circuits used in the telephone industry and in satellite links. A compandored circuit is a variable gain amplifier in the transmitter that increases the volume of weak sounds and reduces the volume of strong sounds. While in the receiver, the compandored circuits restore the voice to its normal level. An illustration of a four-to-one compandor system is showm in Figure 2. In a 4:1 compandor system, unwanted noise signals (being on the same channel) are 8 dB weaker in strength at the receiver than the wanted signal; expandoring would reduce the unwanted signals by more than 32 dB with respect to the wanted signal in the audio output while restoring the normal dynamic range and audio quality.

In summary, the techniques employed in the ACSB radio attempt to overcome the disadvantages of SSB radios in LMR operations. The pilot tone was added to provide or reference for automatic tuning, reference for automatic gain control, positive squelch action, and allows tone squelch and tone signaling. Compandors are used to improve the signal-to-noise ratio to provide a function similar to the FM capture effect.

OPERATIONAL EXPERIENCE

Operational experience in narrowband land mobile radio is somewhat limited in the United States. ACSB deployments include 150-180 systems in the private business sector. Narrowband FM systems are produced for foreign use by U.S. manufacturers and deployments are unknown in the United States. Several companies and Government agencies have made independent operational analyses of narrowband land mobile technology. These experiments were conducted using various methods and covering several operational conditions (i.e., land mobile, land mobile with repeaters, maritime mobile, facsimile, voice scrambling).

National Telecommunications and Information Administration (NTIA)

NTIA's operational experience with narrowband land mobile is limited to several months of testing ACSB, NBFM, and wideband (25 kHz) FM systems. The systems in use were configured as outlined in Section 4 and Appendix A, and operated in a simple base-to-mobile environment. Occasional base-to-base links were established with the FCC lab in Laurel, Maryland (32 km distance). The operation and test area could be considered a moderately congested RF environment. During the period of testing, NTIA made direct comparisons of ACSB, FM and NBFM systems to determine operational range, voice quality, and limited adjacent channel interference behavior. The following discussion summarizes the details of Appendix A and the field tests of the NBFM in Section 4.

The FM system and the ACSB system had virtually the same operational range characteristics under the same output power (average power for FM and peak envelope power for ACSB) and antenna gain conditions. To maintain acceptable communications, the FM system and the ACSB system averaged the same, 13.1 km (8.2 miles). The zone of good communications averaged approximately the same for

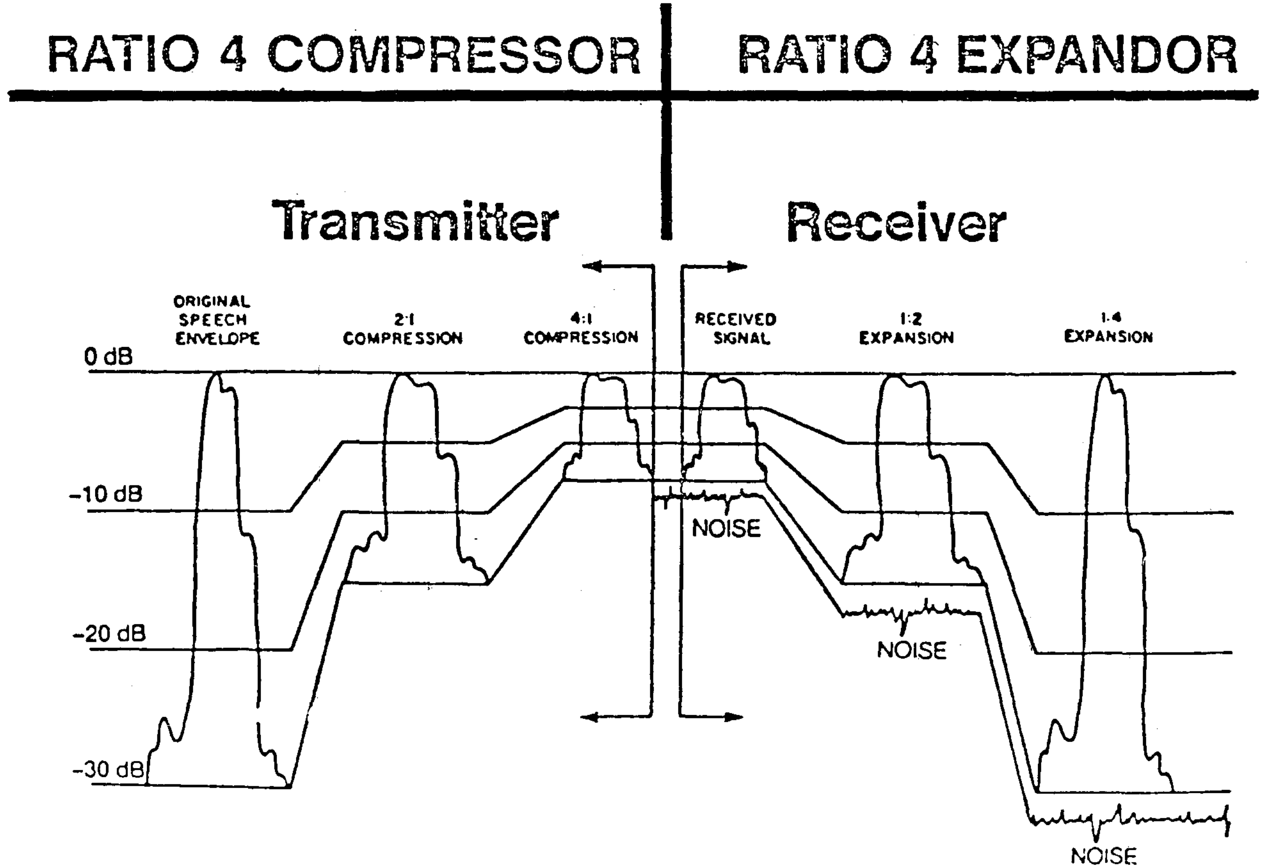

Figure 2. A Four-to-One Compandor System.

FM and ACSB, 8.0 km (5.0 miles). The average values for NBFM for acceptable and good communications were 10.3 km (6.4 mi) and 7.5 km (4.7 mi), respectively. Testing was done in an area of gentle to moderate rolling hills.

The voice quality of both ACSB and NBFM was similar to 25 kHz FM in a high signal environment. In a low signal environment, the voice quality of both narrowband techniques is not as good as that of the 25 kHz FM, the voice quality of NBFM being slightly better than that of ACSB. Under this condition, the NBFM voice signal is subject to distortion probably due to noise pops and capture, while the ACSB voice signal is subject to distortion probably due to companding and pilot tone circuitry and/or reduced audio bandpass.

Federal Communications Commission (FCC)

A test program to determine certain technical characteristics of ACSB was initiated by the FCC in February 1982. The study was undertaken to examine the spectrum efficient properties of ACSB. It consisted of both objective and subjective field and laboratory measurements, and the results were published in October 1983 (FCC, 1983). The study acknowledges that "ACSB is a viable communications medium that compares favorably with FM under certain conditions." However, it was pointed out in this study, that advances in ACSB technology were not likely to improve ACSB interference to FM (adjacent channel), but may permit closer ACSB-to-ACSB channel spacing and better ACSB cochannel re-use performance.

Standard Oil Company (Indiana)

During 1982, Standard Oil Company of Indiana conducted evaluation testing of ACSB radios in a land mobile and maritime mobile environment (Standard Oil Company, Indiana, 1982). The offshore testing was conducted between a base station in Dulac, Louisiana, and vessels that service offshore platforms. The land mobile testing was conducted at the Standard Oil Radio Laboratory in Manhattan, Illinois, about 72 km (45 miles).

The offshore tests consisted of range comparisons of ACSB, FM and Facsimile (FAX) on the ACSB system only. The following general conclusions were made.

1. FAX transmissions were successfully received using the ACSB system.

2. The maximum range for voice transmissions was found to be about 30 percent greater for the ACSB system than for the FM system under the same operating conditions (maritime mobile situation).

3. Davotek voice scramblers were used during testing and found to be compatible with the ACSB system.

During land mobile testing, the ACSB system was found to meet or exceed the performance of the FM system in the areas of range, intelligibility, ignition noise, flutter effect, cochannel capture effect, facsimile, scrambled voice, DTMF signaling, and geophysical data transmissions. Voice appeared to sound more natural on FM than on ACSB. Interference testing indicated that ACSB will cause severe degradation to an FM system 7.5 kHz away. At 12.5 kHz spacing, interference is apparent out to 1.6 km (1 mile). It was found that the potential of FM to interfere with ACSB was much less than the reverse case.

Martin Marietta

Martin Marietta Aerospace conducted ACSB and 25 kHz FM comparison testing in January and February 1982 (Martin Marietta Aerospace, 1982). The following summarizes the results.

1. The system tested included two mobile stations and one base station employing Sideband Technology, Inc., ACSB Pioneer 1000 Mobile Radio units. These units were employed on a daily courier service in the southwest Denver metropolitan area. The terrain varies from rolling foothills to flat, highly developed urban areas. Tests varied from several hundred meters to 26 km (16 miles).

2. During the tests, no significant interference, noise or other reception impairments were noted. The overall quality exceeded that experienced on standard mobile radio nets that operate in the same area.

Storno A/S

The Danish affiliate of General Electric, Storno A/S, conducted a series of tests designed to make a comparison of narrowband FM, ACSB and wideband FM, among others (Storno A/S, 1980). The systems were compared with respect to signal quality, speech intelligibility, propagation range, spectrum utilization, applicational flexibility and pulse noise susceptibility. The most important results of the study are as follows.

1. Both 25 kHz FM and 12.5 kHz FM provide better receiver sensitivity than ACSB at 12 dB SINAD (5 to 6 dB better). However, at 20 dB S/N (voice peak to quieted noise) ACSB provides better sensitivity than 12.5 kHz FM and about the same as 25 kHz FM.

2. At 20 dB weak syllable (-20 dB relative to peak syllable level) to noise ratio, both narrow and wideband FM are equally more sensitive than ACSB.

3. Both FM systems provided better speech intelligibility than ACSB.

4. For the same peak transmitter power, the greatest range was provided by 12.5 kHz FM.

5. For voice as well as for tone modulation, ACSB needed much higher cochannel protection margins than FM.

6. The addition of multipath fading increased the protection margin by only a few dB. The 12.5 kHz FM and 25 kHz FM margins were almost equal.

7. ACSB was shown to have only slightly higher spectrum utilization than narrowband FM.

8. FM systems will generally tolerate a 10 to 25 dB higher pulse noise (60 Hz) level than ACSB.

9. The highest level of application flexibility is provided by the system with the largest channel bandwidth, i.e., 25 kHz FM.

The general conclusion of the Storno A/S study is that 12.5 kHz FM provides the best compromise between transmission quality, spectrum utilization and application flexibility.

Philips Research Laboratories

Philips Research Laboratories in the United Kingdom have been studying the feasibility of SSB for mobile radio for years (United Kingdom, 1980). Some recent field tests were conducted to compare SSB and FM performance. ACSB was not considered because Philips feels that amplitude companding may give some improvement in performance but is not essential. For all measurements, peak envelope power average of the SSB system was set equal to the power average of the FM system. The studies found that:

1. For strong received signals, very little difference in quality was detected; only experienced listeners can tell one from the other readily.

2. For weak signals, the recovered audio sounds "different." The fading of the FM signal is more obtrusive but the effective range of the equipments is the same. Different individuals prefer one or the other system in about equal numbers. Ignition is equally troublesome in each system.

3. For intermediate signals, the FM has less background noise but the occasional loud noise bursts due to deep fades are annoying. The SSB has slightly higher background noise but the fades are much less disturbing.

4. When cochannel interference is present, the differences between the SSB and FM systems are not very great and are unlikely to have much effect on the relative utilization of one system or the other under mobile conditions.

SUMMARY

Generally, operational experience with narrowband land mobile technology is limited to the private sector. Most exposure to spectrum efficient land mobile has been with ACSB. Several companies have carried on independent analyses of ACSB in varied operating environments, and NTIA and the FCC have gained limited operational experience through experimental usage. A number of other companies are using ACSB land mobile radios in their operations. Use of narrowband FM land mobile radios is limited to foreign markets, and investigations have shown this technology to have merit as a spectrum efficient approach.

The following points summarize the major conclusions drawn as a result of this operational and experimental usage.

1. NTIA's experience shows that ACSB and Wideband FM (WBFM) are approximately the same in communication range and general operational behavior. The voice quality of ACSB and NBFM was similar to 25 kHz FM in a high signal environment. However for a low signal condition both the ACSB and NBFM experienced distortion. For FM the distortion was probably due to noise pops and capture, and for ACSB it was probably due to factors such as companding, pilot tone circuitry, and/or reduced audio bandpass.

2. Other accounts indicate a wide variation of experiences ranging from definite superiority of one technology over the other to close comparisons of range and voice quality characteristics.

3. Both ACSB and narrowband FM are viable spectrum efficient LMR technologies that work in actual operating environments.

SECTION 4

SPECTRUM EFFICIENCY

INTRODUCTION

In this section the spectrum efficiency of the ACSB and NBFM radios is addressed. The spectrum efficiency of one system relative to another is defined in terms of bandwidth, space and time required by both systems. This is a general definition and can be used for a large class of communication systems. The relative spectrum efficiency is calculated both for the ACSB and NBFM relative to conventional 25 kHz FM using two different approaches. The first one considers the case of one base station interfering with another base station or its associated mobile unit. This is referred to as the one-on-one approach. The second one considers a large number of base stations that are randomly located in a given area. This is referred to as the simulation approach. Each of these approaches uses a computer program to calculate the respective spectrum efficiency values. Inputs for these programs are the nominal characteristics of the systems (e.g., transmitter power, antenna gain, propagation parameters, receiver sensitivity, etc.) and the cochannel and adjacent signal protection ratios that were measured on the ACSB and NBFM radios. Since these measured parameters were a vital input to the computer programs, the measurements on the ACSB and NBFM made by NTIA and the FCC are discussed in this section along with an analysis of the results.

DEFINITION OF SPECTRUM EFFICIENCY

For purposes of this analysis the spectrum efficiencies of the two narrowband modulation techniques were calculated using the Technical Spectrum Efficiency Factor (TSEF) as defined by the TSC of the IRAC. Mathematically this factor can be expressed using terms of the following type:

$$TSEF = \frac{B_r \times T_r \times S_r}{B_s \times T_s \times S_s} \qquad (5)$$

where:

B_r is the bandwidth the reference system denies to others,

T_r is the time the reference system denies to others,

S_r is the physical space (e.g., area) the reference system denies to others,

B_s is the bandwidth denied by the evaluated system,

T_s is the time denied by the evaluated system, and

S_s is the physical space denied by the evaluated system.

Both the reference and evaluated system accomplish the same mission of voice analog communication. The reference system chosen for this analysis was a high-quality state-of-the-art conventional 25 kHz FM system.

MEASUREMENT OF ACSB

In order to thoroughly understand the technical aspects of a relatively new land mobile technology and to investigate its likely behavior in the existing environment, a series of laboratory tests was conducted to measure the technical characteristics of the equipment.

A joint NTIA-FCC effort was planned and a test plan was written to verify the operational characteristics of ACSB and to determine the interference/susceptibility potential of the technology (NTIA/FCC, February 1982). The plan was organized under three phases of tests including objective laboratory measurements (verify specifications), subjective laboratory measurements (cochannel and adjacent channel interference) and subjective field tests (operational behavior). Due to limitations in resources, NTIA and the FCC pursued individual portions of the measurement plan. The major differences involved NTIA accomplishing detailed objective laboratory measurements and subjective field tests, while the FCC performed subjective laboratory and field tests.

The adjacent signal interference (ASI) degradation criteria used by NTIA was a 12 dB SINAD signal which would represent the minimum acceptable audio quality. This is similar to the EIA measurement method for FM radios. It was also decided that two steps of degradation would be used in the ASI tests: 18 dB SINAD degraded to 12 dB SINAD and 12 dB SINAD degraded to 6 dB SINAD. An 18 dB SINAD signal is considered to be a good quality signal; a 12 dB SINAD signal is generally considered to be "just acceptable" audio quality; and a 6 dB SINAD signal is generally considered to be of unacceptable audio quality. These two steps would give a quantitative indication or measure of the susceptibility of the desired signal to a cochannel or adjacent channel interfering signal. This method offers several advantages. The results are repeatable, and it does not require cumbersome procedures such as articulation score (AS) tests.

The degradation criteria selected by the FCC for their ASI tests were subjective in nature. Data obtained from the measurements reflected ratios of the input desired voice signal to the undesired (or interfering) voice signal for two levels of interference (degradation). These ratios are referred to as the input desired-to-undesired (D/U) or input signal-to-interference (S/I) ratios and are defined in the Radio Regulations as protection ratios. The levels of degradation used were "just noticeable" and "words missed" based on the subjective opinion of the listener (FCC, 1983).

National Telecommunications and Information Administration (NTIA)

NTIA funded the Electromagnetic Compatibility Analysis Center (ECAC) to conduct a series of laboratory measurements on selected ACSB and conventional FM land mobile radios. The resultant report was published as NTIA-CR-83-25 "Interference Measurements on Amplitude Compandored Single Sideband (ACSB) Land Mobile Radio." A general discussion of the conduct and results of this effort follows.

The major objectives of the measurement program were to:

- o Validate nominal characteristics,
- o Reveal the compandored signal characteristics, and
- o Determine ASI interactions of the systems tested.

The approach used included obtaining a basic understanding of the design and operation of ACSB land mobile radios, measuring the nominal characteristics of the ACSB and FM radios used in the study (STI Pioneer 1000, Motorola MAXAR, and G.E. MASTR Progress Line), and investigating the EMC interactions by performing numerous interference tests. During the testing, the manufacturer of the ACSB radios, STI, provided new audio boards for the receivers with improved audio quality and sensitivity. Tests involving the ACSB receiver were repeated with the new audio boards installed. Tape recordings were made of all interference tests.

Each of the transceivers were initially subjected to a series of tests to verify nominal characteristics supplied by the manufacturer. The parameters included power output,[1] emmission spectrum, frequency stability, sensitivity, selectivity and dynamic range. As a result of this preliminary testing, it was found that the STI ACSB, Motorola FM, and the G.E. FM units generally met the manufacturers specifications.

Prior to conducting the interference ACSB tests, two ACSB test parameters had to be identified: the frequency of the tone used to modulate the transmitter of the desired signal and the pilot-to-tone modulation ratio of the desired signal link.[2]

Since the EIA SINAD method for evaluating the performance of FM systems in the Land Mobile Service employs a 1000 Hz tone as the modulating frequency, it was desirable to determine if the 1000 Hz tone would be acceptable for this evaluation. Figure 3 depicts a plot of audio response vs frequency in Hz. The results show that at 1000 Hz the response is within $\pm$ 2 dB of the maximum response of the system, and therefore 1000 Hz was chosen as the modulating frequency for the ASI tests.

To determine the pilot-to-tone modulation ratio (Ap/Am)[3] that would result in the maximum sensitivity, a 1000 Hz tone was used and various ratios were employed while observing the output for both 18 dB and 12 dB SINAD. The results (see Figure 4) show that a pilot-to-tone (Ap/Am) ratio of -5 dB produces maximum sensitivity. However, in a test using a recorded male voice reading from a Harvard list of phonetically balanced sentences (a more realistic determination), the Ap/Am was measured at -10 dB. Since this is near the point of maximum sensitivity and represents the average voice tone used, -10 dB was selected as the pilot-to-tone ratio for the ASI testing.

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[1]Peak-envelope-power was considered a more practical measure of transmitter power for ACSB than the suggested "Peak-syllable-Power" (FCC, 1983).

[2]This is not to be confused with the pilot tone-in-band (TIB) and pilot tone-above band (TAB) discussed in Section 3. The "tone" in this context is a modulating signal frequency.

[3]This designation was used in the ECAC measurements (NTIA, 1983) for the ratio of pilot to modulating signal power.

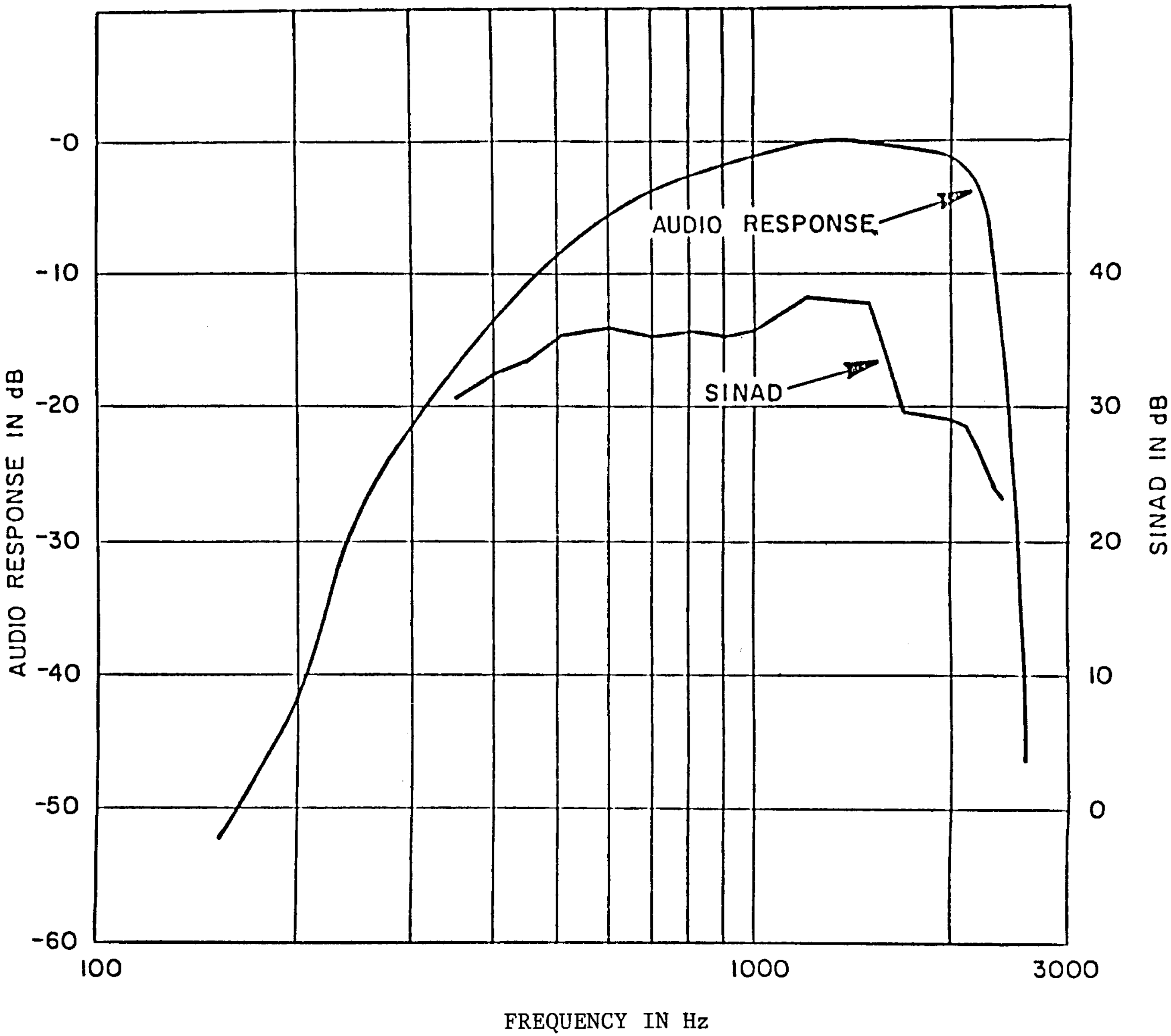


Figure 3. STI ACSB System (TX-RX) Audio Response with New Audio Boards.

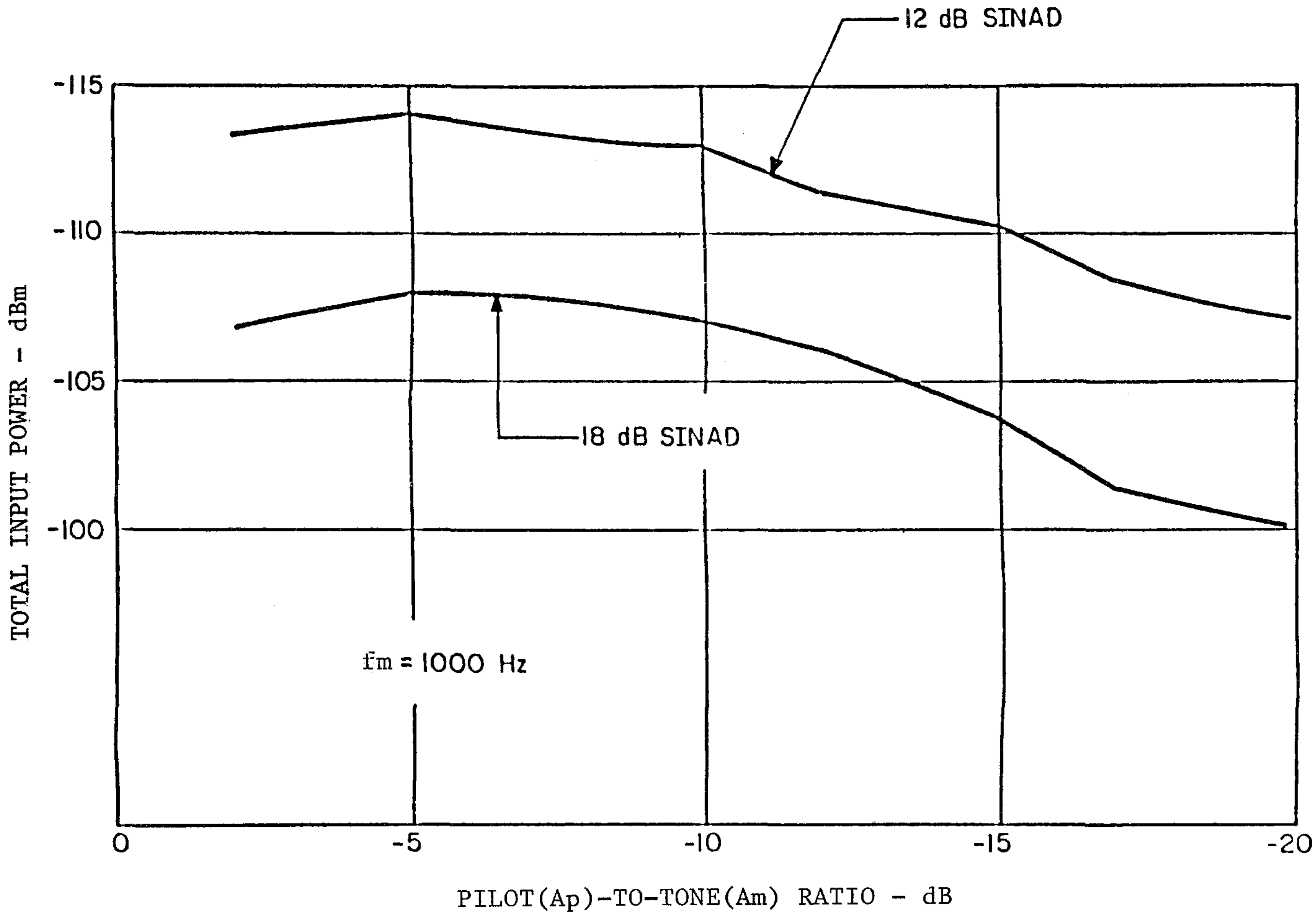


Figure 4. Total Input Power for 18 dB SINAD and 12 dB SINAD versus Ap/Am Ratios.

ASI tests were conducted with both the original and the new audio boards installed. Only those tests affecting the ACSB system as the victim were repeated with the new audio boards installed. ASI tests were conducted under the following situations: ACSB interfering with ACSB, G.E. FM interfering with ACSB, Motorola FM interfering with ACSB, and ACSB interfering with Motorola FM. The tests were run with as many off frequency Δf combinations as possible, and for some ΔF's, a fader was used. A fader is a device that simulates multipath fading.

The method for the ASI tests used a 1000 Hz tone as the desired signal and voice-modulated noise. Figure 5 shows the spectrum of voice-shaped noise used in this test as the undesired signal. The desired test tone selected was at or near the maximum audio response frequency and the pilot-to-tone ratio used for the "desired" signal was -10 dB (a level at which the sensitivity was maximized). The desired signal was then coupled into the desired receiver and the input level was adjusted until the output was at an 18 dB SINAD level. An interfering signal was then inserted and increased in intensity until the output SINAD was 12 dB. The level of the interfering signal was recorded and the tests were repeated for a 12 to 6 dB degradation at the SINAD level. By measuring input desired signal power before degradation and the interfering power required to degrade the SINAD, the input signal-to-interference (S/I) ratio was obtained. Recordings of all tests were made using a taped male voice as the desired and interfering signals. (Substituting for the 1000 Hz tone and voice modulated noise) in order to enable the listener to form a qualitative opinion. Tests for a variety of ΔF's were conducted and the results are represented in Figures 6 (ACSB vs ACSB, desired vs undesired), 7 (G.E. FM vs ACSB), 8 (Motorola FM vs ACSB), and 9 (ACSB vs Motorola FM). These results are discussed in the summary of this section.

Federal Communications Commission (FCC)

The Federal Communications Commission conducted an independent analysis of ACSB technology compared to conventional FM (FCC, 1983). The objectives of the FCC study were to determine:

- o How ACSB affects the existing FM environment,
- o The re-use potential of ACSB channels, and
- o The ACSB-to-ACSB minimum channel spacing.

The FCC measurement program was separated into four phases: objective laboratory measurements (transceiver nominal parameters), subjective laboratory measurements (static cochannel and adjacent channel protection ratios), subjective field measurements (dynamic cochannel and adjacent channel protection ratios), and objective field measurements (field intensity, non-interfering). The study resulted in establishing protection ratios (S/I or D/U ratios) using various desired/undesired system combinations, power levels, and frequency separations. For purposes of comparison the D/U ratios obtained by the FCC for ACSB interfering with ACSB and ACSB interfering with 25 kHz FM are plotted with S/I ratios for the NTIA measurements for the same conditions. The results are shown in Figures 10 and 11 respectively. It is interesting to note that for the condition of ACSB interference to ACSB the results obtained by the two test

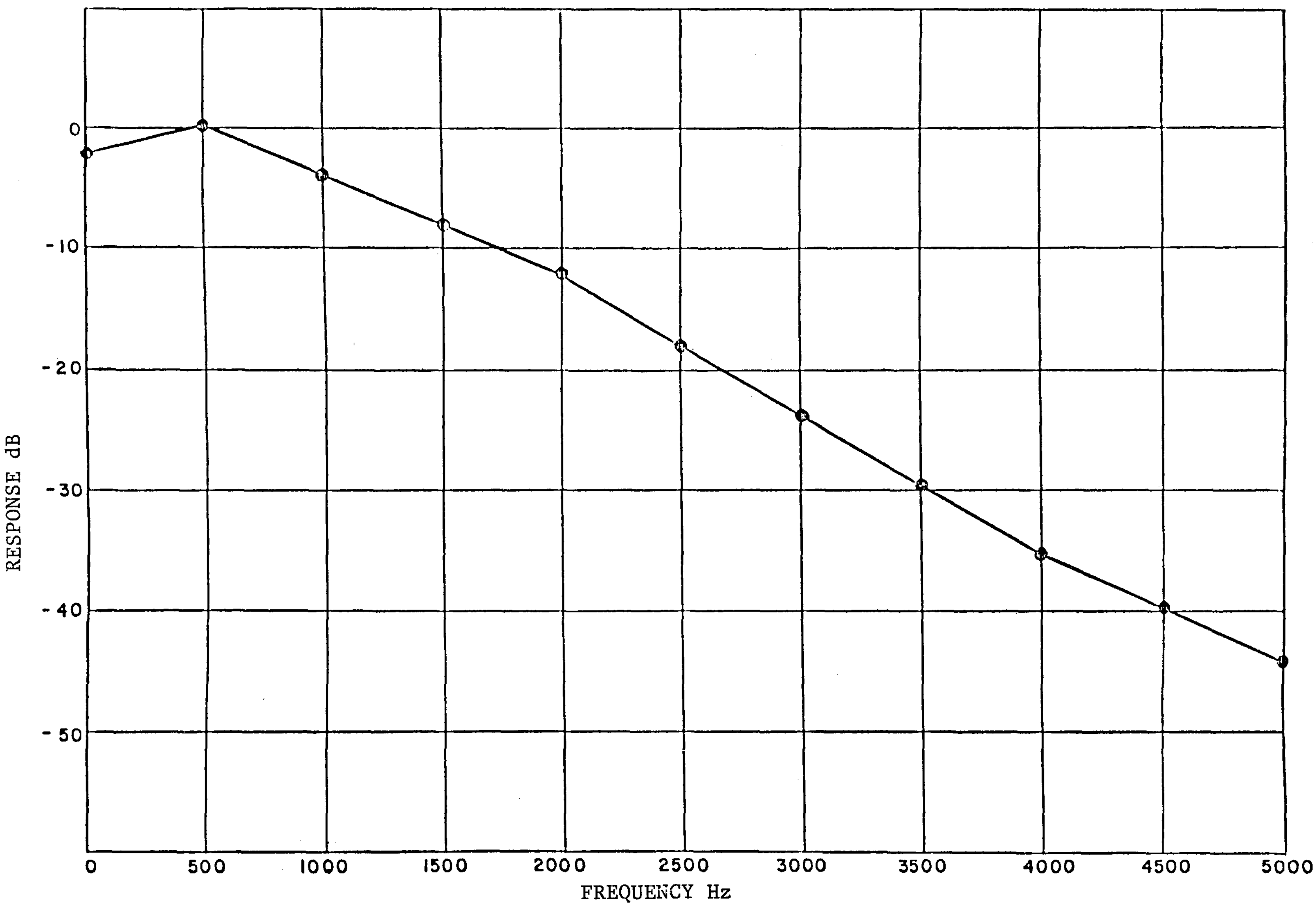


Figure 5. Spectrum of Voice-Shaped Noise Used as Undesired Modulation in ASI Tests.

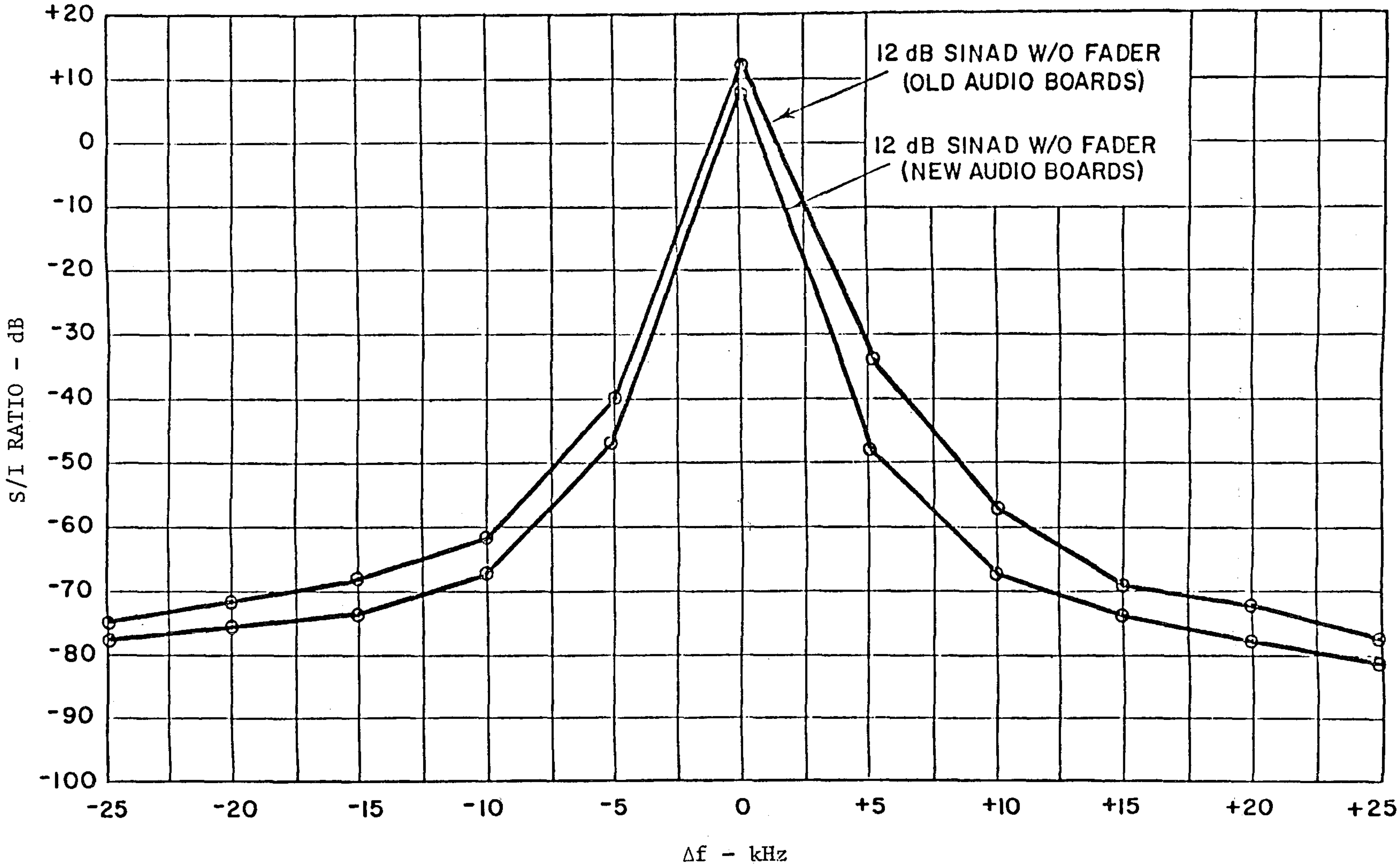


Figure 6. S/I Ratio Versus Δf for STI ACSB Interfering with STI ACSB with Original and New Audio Boards.

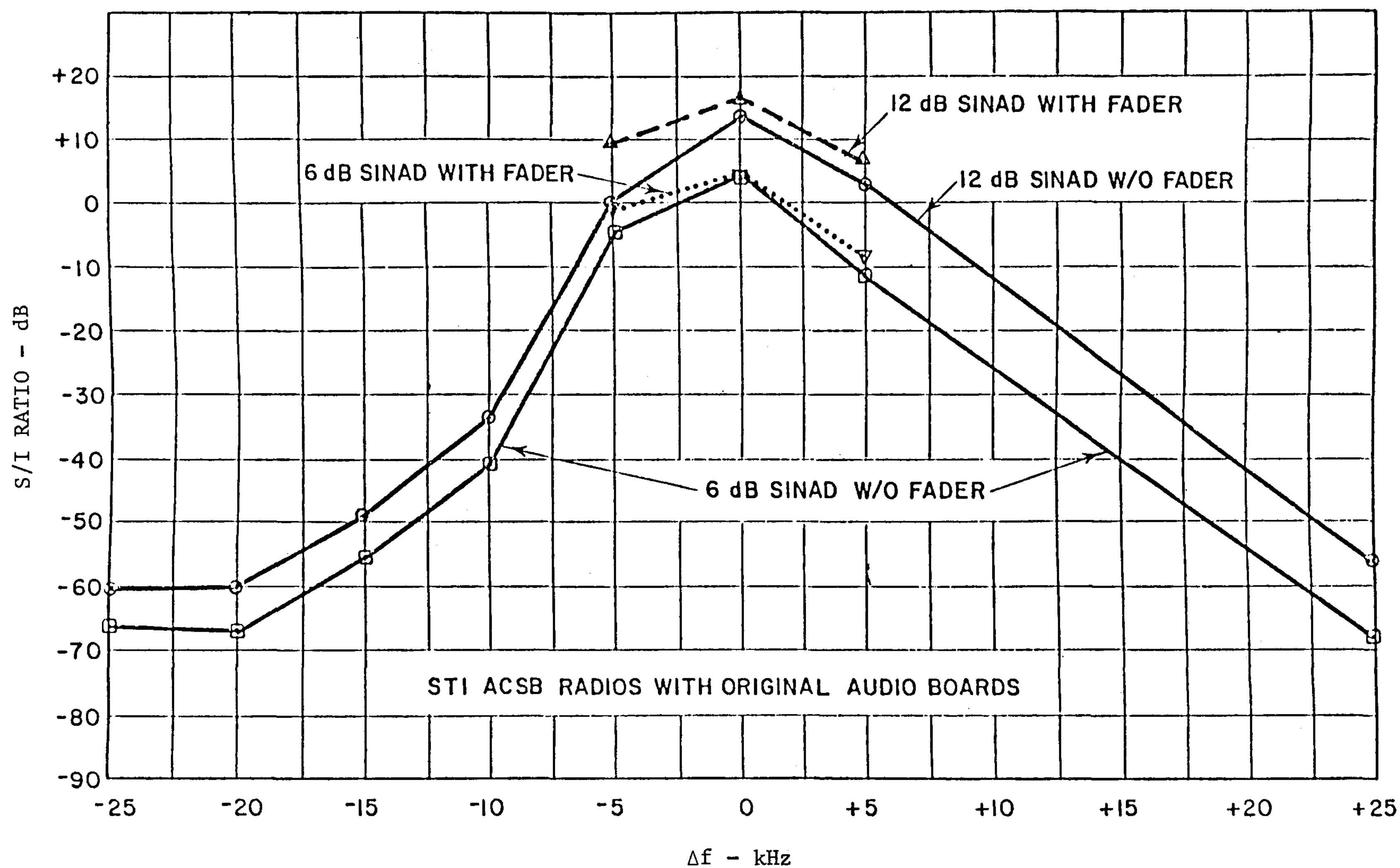


Figure 7. S/I Ratio Versus Δf for GE FM Interfering Transmitter with STI ACSB with Original Audio Boards.

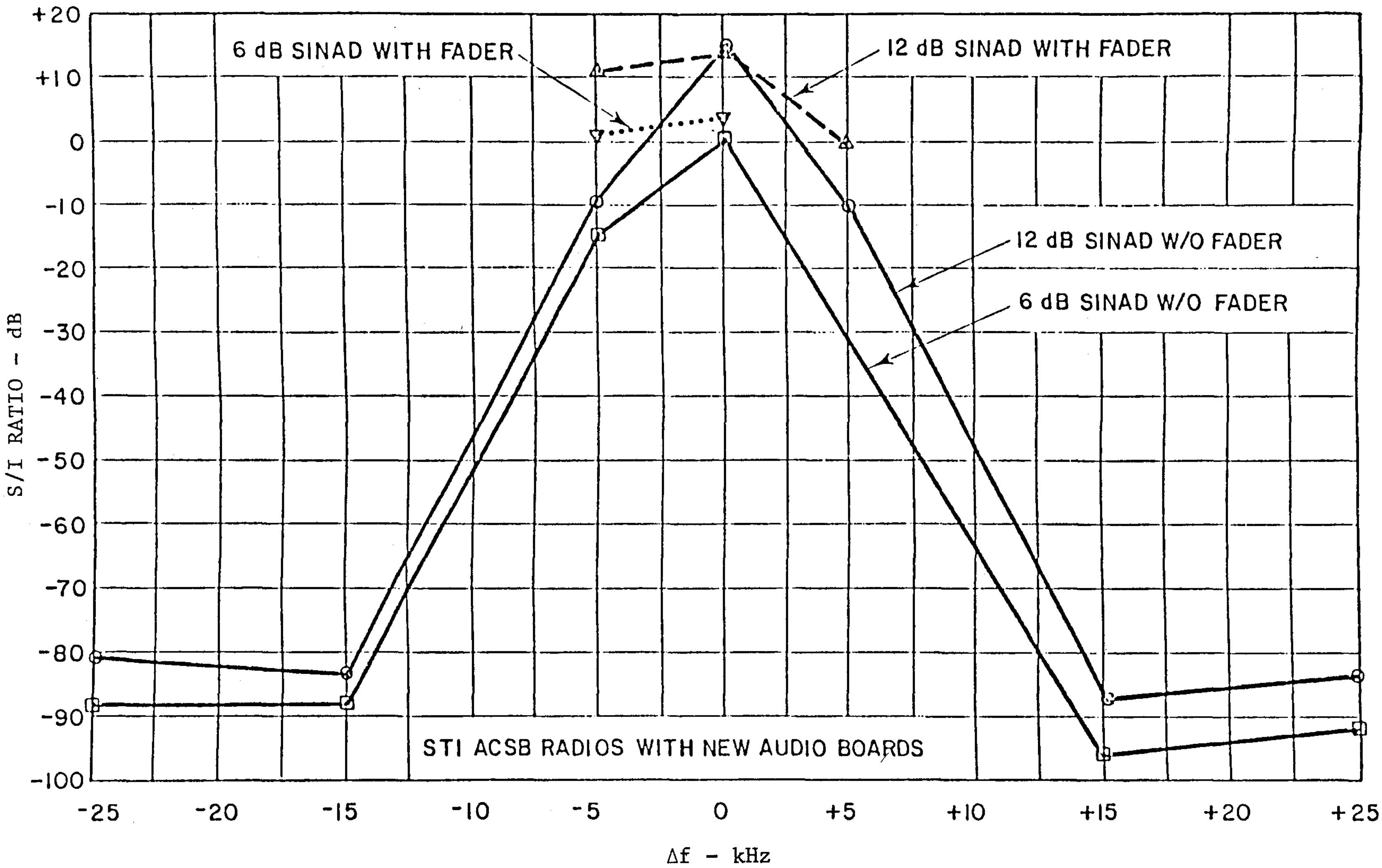


Figure 8. S/I Ratio Versus Δf for Motorola FM Interfering with STI ACSB with New Audio Boards.

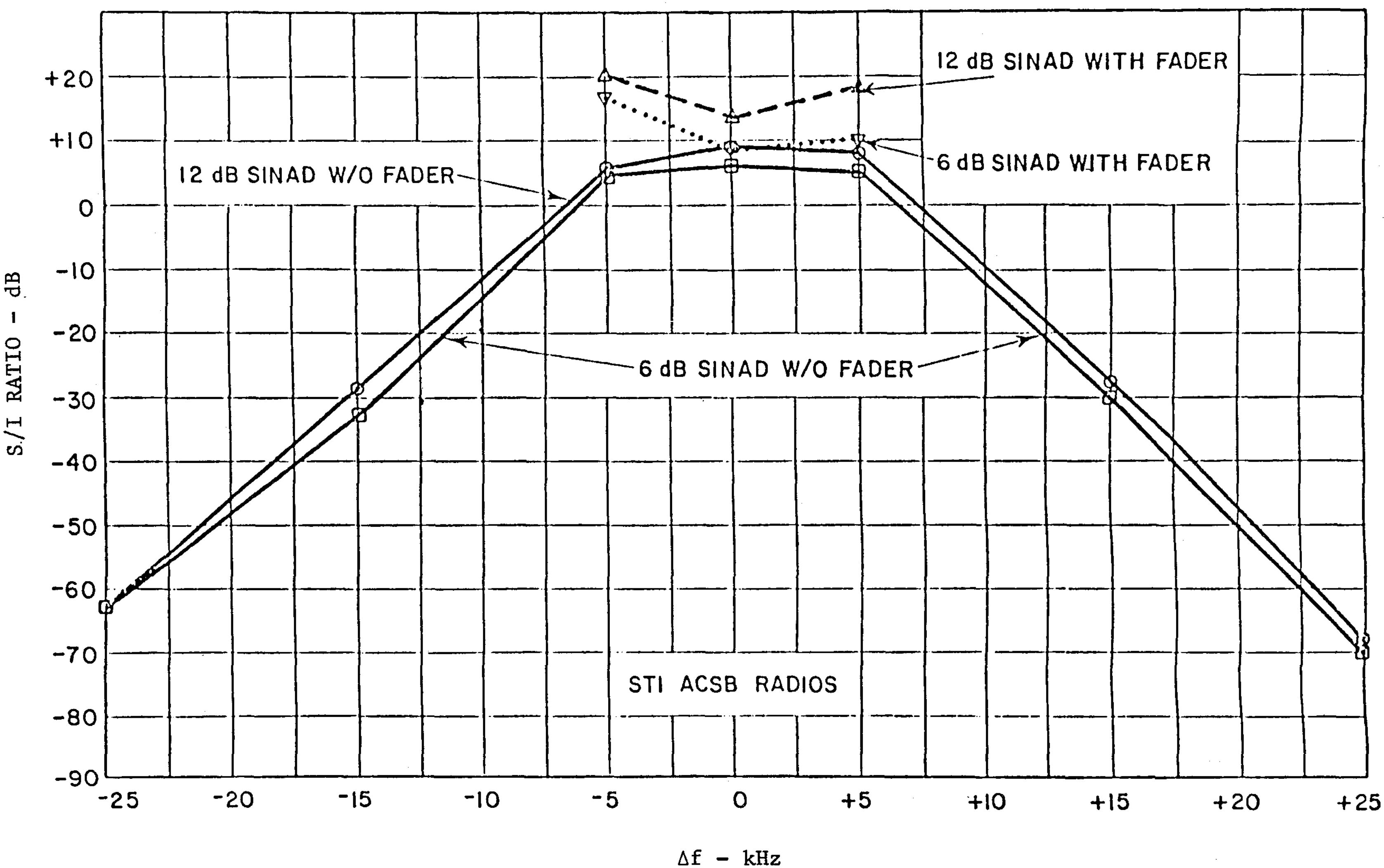


Figure 9. S/I Ratio Versus Δf for STI ACSB Interfering with Motorola FM.

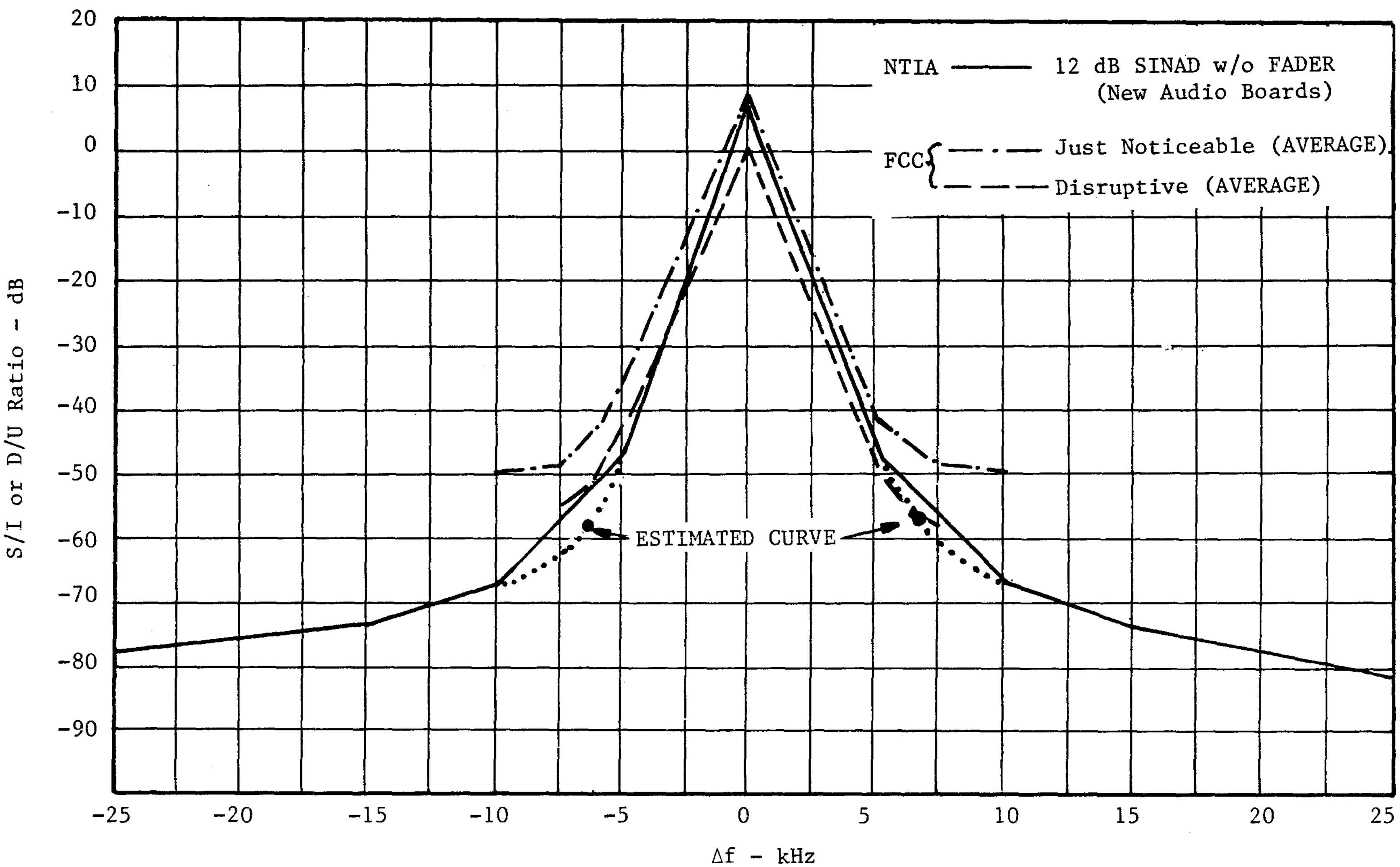


Figure 10. S/I or D/U Ratio Versus Δf for STI ACSB Interfering with STI ACSB

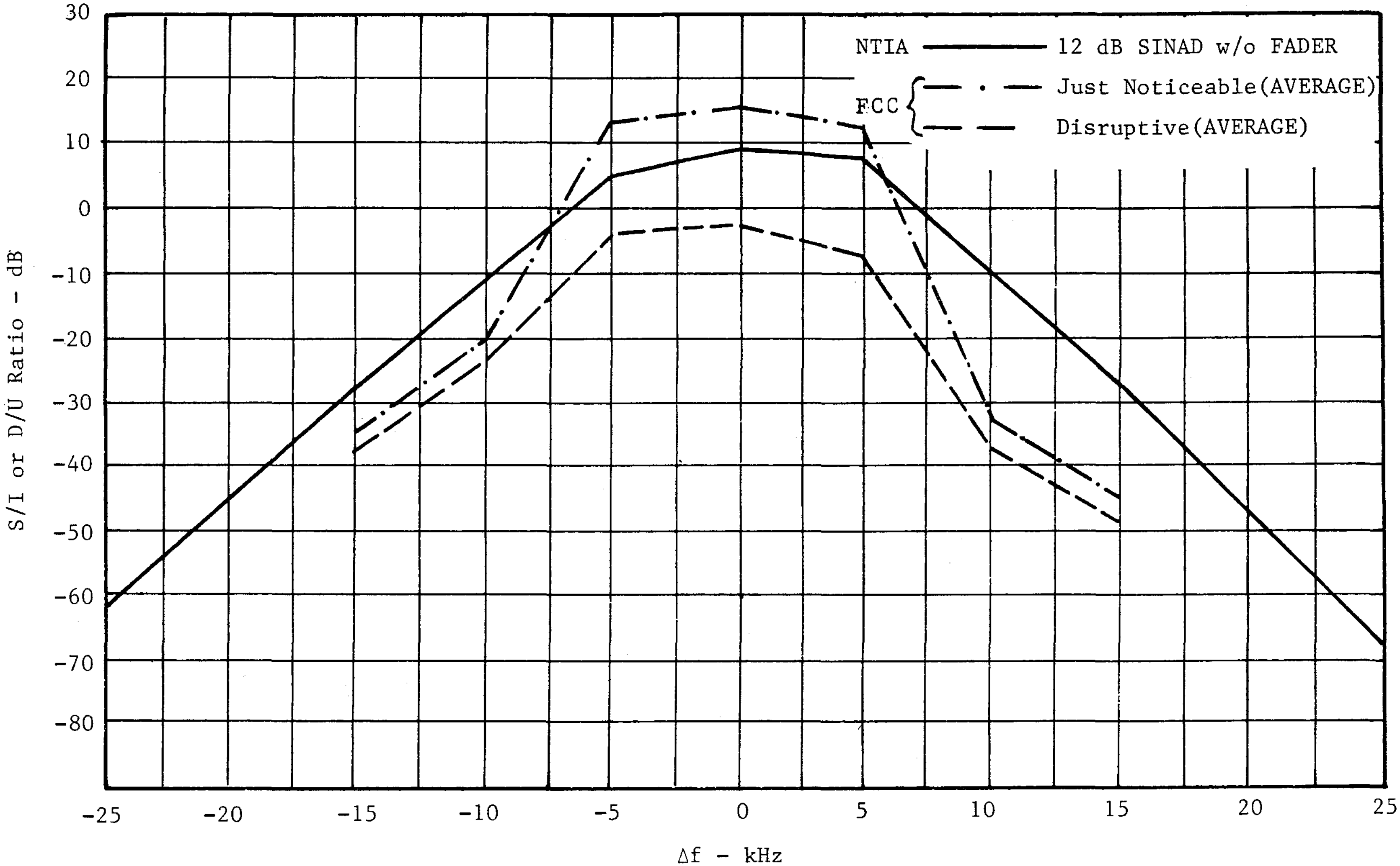


Figure 11. S/I or D/U Ratio Versus Δf for STI ACSB Interfering with Motorola FM

methods are very close. The S/I ratios obtained by the SINAD method lie between the FCC's "JUST NOTICEABLE" and "DISRUPTIVE" values. In the case of ACSB interfering with FM, the results are not as close. This can be explained by the fact that the FM receiver used by the FCC (Motorola Micor) is more selective than the receiver used in the NTIA measurements (Motorola Maxar).

MEASUREMENT OF NBFM

Subsequent to the measurement and analysis of the ACSB radios, two 12.5 kHz FM (NBFM) radios were obtained from Motorola for laboratory and field measurements. These radios were the Motorola Model CD 100, serial numbers (SN's) 004 and 005.

Laboratory Measurements

Laboratory mearsurements were made on the NBFM radios at the Department of Agriculture's Beltsville, Maryland, laboratory. These measurements consisted of a number of the Forest Service standard land mobile measurements (excluding shock, vibration, thermal, etc.) and several measurements requested specifically by NTIA. The laboratory measurements conducted are listed below:

Standard Forest Service Measurements

- Transmitter
  - Power Output
  - Frequency
  - Frequency Error
  - Microphone Sensitivity
  - Audio Distortion
  - Modulation Limiting
  - Spurious Emissions
  - Sideband Emissions (2.5 kHz modulation)
- Receiver
  - Sensitivity
  - Audio Output
  - Audio Distortion
  - Audio Bandwidth
  - Adjacent Channel Selectivity
  - Intermodulation
- Special Measurements
  - Transmitter
    - Sideband Emissions (voice-shaped noise modulation)
  - Receiver
    - Protection Ratio Curve

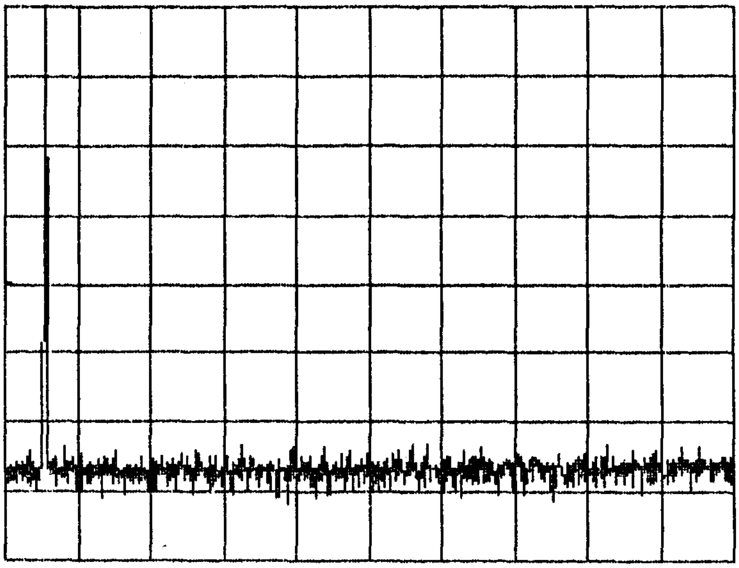
The single value parameters (everything except the spurious emissions, sideband emissions and protection ratio curve) are shown in TABLE 4. The spurious emissions for SN 004 is shown in Figure 12, while the sideband emission with 2.5 kHz tone modulation and 1.5 kHz frequency deviation is shown in

TABLE 4

NARROWBAND FM RADIO (12.5 kHz) MEASURED PARAMETERS

MOTOROLA MODEL CD 100

Parameter \ Serial no.	004	005
Transmitter		
Power Output (Watts)	8.9	9.5
Frequency (MHz)	172.05005	172.05001
Frequency Error (Hz)	50.0	10.0
Microphone Sensitivity (dBV)	-5.0	-6.2
Audio Distortion (%)	2.9	7.1
FM Hum and Noise (dB)	-46.9	-46.8
Modulation Limiting (kHz)		
at 1 kHz(kHz)	2.1	1.9
at 400 Hz(kHz)	2.4	2.3
Receiver		
Audio Output (Watts)	4.4	3.0
Audio Distortion (%)	5.0	5.0
Sensitivity (dBm)	-115.8	-118.0
Hum and Noise (dB)	68.7	64.0
Audio Bandwidth (kHz)	4.8	4.5
Adjacent Channel Selectivity (dB) (upper)	85.2	74.9
(lower)	85.1	74.1
Intermodulation (dB) (upper)	70.5	70.8
(lower)	72.5	71.0

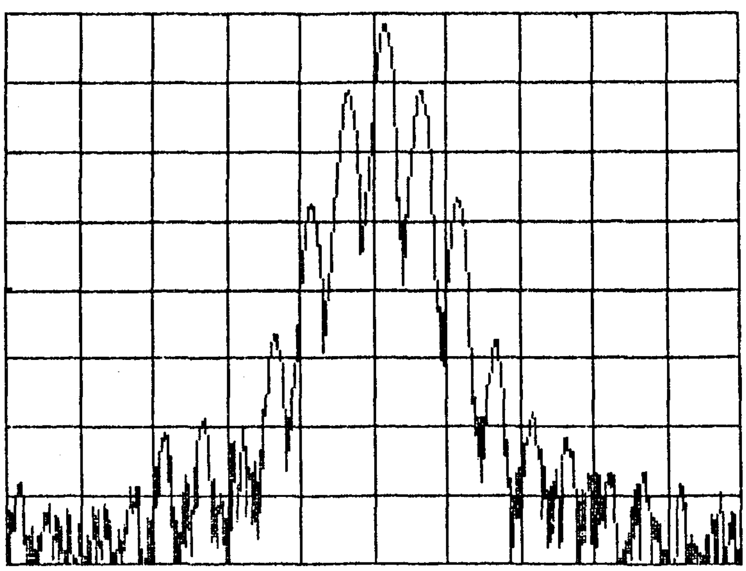


Analyzer Settings

Bandwidth	=	1 MHz
Center Frequency	≈	385 MHz
Reference Level	=	20 dBm
RF Attenuation	=	40 dB
Vertical Amplitude	=	10 dB/Div.
Frequency Span	=	50 MHz/Div.

Motorola Model CD 100, SN 004

Figure 12. Spurious Emissions of 12.5 kHz (NBFM) Radio.



Analyzer Settings

Bandwidth	=	1 kHz
Center Frequency	≈	173 MHz
Reference Level	=	-10 dBm
RF Attenuation	=	20 dB
Vertical Amplitude	=	10 dB/Div.
Frequency Span	=	5 kHz/Div.

Motorola Model CD 100, SN 004
1.5 kHz Frequency Deviation

Figure 13. Emission Spectrum of 12.5 kHz (NBFM) Radio Modulated with 2.5 kHz Tone.

Figure 13. A special test was conducted to measure the emission spectrum under the condition of voice shaped noise as the modulation signal. The resulting spectrum is shown in Figure 14. Another special test was the measurement of the adjacent signal protection ratio for the condition of NBFM interfering with NBFM. The method of EIA RS-204-C to measure the adjacent channel selectivity was extended to other values of frequency separation between the transmitter center frequency and the receiver tuned frequency. A plot of this data is shown in Figure 15.

Field Measurements

Field measurements were conducted on the NBFM radios by setting up a NBFM radio as a base unit at the NTIA Annapolis office and another NBFM radio in a car to act as a mobile unit. The same three routes used for measurement of the ACSB and FM radios (see Appendix A) were used for the NBFM tests. In addition to the NBFM radios in the mobile unit, a FM radio was also installed. A pretaped voice message (phonetically balanced) was used as the modulating signal in the mobile unit. The received signal was recorded at the base. For each route, the point between good communication and acceptable communication (point 1) and between acceptable communication and marginal communication (point 2) was determined. For the three routes, point 1 had an average value of 7.5 km (4.7 mi) while point 2 had an average value of 10.3 km (6.4 mi) for NBFM. These values compare to 8.0 km (5.0 mi) for ACSB and FM for point 1 and 13.1 km (8.2 mi) for ACSB and FM for point 2. (See Appendix A.) It should be noted that the NBFM and FM transmitter powers were tested at 10 watts.

In addition, tests were conducted with the NBFM transmitting and FM receiving and vice versa. For the case of NBFM transmitting and FM receiving there was no problem in understanding the message up to the range limit of the NBFM.

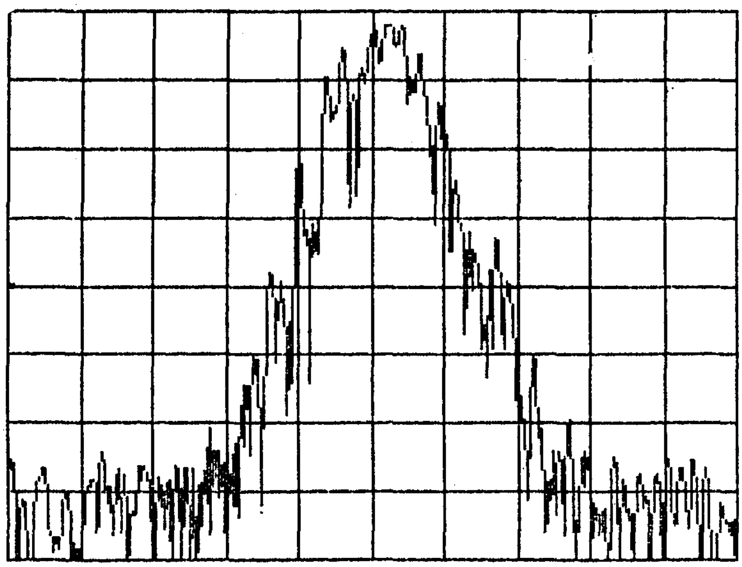
ANALYSIS OF RESULTS

Based on the measurements that have been completed on the ACSB, NBFM and FM radios, a number of observations and conclusions can be drawn relative to adjacent signal performance. The discussion will be presented in three parts, addressing the impact of adjacent signal interference on ACSB, conventional 25 kHz FM, and narrowband 12.5 kHz FM receivers, respectively.

Amplitude Compandored Single Sideband (ACSB)

As part of this study effort fairly extensive adjacent signal interference tests were completed both between ACSB radios as well as between ACSB and conventional 25 kHz FM radios (ECAC, 1983).

Considering first adjacent signal interference between ACSB radios, the inherent limiting factor is related to the degree of non-linearity of the final transmitter RF amplifier and hence the level of intermodulation output. Figure 16 shows measured emission spectrum of an ACSB transmitter using tone modulation. It is seen that the intermodulation products follow expected trends. The highest level shown is the 1000 Hz tone, and at a level 10 dB down is the 3100 Hz pilot. Relative to the transmitter assigned center frequency (corresponding to 1700 Hz audio tone), these signals are at -800 Hz and +1300 Hz, respectively. The major third-order intermodulation products are seen to have



Analyzer Settings

Bandwidth	=	1 kHz
Center Frequency	≈	172 MHz
Reference Level	=	-10 dBm
RF Attenuation	=	10 dB
Vertical Amplitude	=	10 dB/Div.
Frequency Span	=	2 kHz/Div.

Motorola Model CD 100, SN 004
1.5 Frequency Deviation

Figure 14. Emission Spectrum of 12.5 kHz (NBFM) Radio Modulated with Voice-Shaped Noise.

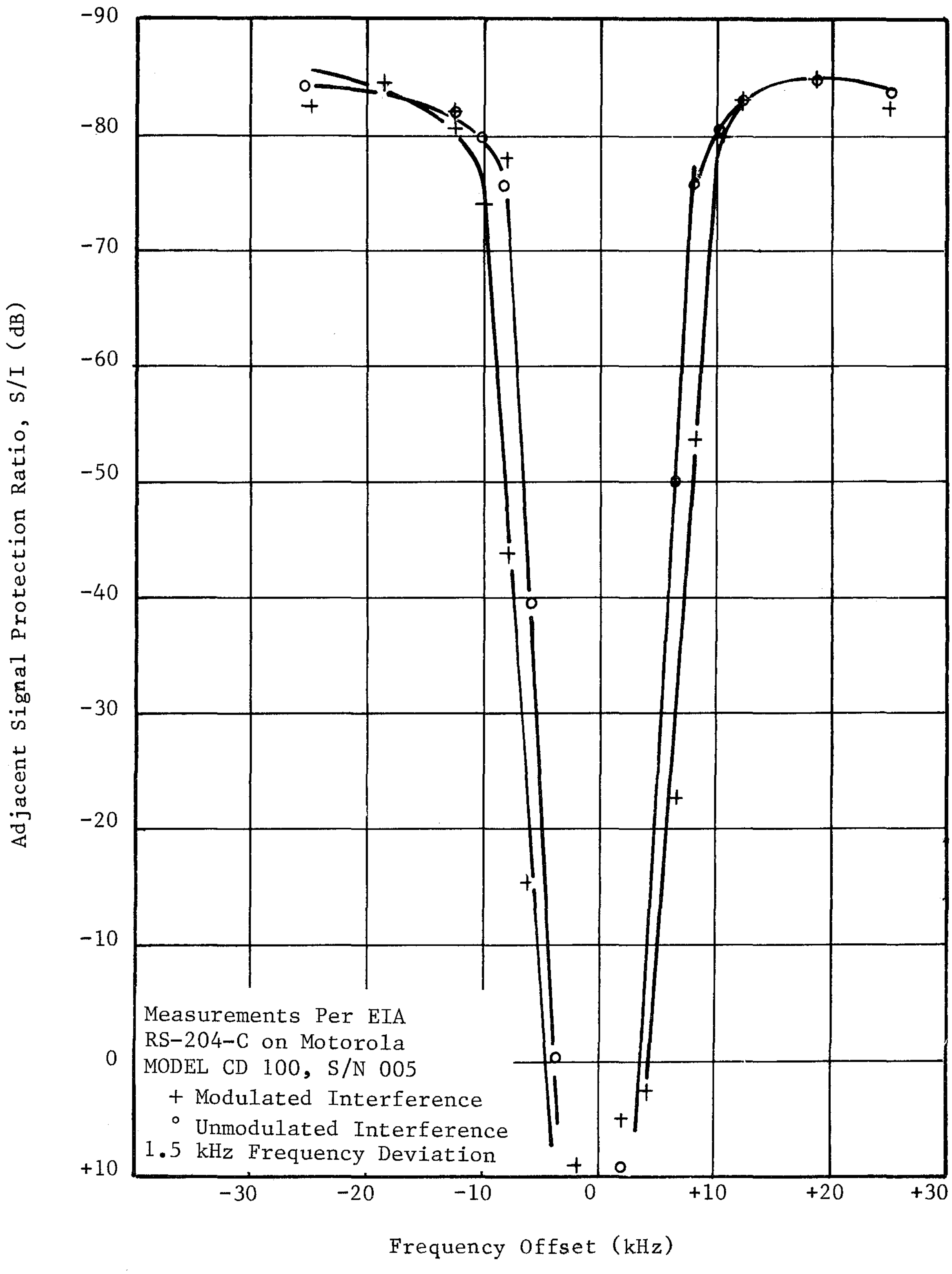


Figure 15. Adjacent Signal Protection Ratio for 12.5 kHz (NBFM) Radio.

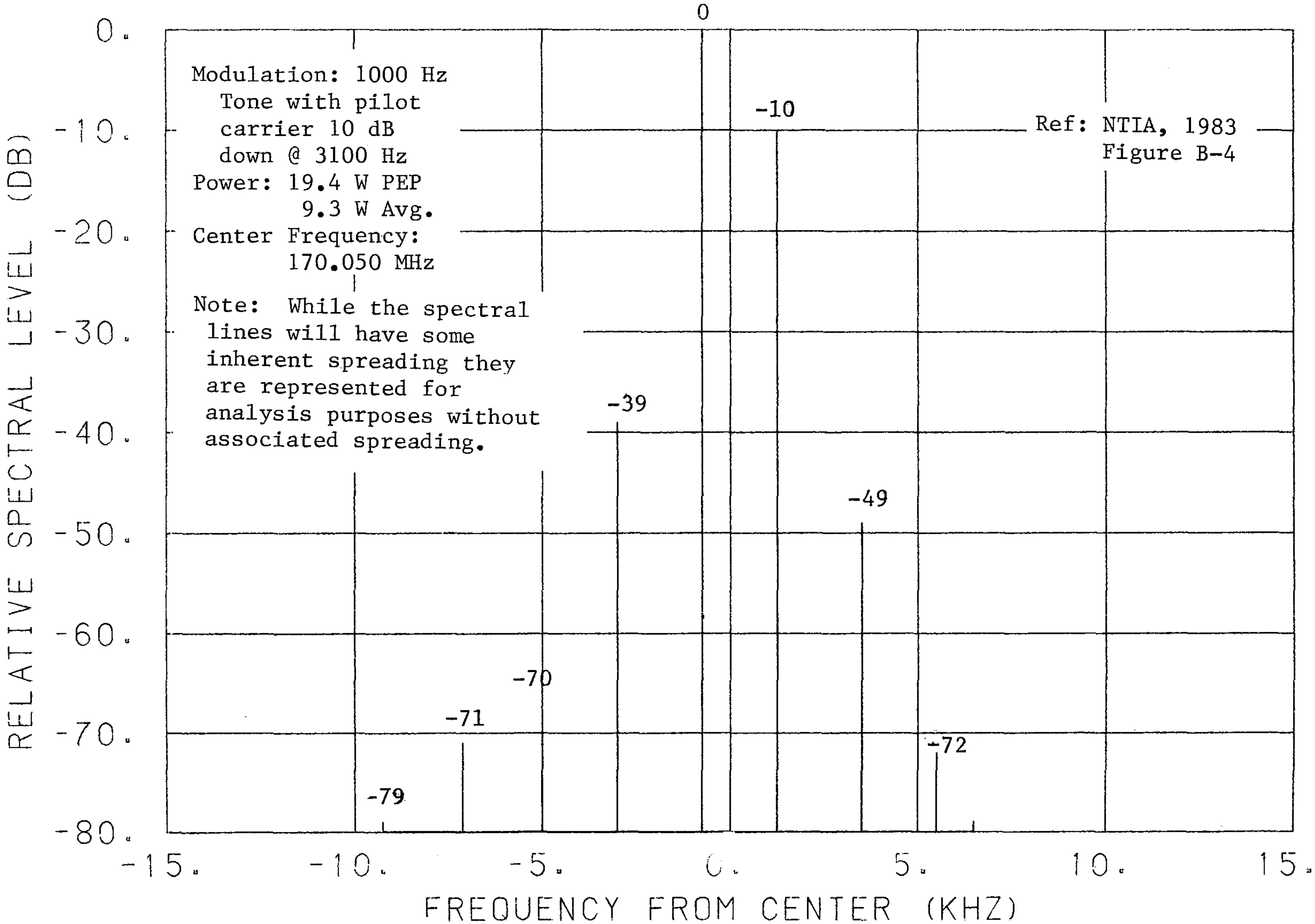


Figure 16. Measured Emission Spectrum of ACSB Transmitter

levels of approximately 39 and 49 dB down from the tone at relative frequencies of -2900 Hz and 3400 Hz, respectively. The frequencies as well as the 10 dB difference in level are in agreement with theory (RADC, 1966).

A standard measure of nonlinearity of an amplifier is the third-order modulation intercept point, the power level of two equal output signals at which the intermodulation products would theoretically be at an equal level (McVay, 1967). The measurements indicate an intercept point of approximately 600 watts as shown in Figure 17. The higher this value, the more linear the amplifier, and hence, the lower the intermodulation products. For each dB increase in the intercept point, the effective intermodulation products are reduced by 3 dB.

Four approaches are possible in lowering the impact of out-of-band intermodulation output products of the transmitter: developing power amplifiers with better linearity (higher third-order intercept point), operating the transmitter with a lower pilot carrier level, using a pilot carrier located within the voice spectrum through application of notch filters, or using channel spacing which avoids the third-order product frequencies. While each of these have a performance or cost impact, it is envisioned that an improvement (decrease) in the intermodulation output is feasible in the near term with further development.[4]

To demonstrate that the adjacent signal interference results are directly related to and can be derived from the measured transmitter emission spectrum, use can be made of a frequency dependent rejection (FDR) computer model. This model described by Cohen (1979) convolves a transmitter emission spectrum with a receiver selectivity function, as the frequency separation is varied, to determine the amount of rejection a receiver would offer for a given interfering signal. In this case, a measured ACSB emission spectrum represented by Figure 16 was convolved with a measured ACSB selectivity given in Figure 18 using the FDR model. The results are shown in Figure 19. Also plotted on the same graph are the measured cochannel and adjacent signal protection ratios for an 18 to 12 dB SINAD reduction criteria. The results show good agreement, and parameter sensitivity analysis confirms the initial assumption that the level of the intermodulation products is the dominant factor. Also suggested by the results, although not included in the ECAC measurements, is that a slightly larger channel spacing such as 6.25 kHz could improve the adjacent channel performance by 10 dB or more, a distinct advantage in congested environments.

Cochannel and adjacent signal interference tests were also conducted between conventional 25 kHz FM transmitters and ACSB receivers. For cochannel operation and an 18 to 12 dB SINAD reduction criteria, a protection ratio of 15 dB was found required. For frequency separations of 15 kHz and 25 kHz, a required S/I protection ratio of -81 to -87 dB was found. Although a value for a frequency separation of 12.5 kHz was not measured, a value of at least 70 dB is anticipated. An analysis of this adjacent signal interference using a measured FM emission spectrum, an ACSB receiver selectivity and the FDR model confirmed the very large interference rejection. At these levels, the effects of desensitization of the ACSB RF amplifier stages may also be involved which are not considered in the FDR model.

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[4]NTIA received a letter from STI indicating that an adjacent signal protection ratio of -58 dB at a Δf of 5 kHz has been obtained on their newer radios. These units were reported by STI, to have been in production since January 1984.

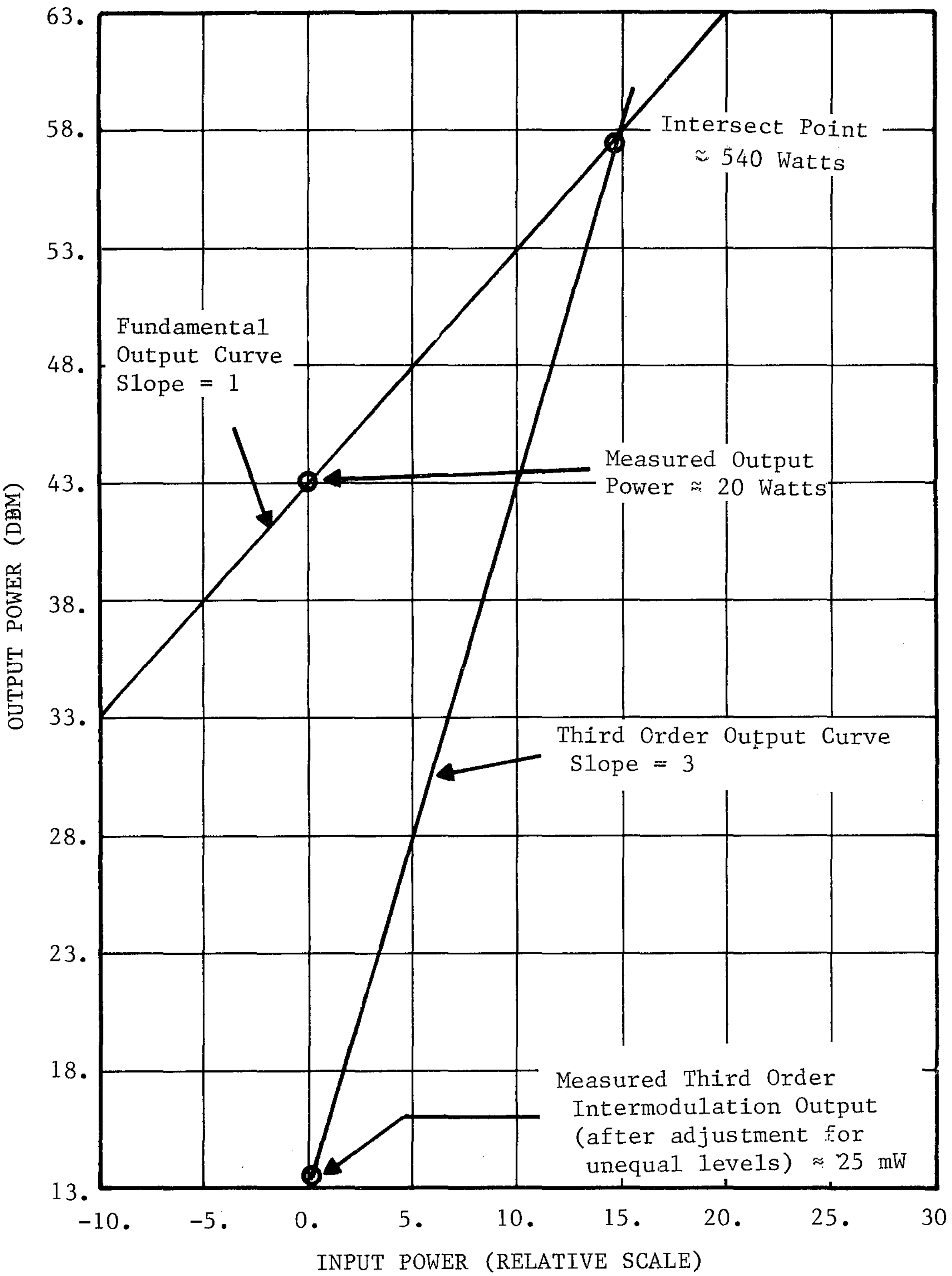

Figure 17 . Determination of 3rd Order Intermodulation Intersect Point for ACSB Transmitter.

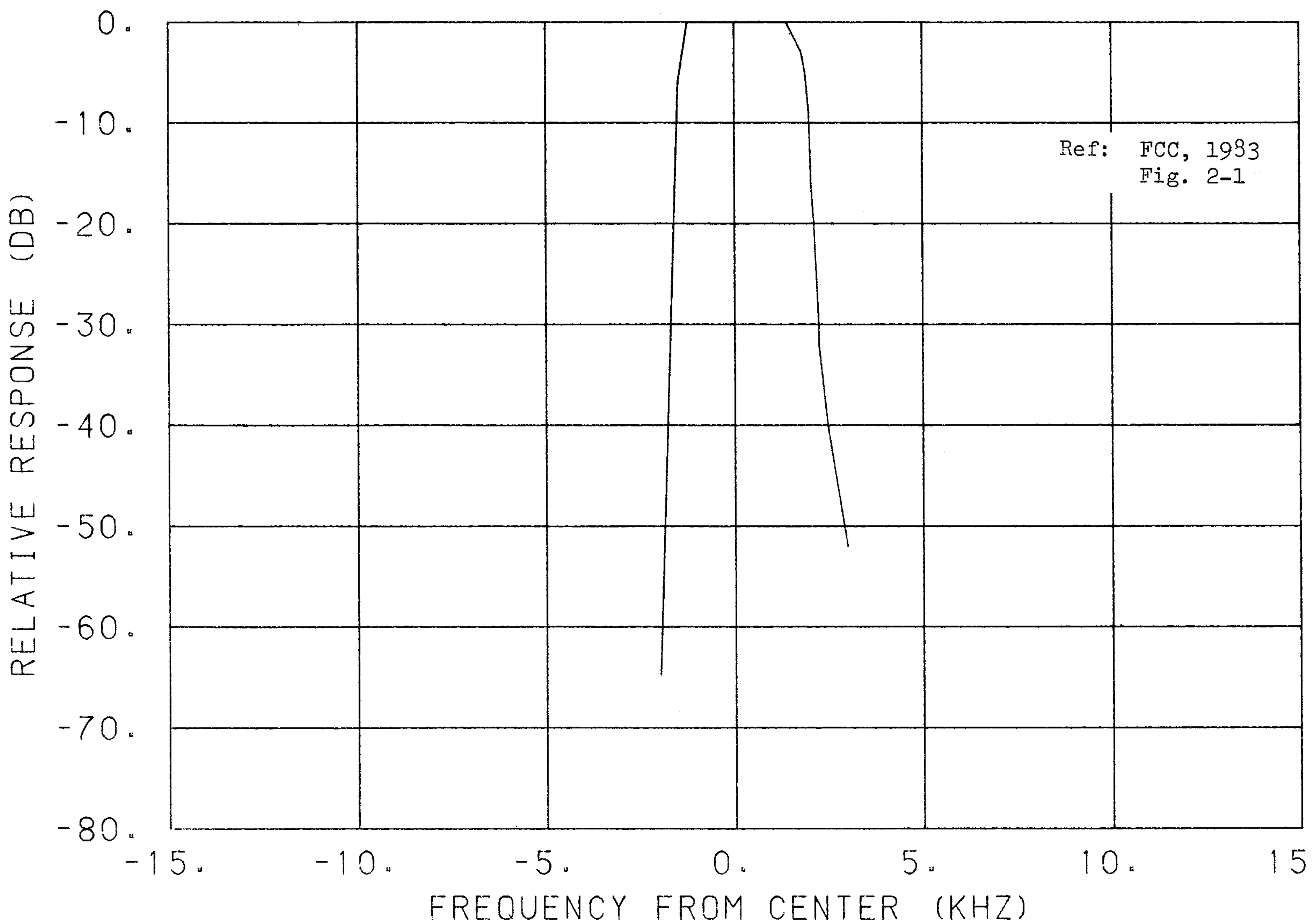

Figure 18. Measured IF Selectivity of ACSB Receiver.

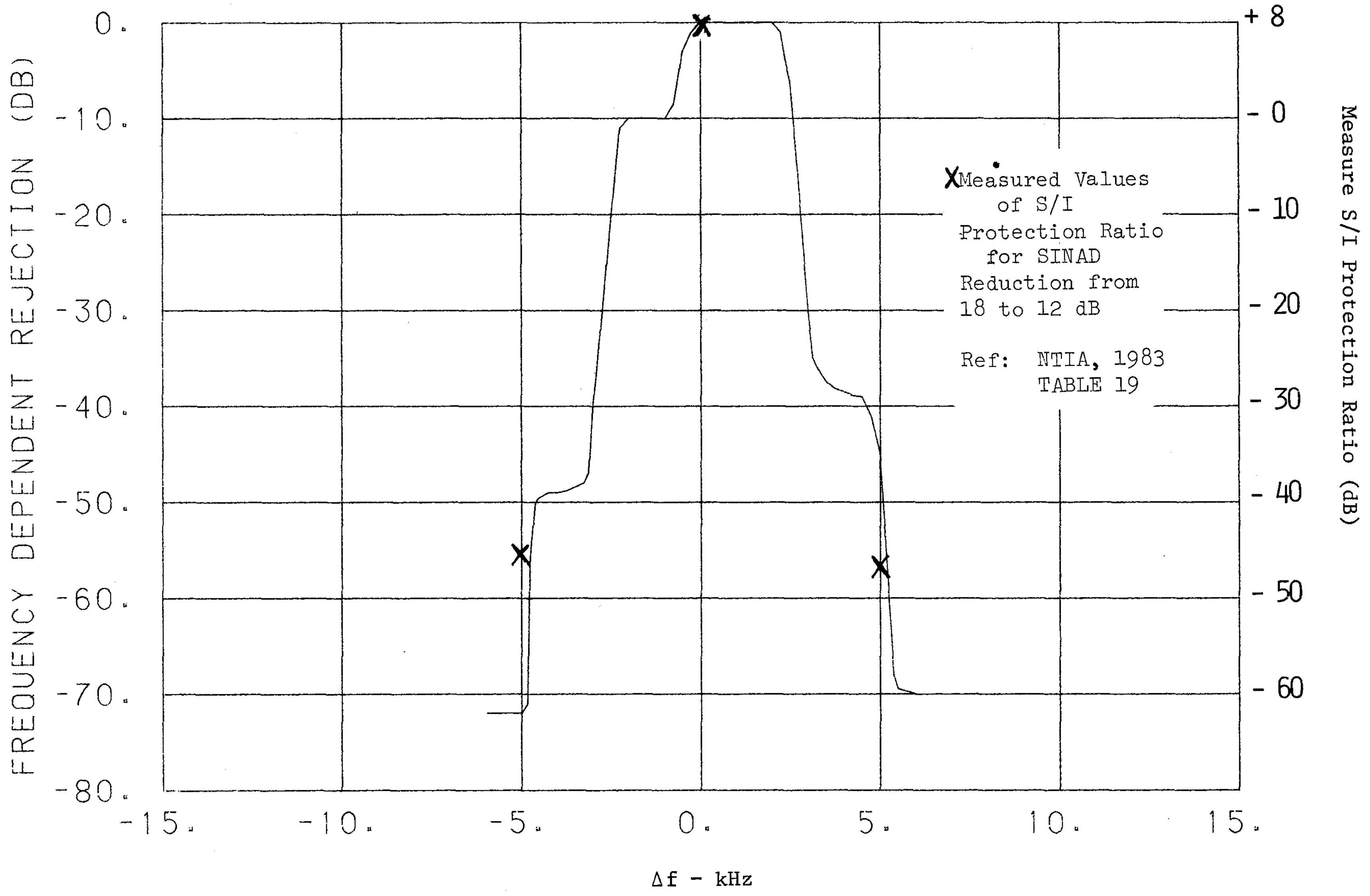

Figure 19 . Calculated Frequency Dependent Rejection and Measured S/I Ratio versus Δf for ACSB Transmitter and ACSB Receiver

In considering adjacent signal interference from NBFM to ACSB, it is noted that the emission spectrum of NBFM is similar to but more narrow than conventional FM. (See Figure 14 and Figure C-2 of NTIA, 1983.) The adjacent signal protection ratios are therefore similar.

25 kHz FM

Adjacent channel interference tests conducted between ACSB transmitter and FM receivers clearly demonstrated that ACSB interference to FM was substantially worse than FM interference to ACSB. In considering the possible interleaving of ACSB radios between existing FM channels, a frequency separation between the two of 12.5 kHz is the crucial value to be investigated. It can be shown that the controlling factor is the available selectivity offered by the FM radio.

As before, an FDR model is used, with the measured ACSB emission spectrum given by Figure 16 and the measured FM intermediate frequency (IF) selectivity given by Figure 20. The resulting frequency dependent rejection, as a function of frequency separation, is shown in Figure 21. As before, the measured cochannel and adjacent signal protection ratios for an 18 to 12 dB SINAD reduction criteria are plotted on the same figure with excellent correlation. A parameter sensitivity analysis clearly shows the dominant factor to be the FM selectivity rather than the ACSB emission characteristics. It is thus demonstrated that the adjacent channel interference between ACSB and FM can be derived once the FM selectivity characteristics are known. Since the measurements completed by ECAC involved only one available FM radio, it is of interest to extend the results to other radio model types. Figure 22 is a collection of IF selectivities for various radios. The data indicate a great variation of selectivity values at a 12.5 kHz offset. Through the use of the FDR program, the required protection ratio at 12.5 kHz for each of these radios is tabulated below.

Tabulated Values of Calculated S/I Protection Ratios from ACSB Transmitter to Various FM Receivers at 12.5 kHz Separation.

	+12.5 kHz	-12.5 kHz
Motorola Micor	- 30 dB	- 34 dB
GE Master Progress	- 47 dB	- 53 dB
GE Master II	- 44 dB	- 45 dB
GE Delta S	- 44 dB	- 48 dB

Based on a survey of typical equipment types in use within the Federal Government inventory, a value of 35 dB is considered a representative value.

As a part of this study, measurements were not taken of conventional FM to conventional FM interference since extensive data exist (Juroshek, 1979; ATT, 1983). These data indicate a protection ratio of approximately -25 dB at 12.5 kHz separation. While these sources used a 12 dB to 6 dB SINAD reduction criteria, the results should be quite similar for an 18 dB to 12 dB criteria based on trends evident in the ECAC measurements.

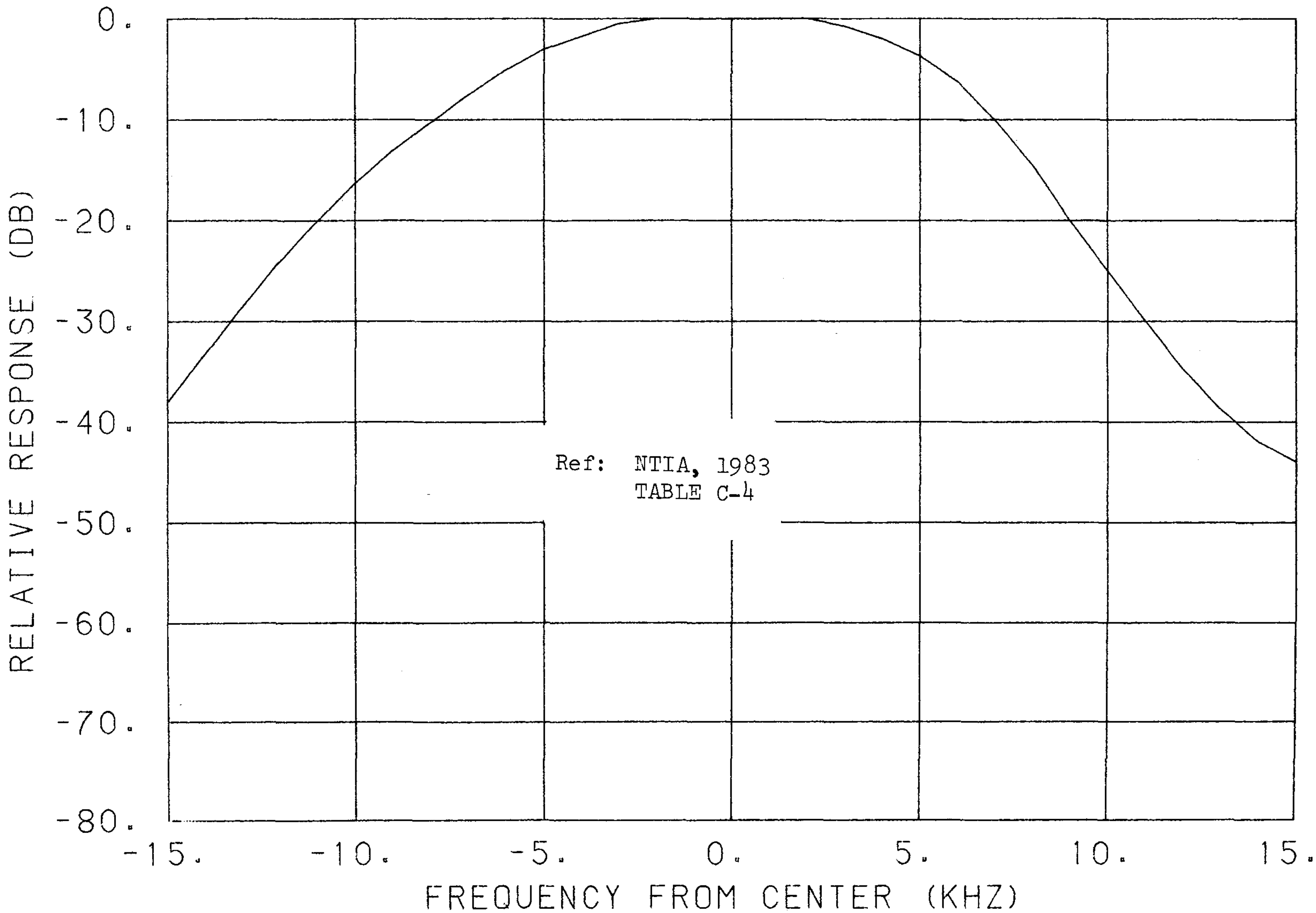

Figure 20. Measured IF Selectivity of Motorola Maxar FM Receiver

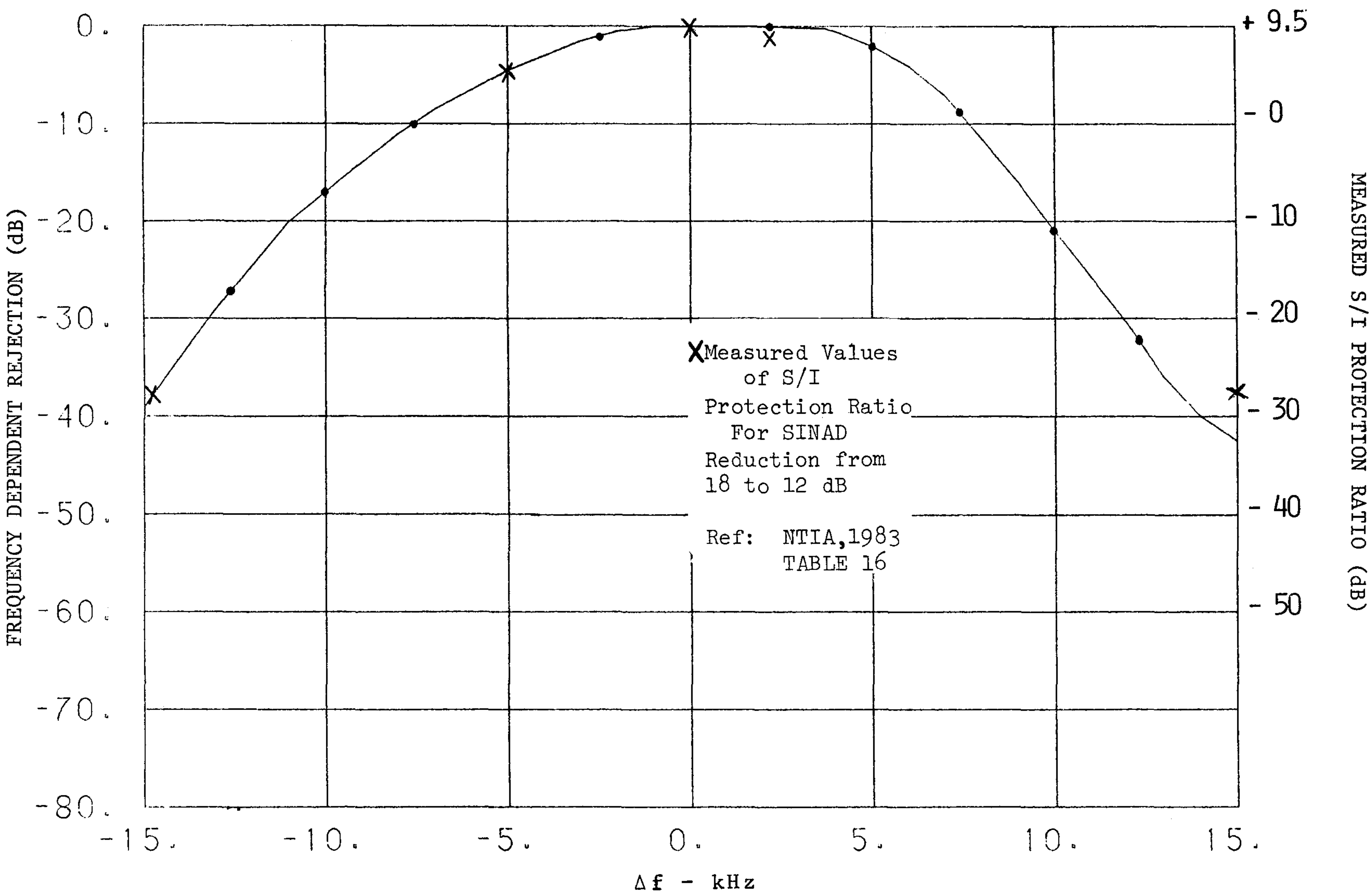

Figure 21. Calculated Frequency Dependent Rejection and Measured S/I Ratio versus Δf for ACSB Transmitter and Motorola Maxar FM Receiver.

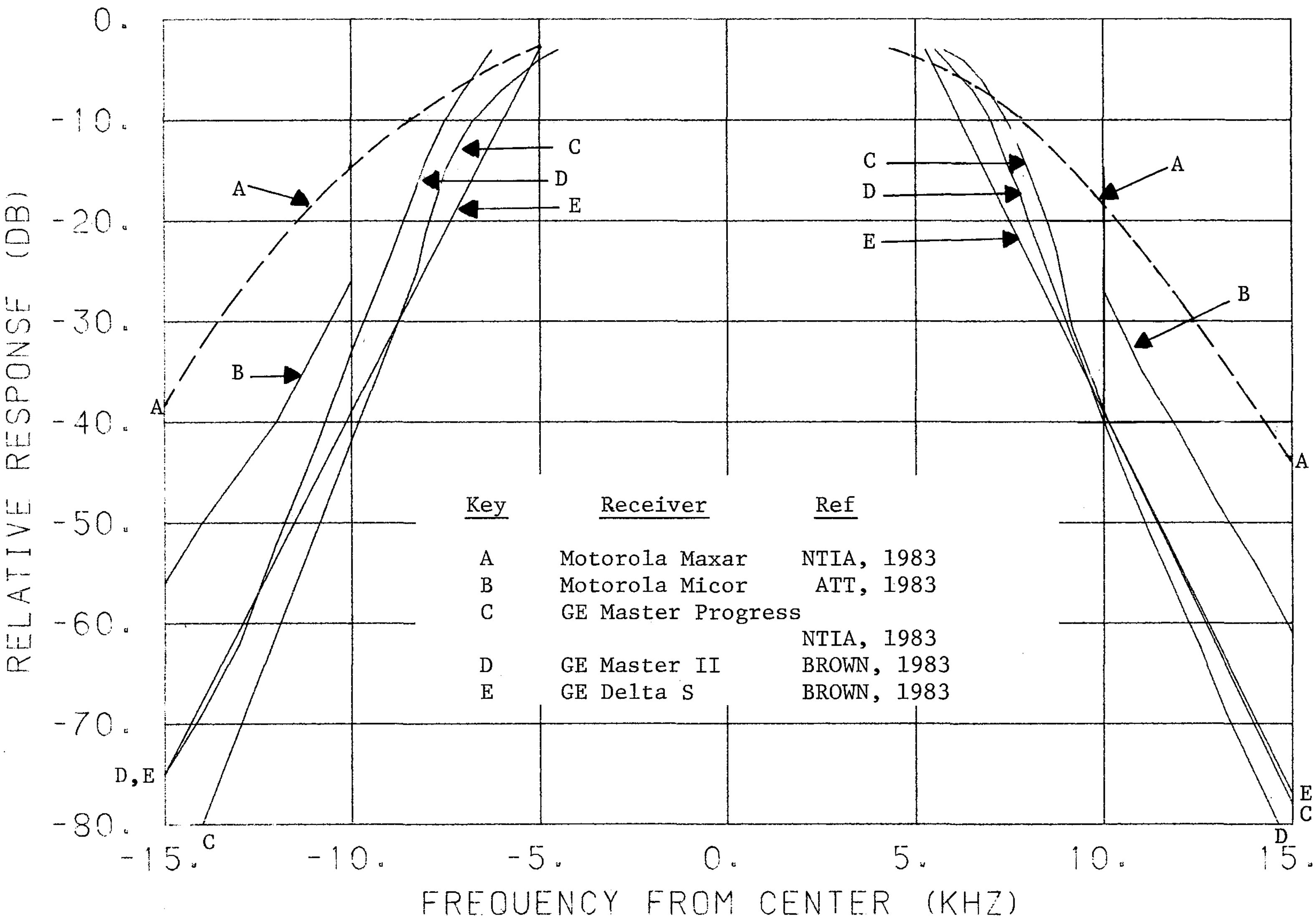

Figure 22. Collection of FM IF Selectivity Curves.

Because the effects of interference to conventional FM receivers at 12.5 kHz offset are clearly a function of the receiver selectivity, the impact of NBFM interference can be determined through use of the FDR model. Using the FDR model with the NBFM spectrum of Figure 14 and a representative receiver selectivity (Receiver C from Figure 22), an adjacent signal performance was found to be -35 dB at 12.5 kHz and -80 dB at 25 kHz.

12.5 kHz FM (NBFM)

Using the method described in the EIA Standard RS-204-C, the adjacent signal protection ratio was measured for the condition of NBFM interfering with NBFM. This data is shown in Figure 15 and indicated an adjacent channel (12.5 kHz) protection ratio of greater than 80 dB. This value exceeds the manufacturers' specification of 70 dB. In view of these measurements and manufacturers' specification, it is apparent that NBFM radios could operate on 12.5 kHz channel spacing. Also shown is a comparison of the measured and theoretical emission spectrum of the NBFM transmitter (see Figure 23).

SUMMARY

The above discussion examines measurement results involving ACSB, NBFM and conventional FM radios with respect to the required cochannel and adjacent signal protection ratios. The results of the measurements were compared to theoretical results obtained through use of a frequency dependent rejection model with excellent correlation. With this agreement between measured and theoretical results, it was considered practical to accurately extend the results to cases in which specific measurements were not made through the use of the FDR model. Specific instances where the measurement results were extended include different frequency separations, receivers having characteristics other than those measured, as well as extension to NBFM.

The overall results are shown in TABLE 5. Three key areas of this table are of interest. The first is the adjacent channel protection afforded by conventional FM receivers at a separation of 12.5 kHz. The typical value of 35 dB protection from ACSB interference was substantiated by measurement (NTIA, 1983; FCC, 1983), FCC filing (ATT, 1983) as well as theoretical analysis. Improvements in this value are possible given an adequate incentive to equipment manufacturers. However, since this value is applicable to a large number of existing equipments in a mature FM technology, significant improvements in this value may be very slow in arriving.

This value is crucial when considering implementation schemes in which ACSB assignments are interleaved between existing FM assignments. A similar level of adjacent signal protection is considered valid for interleaving of NBFM assignments between existing FM assignments. This level of adjacent channel protection is not significantly larger than the typical 25 dB protection by assigning conventional FM radios on 12.5 kHz channels. This value increases to typically 35-40 dB for a 15 kHz separation between FM assignments. While NTIA has no specific rules governing distance separation between stations, FCC Rules (FCC, 1983) call for a minimum of 10 miles separation between FM base stations

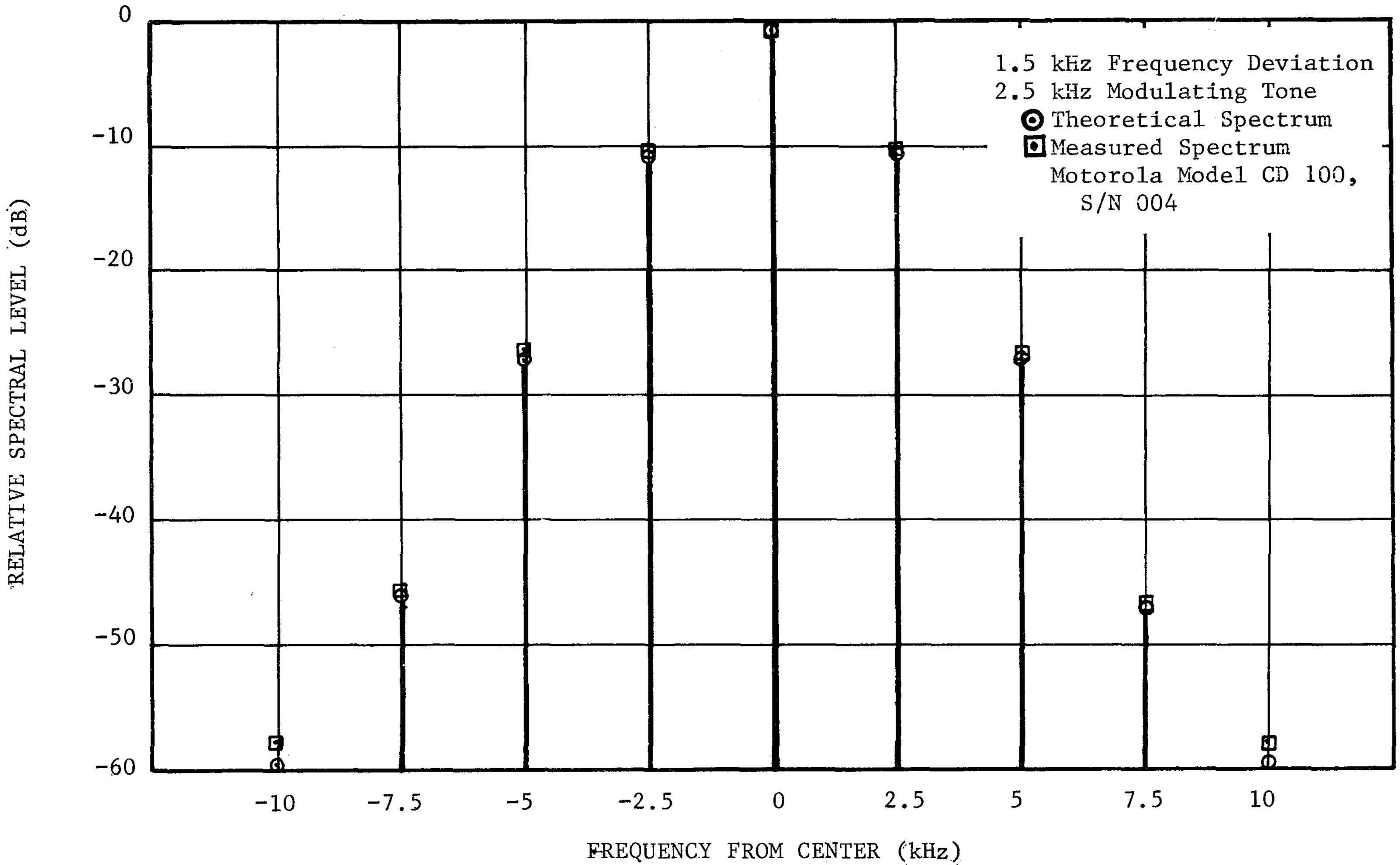

Figure 23. Measured and Theoretical Emission Spectrum of 12.5 kHz (NBFM)

TABLE 5

COCHANNEL AND ADJACENT SIGNAL PROTECTION RATIOS
(SIGNAL-TO-INTERFERENCE (S/I) RATIO IN dB)

INTERACTION		FREQUENCY SEPARATION (kHz)				
XMTR	RCVR	0	5	6.25	12.5	25
ACSB	ACSB	8	-47	-58	-70	<-80
25 kHz FM	ACSB	15	--	--	-70	<-80
NBFM	ACSB	15	--	--	-70	<-80
ACSB	25 kHz FM	9	--	--	-35	<-80
25 kHz FM	25 kHz FM	5	--	--	-25	<-80
NBFM	25 kHz FM	5	--	--	-35	<-80
ACSB	NBFM	9	--	--	-70	<-80
25 kHz FM	NBFM	9	--	--	-70	<-80
NBFM	NBFM	9	--	--	-80	<-80

S/I at Input Required to Reduce SINAD from 18 dB (without interference) to 12 dB (with interference).

-- not available

These S/I values represent the best available information. Additional measurements are needed to verify some of the values given.

assigned on 15 kHz spacing. Similar geographic spacing requirements may thus be appropriate for interleaving of ACSB or NBFM assignments between FM assignments.

The second key result was the adjacent channel protection afforded for ACSB-to-ACSB interference. The nominal measured value at ± 5 kHz was 47 dB. Measurements were not made at ± 6.25 kHz; however, a value of -58 dB was estimated from measurements made at ± 5 and ± 10 kHz (see Figure 10). Because the tests were made on early production models in an emerging technology, it is considered practical and likely that further development could significantly improve upon this value. The manufacturer of the ACSB unit tested stated that the test frequencies near 172 MHz were somewhat out of the initial design tuning capabilities of the radio resulting in an approximate 8 dB increase in intermodulation output. Further improvements in transmitter linearity and pilot carrier processing appear feasible (see footnote on page 44). Equally important is the channel spacing. Both the FCC measurements (FCC, 1983) and theoretic studies herein suggest that a 6.25 kHz spacing would offer 10 dB or more improvement in adjacent signal protection over a 5 kHz spacing. It can be shown that at 5 kHz spacing, the important third-order intermodulation emission products fall within the passband of an adjacent channel receiver. At a 6.25 kHz separation, the third-order products are substantially avoided leaving only higher-order products with which to contend. This suggests both a short-term as well as long-term advantage results with 6.25 kHz spacing vice 5 kHz. Also, use of 6.25 kHz spacing would be more compatible with a possible future channeling scheme involving 12.5 kHz NBFM.

The third key result was the adjacent channel protection afforded by NBFM receivers. Manufacturers' product data as well as NTIA measurements support that at 12.5 kHz spacing, 80 dB adjacent signal protection is practical and realizable within existing technology. (A protection ratio slightly greater than 80 dB was measured.)

EVALUATION OF SPECTRUM EFFICIENCY

One-on-One Analysis Approach

In the one-on-one analysis (Appendix B), the technical spectrum efficiency factor was calculated for the scenario and likewise mission of a single base station and an associated mobile unit. The technical spectrum efficiency was calculated both for the ACSB and NBFM referenced to FM. From equation (5) the technical spectrum efficiency factor is:

$$\text{Technical Spectrum Efficiency Factor} = \frac{BW_{FM} \times \text{Area Denied}_{FM} \times \text{Time}_{FM}}{BW_{ACSB} \times \text{Area Denied}_{ACSB} \times \text{Time}_{ACSB}} \qquad (6)$$

It was assumed that time utilization for both systems is the same, therefore equation (6) reduces to:

$$\text{TSEF (equal time dependencies)} = \frac{BW_{FM} \times \text{Area Denied}_{FM}}{BW_{ACSB} \times \text{Area Denied}_{ACSB}} \quad (7)$$

A similar equation was used to calculate the technical spectrum efficiency of NBFM referenced to FM. The denied area of a base station is that area which another base station must be kept out of so that the second base station will not interfere with the first base station or one of its mobile units. The denial areas were calculated for the condition of base-to-base interference and base-to-mobile interference. The bandwidths were determined as a function of the adjacent signal protection ratios. See TABLE 6.

A probabilistic model was used to calculate the denial area for the ACSB, NBFM and FM modulation techniques for the condition of base-to-base and base-to-mobile interference. This model, PRODSIR, calculated the probability distribution function of the receiver S/N and S/I ratios from the probability distribution functions of the random variables in the S/N and S/I equations. The predominant independent variable is the distance separation between the two base stations. The communication range between the base station and the mobile is defined as that range which would produce a 90 percent probability of successful communication when no interference is present. Likewise, the denial range is defined as that range (between the base stations) which would produce a 90 percent probability of successful communication when interference is present. Successful communication is defined as the S/N greater than α (no interference) or S/I greater than β (with interference) where α and β are both threshold values. The effect of fast fading was included by adding 9 dB to the threshold values. The values of α and β along with other system parameters are listed in Appendix B.

The probability distribution function of a random variable is the probability that the random variable is less than a given value. The complementary probability distribution function is defined as one minus the probability distribution function or the probability that the random variable is greater than a given value. Using this concept, the communication range was calculated as that range which produced a 0.90 complementary S/N probability distribution function at the threshold value. Likewise, the denial range was calculated as that range which produced a 0.90 complementary S/I probability distribution function at the threshold value. These ranges were calculated using the PRODSIR model and are listed in Appendix B. The denial area was calculated as $\pi\,(\text{denial range})^2$. Using the denial areas (TABLE 7) and bandwidths, the technical spectrum efficiencies were calculated and are shown in Figure 24 for the conditions of base-to-base and base-to-mobile interference. These efficiencies are a function of the adjacent signal protection ratios.

Simulation Approach

In the simulation approach, a frequency assignment computer program was used to calculate the technical spectrum efficiency of ACSB and NBFM modulation techniques (Cronin and Berry, 1984). The approach used was to compare, for the same mission, the total bandwidth (number of channels x channel bandwidth) required by a fixed number of ACSB or NBFM systems with a reference FM system under several different scenarios. The interference rejection characteristics of the systems were represented by frequency-distance (F-D) separation rules, and

TABLE 6

FREQUENCY SEPARATION REQUIRED (kHz) FOR
VARIOUS ADJACENT SIGNAL PROTECTION RATIOS

Protection Ratio (dB) \ Modulation	ACSB[(1)] vs ACSB	NBFM[(2)] vs NBFM	FM[(3)] vs FM
-30	3.7	7.0	12
-40	4.2	7.5	13
-50	5.3	8.3	14
-60	6.5	9	16
-70	12	9.7	17.5

Notes:

(1) Figure 10

(2) Figure 15

(3) Juroshek, 1979

the systems were assigned channels with a computer program that minimized the total bandwidth required. It was assumed that intersystem interference was prevented by imposing frequency distance rules on the base stations. These rules were determined by relating transmitter emission characteristics, receiver selectivity, propagation loss and signal-to-interference criteria. The frequency assignment computer program employed several graph coloring algorithms to assign frequencies to transmitters given the frequency constraints between transmitters. These constraints consisted of forbidden channel separations restricting the frequencies that can be assigned to transmitters. The program also generated random transmitter locations and applied the frequency-distance rules to produce the frequency constraints between transmitters.

The computer program was used to calculate the total bandwidth required for several different transmitter location scenarios. These scenarios were:

1. transmitters randomly distributed (uniform distribution) in a square, 400 mi x 400 mi,

2. transmitters randomly distributed (exponential distribution) about several city centers with the city centers randomly distributed (uniform distribution) in a square 400 mi x 400 mi; and

3. transmitters collocated at preferred locations.

In addition, the total bandwidth required for the scenario of interleaving the ACSB with the FM was investigated.

For each scenario considered, the computer program generated 10 sets of transmitter locations. Each frequency assignment problem addressed by the program consisted of one set of characteristics (frequency-distance rules, number of transmitters, etc.) and one set of transmitter locations. For each problem 14 suboptimal frequency assignment algorithms were used to assign frequencies. One or more of the resulting 14 frequency assignments used the least amount (minimum) of spectrum. This procedure was repeated for a total of 10 different sets of transmitter locations with the final output being the average of the minimum bandwidth for each assigned problem.

For the first scenario considered, the computer program generated the number of channels required for a range of numbers (100 to 400) of total base stations and two cochannel distance separation requirements (one for the ACSB and one for the NBFM and FM). Using this data, an equation from the average minimum number of channels required was derived. This equation for the number of channels is

$$M = 4.19 + N(0.140\ R + 0.722\ R^2) \tag{8}$$

where:

N is the number of transmitters

R is the ratio of cochannel distance separation required to the length of the square side.

Using equation (8), the total bandwidth for the ACSB, NBFM and FM was calculated. For this analysis, the denial area was the same for all three systems; hence, the technical spectrum efficiency factors were calculated as the ratios of the appropriate bandwidths, with the FM as the reference system. TABLE 8 lists the number of channels required and technical spectrum efficiencies for the ACSB, NBFM and FM radios. The FM (of course) has a technical spectrum efficiency of one.

For the second scenario, the computer program generated the number of channels required for 40 base stations randomly distributed (with exponential distribution) about 10 city centers randomly distributed (uniform distribution) in a square 400 mi x 400 mi. The number of channels was calculated for the ACSB, NBFM and FM for three different mean values of the exponential distribution. The spectrum efficiencies were calculated as the ratio of bandwidths, as was done for the first scenario. TABLE 9 lists the number of channels required and the relative spectrum efficiencies of ACSB, NBFM and FM.

A computer program was not used for the third scenario; however, an inspection of the cochannel and adjacent channel distance requirements lead to the following equations for the number of channels required:

NBFM and FM: The number of channels is

$$M = 3N - 2 \tag{9}$$

where:

N is the number of transmitters

"3" is the number of adjacent channel separation that must be observed (2nd) plus one

"2" is the number of adjacent channel separation that must be observed (2nd)

ACSB: The minimum number of channels is

$$M = 6N - 5 \tag{10}$$

where:

N is the number of transmitters

"6" is the number of adjacent channel separation that must be observed (5th) plus one

"5" is the number of adjacent channel separation that must be observed (5th)

General Band: The minimum number of channels is

TABLE 8

AVERAGE MINIMUM NUMBER OF CHANNELS REQUIRED AND TECHNICAL SPECTRUM EFFICIENCY FACTOR (Uniform Distribution)

No. of Base Stations / Modulation	N = 100		N = 200		N = 300		N = 400	
	No. of Channels	Technical Spectrum Eff. Fact	No. of Channels	Technical Spectrum Eff. Fact	No. of Channels	Technical Spectrum Eff. Fact	No. of Channels	Technical Spectrum Eff. Fact.
ACSB	20.46	3.30	36.72	3.11	52.99	3.03	69.25	2.99
NBFM	13.5	2.00	22.81	2.00	32.12	2.00	41.43	2.00
FM	13.5	1.00	22.81	1.00	32.12	1.00	41.43	1.00

N Base Stations randomly distributed by a uniform probability distribution in a square 400 mi x 400 mi.

TABLE 9

AVERAGE MINIMUM NUMBER OF CHANNELS REQUIRED AND TECHNICAL SPECTRUM EFFICIENCY FACTOR (Exponential Distribution)

Mean of Exponential Distribution / Modulation	$\mu = 10$		$\mu = 25$		$\mu = 50$	
	No. of Channels	Technical Spectrum Eff. Fact.	No. of Channels	Technical Spectrum Eff. Fact.	No. of Channels	Technical Spectrum Eff. Fact.
ACSB	152.1	3.84	132.5	3.64	112.7	3.94
NBFM	117	2.00	96.3	2.00	89	2.00
FM	117	1.00	96.3	1.00	89	1.00

40 base stations randomly distributed (exponential distribution) about 10 city centers randomly distributed (uniform distribution) in a square 400 mi x 400 mi. Total number of base stations is 400.

$$M = (k + 1) N - K \quad (11)$$

where:

N is the number of transmitters

K is the number of adjacent channel separation that must be observed

Using equation (7), the spectrum efficiencies can be calculated as:

$$\underset{\text{ACSB referenced to FM}}{\text{TSEF}} = \frac{(3N-2)\ (25\ \text{kHz})}{(6N-5)\ (5\ \text{kHz})} = \frac{5(3N-2)}{6N-5} \quad (12)$$

$$\underset{\text{NBFM referenced to PM}}{\text{TSEF}} = \frac{(3N-2)\ (25\ \text{kHz})}{(3N-2)\ (12.5\ \text{kHz})} = 2 \quad (13)$$

Summary

Two approaches were used to calculate the Technical Spectrum Efficiency Factor (TSEF) for both the NBFM and ACSB relative to a 25 kHz system: one-on-one analysis approach and simulation approach. Using a one-on-one analysis approach, the TSEF for the ACSB and NBFM was calculated for various adjacent signal protection ratios available from the two systems. This method produced a TSEF for the ACSB varying from a low of 1.04 to a high of 2.53. The high value corresponds to low adjacent signal protection ratios and the low value to high protection ratios. For the NBFM, the TSEF was essentially the same at 1.7 to 1.8 for all values of protection ratios (see TABLE B-6). Using a simulation approach, the adjacent signal protection ratios were only of secondary importance in the final result. With this method, the TSEF for the ACSB varied from a low of 3.0 to a high of 3.9. In this approach, the TSEF was a constant 2.0 (see TABLES 8 and 9). It was felt that the more realistic approach to analyzing the spectrum efficiency of these two systems would be to put more emphasis on the method which utilizes the adjacent signal protection ratio. Therefore, the maximum values of the TSEF for the ACSB and NBFM are considered to be 2.5 and 1.8, respectively.

SECTION 5

IMPLEMENTATION

INTRODUCTION

This section provides an overview of the various factors affecting the implementation of narrowband technologies in the Government VHF fixed and mobile bands. Emphasis of this discussion is in the 138-225 MHz region, although application of these techniques outside of this range is clearly possible. The discussion is presented in three parts. The first, Comparative Factors, is an overall comparison of key factors which may influence both the Federal agencies decisions in purchasing these technologies as well as NTIA regulatory approach. The second part, Implementation Methods, examines the merits of four different approaches towards introducing these technologies into the existing bands. The final part examines several spectrum management options available to NTIA to stimulate the purchase and use of appropriate technologies by Federal agencies.

COMPARATIVE FACTORS

This subsection provides a discussion of several key factors (TABLE 10) which need to be considered regarding these narrowband technologies. It is to be emphasized that the list is clearly not all-inclusive and no attempt has been made to place a weighting on each factor. For special Federal agency requirements, one factor out of the several considered, or indeed a factor not even on the list, may clearly dominate all others. The discussion does, however, cover most factors which must be considered by agencies considering purchase as well as NTIA policymaking.

Equipment Standardization

In the area of equipment standardization, use by Federal agencies of NBFM offers certain advantages over ACSB. As with conventional FM, manufacturers of NBFM equipment have few, if any, design variation options which affect its performance. An audio bandpass of approximately 300-3000 Hz, a peak deviation of ± 2.5 kHz and an IF bandpass of approximately 7-8 kHz would be used by all manufacturers and, in general, all such systems will be interoperable with little or no performance degradation.

With ACSB, however, an extensive number of design options are possible which may result in degraded or non-performance if equipment from different manufacturers are used within the same network. These include:

1. Companding compression ratio (4:1 vs 2:1)

2. Pilot frequency

3. Pilot level (constant versus variable)

4. Definition of center RF frequency

TABLE 10

COMPARATIVE FACTORS FOR NARROWBAND LAND MOBILE TECHNOLOGIES
(SUMMARY CHART)

Comparative Factors	Evaluation Factors 25 kHz FM	 ACSB	 NBFM
1. a/ Channel Spacing (kHz)	25	5-6.25	12.5
2. Spectrum Efficiency (Relative to 25 kHz FM)	1.0	2.5	1.8
3. b/ Adjacent Channel Protection Ratio provided (dB)	-80	c/ -47 to -58	-80
4. Communication Range	Approximately the same for all sets		
5. Interoperability with existing equipment (25 kHz FM)	Yes	No	Yes, with minor performance degradation
6. Equipment Availability	Widespread	Limited	Not marketed in United States (Available in Europe)
7. Availability of Convenience Circuits	Yes	Yes	Yes
8. Maintenance/Testing Procedures compared to existing environ. (25 kHz FM)	Same	Modified	Same
9. Standardized equipment design	Yes	No	Yes
10. Maximum Data Handling Capability of Audio Bandpass (Kilobauds)	1.2-1.8	1.2-1.8	1.2-1.8
11. Maximum Data Handling Capability Using Full Channel Spacing (Kilobauds)	10-12	1.2-1.8	5-6
12. Channel spacing compatible with current digital voice techniques	Yes	No	No
13. Channel spacing compatible with current analog encryption techniques	Yes	Yes	Yes
14. Compatability with trunking techniques	Yes	Yes	Yes
15. Voice Quality compared to existing environment (25 kHz FM)	Same	d/ Good	d/ Good
16. Cost compared to existing equipments	Same	See Table 11	5% to 10% increase

a/ Values in this Table are based on these channel separations.

b/ 25 kHz FM vs 25 kHz FM, ACSB vs ACSB and NBFM vs NBFM, respectively.

c/ -47 dB for 5 kHz channel spacing
-58 dB for 6.25 kHz channel spacing

d/ See Section 5 for further discussion

5. Pilot signal lock-on circuitry

6. Audio bandpass characteristics

Until such time as a standard ACSB design is achieved, equipment from one manufacturer may be incompatible with another. This may lead to difficulties with Government competitive procurement requirements since once an initial purchase is made, all subsequent purchases for that communication network must be from that same manufacturer. Future standardization of ACSB design will eliminate this problem.

Maintenance

Many Government agencies which are large users of land mobile equipment employ a staff of radio technicians to maintain equipment rather than vendor maintenance. These vary from large centralized staffs to many "one man shops" distributed throughout the country. These staffs have been, of course, trained in maintenance of conventional FM equipment. Often, specialized or fully automated test equipment has been purchased for this purpose. In general, equipment design as well as test procedures for NBFM will be identical to conventional FM equipment. Retraining of maintenance personnel and purchase of additional test equipment should be minimal.

ACSB technology, however, employs circuitry and techniques which may be unfamiliar to many experienced radio technicians and may require additional training. Conventional receiver performance tests such as sensitivity, adjacent channel selectivity, and intermodulation response require specialized procedures and, in general, cannot be performed with existing land mobile automated test equipment. In general, test procedures which are useful in comparing radio performance have been the subject of much conflicting discussion in the literature, and standard procedures have not been developed. The tests completed on the ACSB radios by NTIA and the FCC described key adjacent signal performance characteristics, but required the use of an RF shielded screen room in each instance. Use of RF-shielded screen rooms, subjective voice comparison or any complex procedure would be unacceptable for routine agency purposes. Simple test procedures to assure that contract specifications are met is a requirement.

Of particular importance is maintaining the linearity of the ACSB transmitter RF amplifier to minimize adjacent signal interference due to intermodulation. Unlike an FM radio, attempts by radio technicians to "soup up" an ACSB radio to squeeze a few more watts out of the transmitter can be disastrous.

Another factor that needs more study is the effects of equipment aging on equipment performance. For NBFM, as in conventional FM, the critical factor that affects adjacent signal performance is the frequency tolerance and IF selectivity which are both controlled by quartz crystals. Such crystals have well known aging characteristics. For ACSB, the critical factor affecting adjacent signal performance is the linearity of the transmitter RF amplifier. Experience with these transmitters will in time establish such aging trends.

Interoperability

Many functions performed by Federal agencies including law enforcement and natural resource management require communication networks which are interconnected. Within these networks, as equipments are replaced due to age or failure, it is often accomplished in an evolutionary, piecemeal manner. Because of budget constraints, as well as overall efficient property management, it is not always possible or practical to replace an entire communication network at one time. The introduction of NBFM into the environment offers advantages over ACSB in that, with some performance degradation, (approximately a 5 dB reduction in sensitivity compared to 25 kHz FM) it is interoperable with existing equipment. The equipment can be gradually phased in just as the current generation of FM equipments was phased in from previous 50 kHz channelized radios having a 36 kHz bandwidth. For example, consider a network consisting of several base and repeater stations and numerous mobiles. With the base and repeater stations adjusted for a peak deviation of ± 2.5 kHz, new NBFM mobiles can be gradually phased in over a period of years, with only a nominal reduction in communication range. Once the conversion of mobiles is complete, then conversion of the base and repeaters could take place to complete the update. A gradual phase-in of NBFM radios may also be possible in other network configurations.

Introduction of ACSB radios into the environment, being non-interoperable with existing FM equipment, is best accomplished for new communication requirements, or where complete conversion of the entire network is feasible.

Equipment Availability

Due to its widespread use and popularity, current 25 kHz FM systems are readily available in large numbers and diverse product lines. Production capability of the major manufacturers is extensive.

The early introduction of both ACSB and NBFM would be hampered initially by equipment availability limitations. As of the time of this report, ACSB radios are being produced by two manufacturers for marketing within the United States but have somewhat limited product lines. In particular, handheld portables are just becoming available, while transmitter power of all units is limited to 25 watts. Also, a diversity of product lines, from low-cost models to top-of-the-line models is not currently available. Production capability of these companies is presently at 100-150 units per month and could be increased to about 300 units per month on short notice.

NBFM equipment is currently available from several manufacturers which also produce conventional FM equipment. The predominant use of this NBFM equipment is for use abroad, where extensive use of NBFM is practiced. Within the overseas market, a diversity of product lines and extensive production capability has been reported, but plans for marketing these products within the United States were not determined.

For both ACSB and NBFM, increasing demand by users would encourage more widespread availability and diversity within the United States.

Communication Range

Generally, the operational range of narrowband FM, ACSB, and wideband FM has been found to be the same. Section 3 of this report summarizes the results of range tests conducted by several companies and Federal agencies.

Data Handling Capability

It is apparent that the advantage in the transmission of digital data lies with wideband FM. The maximum practical bit rate which can be used with the systems studied are roughly as follows (Hansen, 1981):

- 25 kHz FM — 10-12 k bps
- 12.5 kHz FM — 5-6 k bps
- 5 kHz ACSB — 1.2-1.8 k bps

Modern FM systems already operate at data rates of up to 2400 bps and there is a clear trend towards higher bit rates through use of frequency shift keying or phase shift keying techniques. ACSB systems have been tested at baud rates up to 1200 bps with bit-error rates of better than 1 in 10^{3}. Additionally, one of the manufacturers of ACSB systems (STI) has claimed successful rates of up to 1200 bps. Data transmission using narrowband technology is feasible with acceptable bit-error rates, but the clear advantage lies with the wider band systems.

Encryption Techniques

Current digital voice techniques preclude its adaptation to available ACSB and NBFM systems because of data rate limitations. For voice security, these digital encryption techniques are being used heavily by the Federal Government. Minimum bit rates for digital voice systems are typically 9.6 to 12 kbps. Advances in digital speech processing may reduce the bit rate by a factor of 2. However, at lower bit rates, speech quality will probably degrade. Advances in encryption techniques such as digital predictive coding may enable narrowband systems to provide quality voice communications with speaker recognizability. However, analog encryption techniques can be applied to both narrowband technologies. It has been reported that analog voice scramblers have been in use with ACSB radios (see Section 3).

Voice Quality

When considering the introduction of a new technology, it is natural to compare the quality of the communications to the existing environment. It is generally considered that current 25 kHz FM radios offer the user excellent voice quality with high intelligibility and speaker recognizability. The voice quality of both ACSB and NBFM was similar to 25 kHz FM in a high signal environment. In a low signal environment, the voice quality of both narrowband techniques is not as good as that of the 25 kHz FM; the voice quality of the NBFM being slightly better than that of the ACSB. Under this condition, the NBFM voice signal is subject to distortion probably due to noise pops and capture, while the ACSB voice signal is subject to distortion probably due to the companding, pilot tone circuitry, and/or reduced audio bandpass.

Cost

While cost of the equipment is clearly a major factor in the purchase of a land mobile radio system, it is quite difficult to accurately compare price structures of the new narrowband technologies versus existing FM. Factors that must be included are short-term vs long-term comparison, production levels, marketing strategies, competitive environment, productivity as well as the actual hardware costs. A total life cycle cost comparison of land mobile systems must include many factors such as maintenance, reliability, and durability. For a realistic comparison, equipments of comparable quality must be used. Whereas, current production of ACSB radios has a somewhat limited product line, manufacturers of current FM equipment have extensive product lines with a wide range of price levels. The choice of comparable product lines is not easily made. With NBFM, the available product lines are somewhat more diverse; however, sales are aimed almost exclusively at the overseas market and a realistic cost comparison again presents difficulty. In the end, the potential user of the equipment must weigh the factors which are most important for his/her application. As one example of such a comparison, TABLE 11 provides costs based on a given set of assumptions for various mobile radio equipment using prevailing retail costs. Caution should be observed in extrapolating these data to a different set of assumptions.

To supplement the data given in TABLE 11, it is informative to examine the hardware aspects alone and the possible long-term cost differential of the narrowband technologies as compared to conventional FM.

Consider narrowband FM. The design of NBFM radio equipment is virtually identical to that of conventional FM, with three exceptions: the peak deviation of the transmitter is reduced from ± 5 kHz to ± 2.5 kHz, the IF filter and discriminator bandwidths are reduced from approximately 14 kHz to approximately 7 kHz, and the frequency tolerance is reduced from the commonly used 5 ppm to 2 ppm. Only the latter is expected to result in a significant long-term cost impact. For a single channel, or frequency synthesized radio, the cost differential between 5 ppm and 2 ppm crystals is approximately $50; for a four-channel radio, the cost differential would then be $200. As a percentage of the cost of a mobile radio, this could amount to as low as 2 percent or as high as 20 percent or more depending on many factors. In a possible future narrowband environment where a 2 ppm tolerance was the standard, market forces could well reduce this cost impact considerably.

For ACSB, a number of design factors are different than conventional FM which may have a long-term cost impact. Among these are: the frequency tolerance is reduced from the commonly used 5 ppm to a typical 2 ppm, use of a highly linear transmitter RF power amplifier, use of pilot frequency generation and detection circuitry, use of AFC, use of narrow and linear IF circuitry, use of single sideband generation and detection circuitry, and use of companding circuitry. The long-term cost differential of these factors as compared to conventional FM is difficult to assess. Clearly, the same comments apply with regard to frequency tolerance. A significant factor is the requirement for a highly linear RF power amplifier versus the saturated amplifier used for FM. For

TABLE 11

COST COMPARISON OF CURRENT NARROWBAND LAND MOBILE TECHNOLOGIES AND CONVENTIONAL FM[1]

Type	Model	Power	Stability	Cost[4]
ACSB	STI Pioneer 1000 (Front)	25W PeP	4 ppm	$1885.00
ACSB	STI Pioneer 1000 (Trunk)	25W PeP	4 ppm	$2485.00
ACSB	Stevens SEA175 (Front)[2]	25W PeP	2 ppm	$1520.00
FM	Motorola MITREK (Front)[2]	40W Av.	5 ppm	$1745.00
FM	Motorola SYNTOR (Trunk)[2]	25W Av.	2 ppm	$1695.00
FM	Motorola MOXY (Front)	25W Av.	5 ppm	$ 628.00
FM	GE Executive II (Trunk)	35W Av.	5 ppm	$2175.00
FM	GE Master II (Trunk)	40W Av.	5 ppm	$2295.00
FM	GE DELTA (Trunk)[2]	40W Av.	5 ppm	$1815.00
NBFM	Motorola[3]	Comparable	Comparable	5% to 10% Increase
NBFM	GE (STORNO A/S)	No Information Available		

Data as of December 1, 1983

Note:

1. For purposes of this comparison, all systems are front or trunk mount mobile units with 4-channel capacity (installed), microphone and mounting hardware included, and convenience circuits included.

2. Indicates frequency synthesized.

3. Complete information is not available. If marketed in the United States, units offered would be comparable in most aspects to current line. Cost is additive to current line prices.

4. These figures are based on Manufacturer's suggested list price. For non-synthesized models, the cost of additional crystals is included. GSA schedule costs may differ.

use of ACSB in a congested adjacent channel interference environment, amplifiers even more linear than current production models may be required. This will undoubtedly result in a long-term cost impact. The various audio processing circuits, in at least one of the current ACSB production radios, require a significant number of separate additional components not required by the FM techniques and suggest a clear cost differential with FM. With future increased volume in production, development of miniaturization and integration of these functions should reduce this differential considerably, although development costs of such integration efforts are typically high.

Compatibility of Trunking Techniques

Trunking is a system design developed by the telephone industry which employs switching devices at each telephone exchange such that a large number of users can be served over a much smaller number of talk paths or trunks. When a call is made, a talk path is established which was previously used by another user and will be used soon by others. The next call made on the same number will not necessarily be connected by the same talk path. The use of trunking achieves a higher degree of facility loading and utilization for a telephone system.

Recently, this concept of trunking has been applied to mobile radio. The application of trunking to mobile radio was not practical until the advance of technology enabled high-speed automatic switching of frequency channels in a mobile radio unit. There are several different trunking methods presently available in mobile radios made by a variety of manufacturers [Mobile Times, 1980] and more are in the process of being developed. These trunking methods do not depend upon modulation techniques, therefore they can be considered for application to either ACSB or NBFM technologies.

Availability of Convenience Circuits

Convenience circuits are defined, for the purpose of this discussion, as those which provide for tone-coded squelch and other tone signaling. As stated previously, the pilot tone signal incorporated in the design of ACSB technology allows for the addition of convenience circuits. Tone-coded squelch is presently available as an option for the ACSB and NBFM radios investigated herein.

IMPLEMENTATION SCHEMES

In the following discussion four methods of implementing narrowband technologies are examined: interleaving between existing 25 kHz channel assignments, dedicating specific channels for exclusive use by narrowband technology, use of the splinter channels in the 162-174 MHz band, use of new alternative bands.

Interleaving

Interleaving of narrowband frequency assignments between existing 25 kHz FM channels has been often proposed as an effective method to implement these techniques. For example, the FCC currently authorizes ACSB under developmental license procedures between current channels in the private radio services portion of the 150.8-162.0125 MHz band. These channels are spaced at 30 kHz rather than 25 kHz as for Government channels.

A key to the long-term efficiency of this interleaving method is the adjacent signal performance. With this approach, the frequency separation with the existing FM assignments will be 12.5 kHz. It was found from the measurements and analysis of adjacent signal performance (see Section 4) that an adjacent signal protection ratio of approximately 35 dB is required between ACSB and conventional FM spaced at 12.5 kHz. It is observed that interleaving of NBFM between conventional FM assignments would require essentially the same 35 dB protection ratio. Thus for interleaving, the higher potential spectrum efficiency of ACSB versus NBFM would not be realized. The lower expected cost, as well as various other operational factors discussed, would favor NBFM over ACSB if interleaving were chosen as the only method of accommodating narrowband technologies. With either NBFM or ACSB, a 35 dB protection ratio is considered unacceptable for many congested environments. The current EIA (1982) recommendation calls for a minimum of 20 dB. Thus, implementation of NBFM between existing 25 kHz assignments will likely require a distance separation between assignments to preclude adjacent signal interference. A distance on the order of 16 kilometers (10 miles) is typical. In congested environments, a distance separation of this magnitude may not provide the additional channels which was being sought through use of narrowband technologies.

Dedicated Channels

A second approach to accommodating narrowband technologies is to set aside specific channels or contiguous groups of channels exclusively for their use. In this way, three to five ACSB assignments could be accommodated on one former 25 kHz FM channel, and two NBFM assignments could be likewise accommodated. The number of ACSB assignments which could be accommodated depends on both the channel spacing and on whether single isolated channels or groups of contiguous channels are used. The channel spacing proposed for ACSB has heretofore been 5 kHz. It has, however, been shown in Section 4 that a somewhat larger value, for example 6.25 kHz, would result in an improvement of 10 dB or more in adjacent signal performance. In congested environments, a tradeoff of 20 percent in channel usage for an approximate 10 dB improvement in adjacent signal performance clearly appears desirable.

If a contiguous block of channels were so converted, the logical approach would be to divide the channel into four 6.25 kHz segments with the ACSB assignments centered on each segment. If single isolated channels were converted to use by ACSB, a different approach may be warranted. With the above channeling scheme, the minimum frequency separation from the existing adjacent FM channel would be 15.625 kHz. While this separation may provide adequate adjacent signal performance, a more conservative approach would be to permit three rather than four ACSB channels spaced at 6.25 kHz. This then would result in a minimum frequency separation from the existing adjacent FM channel of 18.75 kHz. This would provide adequate adjacent signal performance in all but the most difficult cosite interference conditions.

Accommodation of NBFM on channels dedicated for narrowband techniques is simply a matter of dividing the former 25 kHz channel in two with a NBFM assignment centered on each half. This also provides a minimum of 18.75 kHz separation with existing FM channel. Channels designated for use by narrowband techniques, need not be so designated nationwide but could be done on a regional basis or any convenient geographic basis. From the standpoint of protecting the existing FM environment from unacceptable adjacent signal interference, this method of dividing channels for use is clearly superior to simply interleaving.

Use of Splinter Channel Assignments

Section 4.3.8 of the NTIA Manual identifies the Government channeling plan for splinter channel assignments in the band 162-174 MHz as shown in TABLE 12. Thirty of these channels identified are available for operations requiring a bandwidth up to 5 kHz, and fifteen channels overlapping those are available for operations requiring a bandwidth of up to 10 kHz. Two restrictions on the use of these channels limit their availability for use by narrowband voice applications. The principal limitation states that voice will not be authorized except for maintenance support of the primary operation. The second is the limitation on bandwidth to 10 kHz versus the 11 kHz required of NBFM.

If these limitations can be relaxed or eliminated, use of these channels for narrowband and voice applications may be an appropriate first step to stimulate their introduction. As their usage expands and technologies mature, additional channels could be designated for narrowband use as previously described.

Current assignment statistics based on data from the Government Master File (GMF) are provided in Figure 25 and TABLE 13. It is found that usage is predominately narrowband telemetry or telecommand functions in a limited number of states. It appears that, with some geographic limitations, further use could be made of these channels for voice applications without impacting current operations. It is also proposed that the current bandwidth limitation of 10 kHz could be expanded to 11 kHz, to accommodate NBFM, without any additional impact on adjacent channel operations. TABLE 12 provides a proposed change to Section 4.3.8 of the NTIA Manual to permit the use of narrowband voice operations in these channels.

New Band

Another possible means of effectively implementing these new narrowband technologies (especially ACSB, because of its lack of interoperability with FM) is to encourage the use of the 216-225 MHz band. In the United States, the 216-220 MHz portion of this band is allocated primarily to the Maritime Mobile Service and on a secondary basis to the Radiolocation, Fixed, Land Mobile and Aeronautical Mobile Services (footnotes US210, US229, US274, 627, G2, NG121 apply). The 220-225 MHz band is allocated (in the United States) on a primary basis to the Amateur, Fixed and Mobile Services, and on a secondary basis to the Radiolocation Service (footnotes US243, 627 and G2 apply).

A spectrum resource assessment of the 216-225 MHz band (NTIA-TR-81-85) points out that generally, the 216-225 MHz band is not extensively used throughout the United States. Figure 26 shows a graphic distribution of Federal Government frequency assignments in this band.

TABLE 12

SPLINTER CHANNEL ASSIGNMENTS IN THE 162-174 MHz BAND
WITH PROPOSED CHANGES TO PERMIT NARROWBAND VOICE OPERATION

4.3.8 Channeling Plan for Splinter Channel Assignments in the Band 162-174 MHz

The frequencies shown in this plan are available for assignment to all Government agencies in accordance with allocation footnote G5 and as specified herein.

162.590625 [1]
.593750 [2]
.596875 [1]
.803125 [1]
.806250 [2]
.809375 [1]

163.390625 [1]
.393750 [2]
.396875 [1]
.603125 [1]
.606250 [2]
.609375 [1]
.790625 [1]
.793750 [2]
.796875 [1]

164.003125 [1]
.006250 [2]
.009375 [1]
.840625 [1]
.843750 [2]
.846875 [1]

165.803125 [1]
.806250 [2]
.809375 [1]

166.415625 [1]
.418750 [2]
.421875 [1]
.653125 [1]
.656250 [2]
.659375 [1]

167.190625 [1]
.193750 [2]
.196875 [1]
.803125 [1]
.806250 [2]
.809375 [1]

171.215625 [1]
.218750 [2]
.221875 [1]
.403125 [1]
.406250 [2]
.409375 [1]

173.190625 [1]
.193750 [2]
.196875 [1]

[1] These frequencies are available for operations requiring a bandwidth up to 5 kHz.

[2] These frequencies are available for operations requiring a bandwidth between 5 and ~~10~~ 11 kHz, inclusive.

Conditions for Use

2. Audio tone frequencies may be entered on applications in the CIRCUIT REMARKS field following the identifying code *AGN. Use of a continuous carrier with the associated tone may be indicated, including use of a continuous tone transmitted simultaneously only when other tones that carry the intelligence are transmitted. Examples: *AGN, 450, 475, 625; *AGN, 450, 475C, 625.

~~3~~. The technical standards applicable to the use of the splinter channels listed above are shown in paragraph 3 of Section 5.4.5.

~~4~~. Directional antennas shall be used where practicable on point-to-point circuits.

~~5~~. Prior to filing an application for a splinter channel with footnote 1, coordination shall be effected with any agency with adjacent channel assignments within the same splinter channel in the same geographic area.

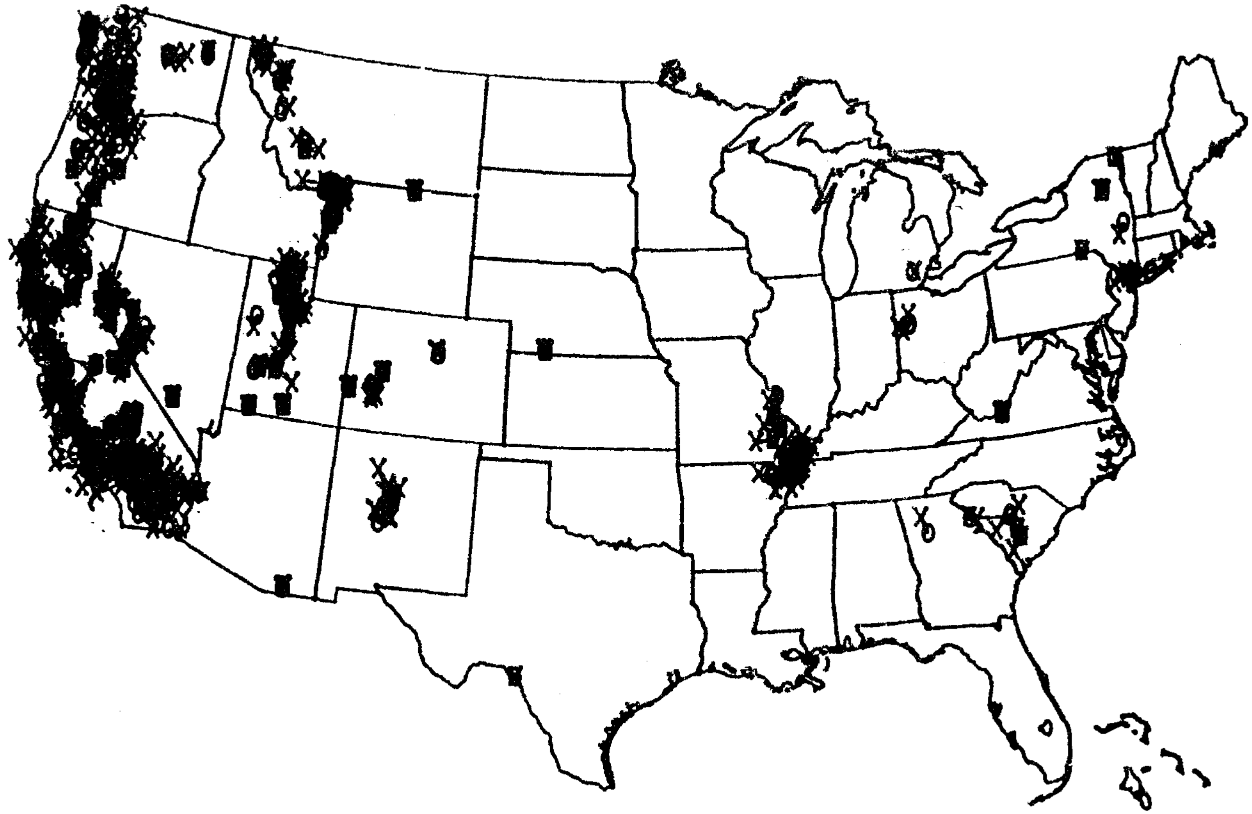

Figure 25. Geographic Distribution of Splinter Channel Assignments in the 162-174 MHz Band in the Continental United States.

TABLE 13

SUMMARY OF FREQUENCY ASSIGNMENTS
OF KEY GOVERNMENT DEPARTMENTS
FOR THE 138-174 MHz BAND*

Department	138-144 MHz	148-150.8 MHz	157.0375-157.1875 MHz	162.0125-173.2 MHz	173.4-174 MHz	Total Thousand
Army	2051	993	126	2785	276	
Air Force	1590	1941	13	1250	394	14.5
Navy	1975	767	12	282	13	
Justice	2	-	4	9023	5	9.0
Interior	-	37	33	6907	24	7.0
Agriculture	-	-		6619	13	6.6
Treasury	-	-		3870	4	3.9

*Data taken from the Government Master File as of September 1983. The number of frequency assignments do not necessarily reflect the number of equipments nor the actual extent of spectrum use by these agencies.

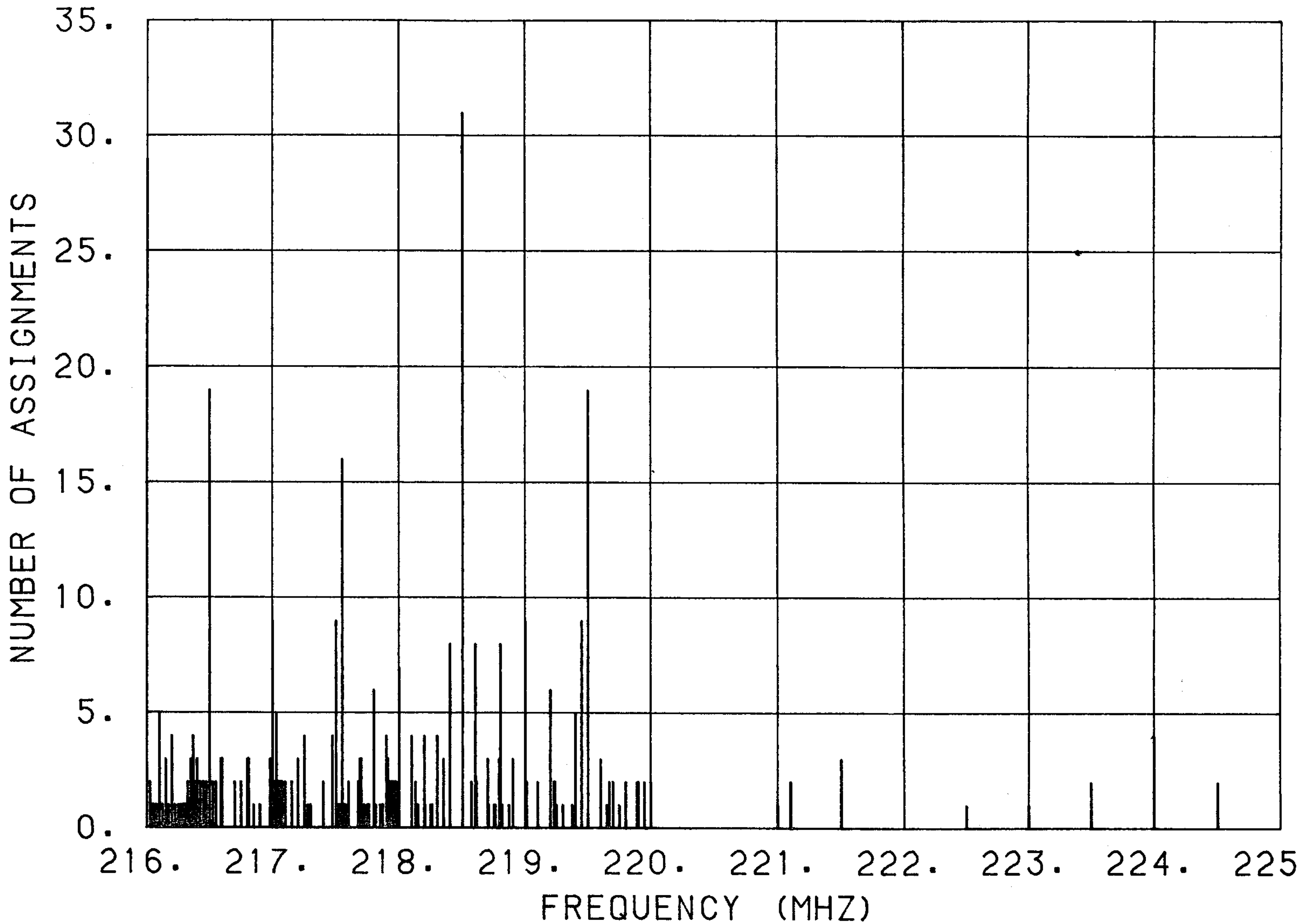

Figure 26. Frequency Assignments of Government Agencies in the 216-225 MHz Band.

An area of concern in the 220-225 MHz portion of this band is the potential interactions with amateur assignments. Data gathered by the American Radio Relay League, Inc., and published in the 1981-1982 edition of the ARRL Repeater Directory indicate that repeater assignments are predominant in the upper portion of the band. Figure 27 gives an indication of the number of amateur repeater assignments versus discrete frequency.

SPECTRUM MANAGEMENT STRATEGIES

As new technologies have been introduced into the radio spectrum, NTIA has in the past examined the potential benefits to be gained as well as possible drawbacks. Such has been the case as satellite communications, digital and spread spectrum modulations, etc., have evolved and been incorporated into the environment. As this occurs, several regulatory approaches can be used. A simple approach, and one that has been successfully used often in the past, might be called a "marketplace" approach. Here, the Federal Government neither encourages nor discourages the technology, but rather the users determine and purchase that technology which best suits their needs. The opposite to this would be a strong regulatory approach where the potential benefits far outweigh the drawbacks and positive steps are taken to ensure the introduction of that technology. This approach was taken by the FCC in adopting the "all channel TV regulations" which required all television receivers sold to include UHF channel reception. A third approach between these two extremes, is one in which the Federal Government adopts policies and procedures that would actively encourage the introduction of a desirable new technology but would not require its use. These three approaches are examined in the next paragraphs to identify alternative approaches for NTIA relative to narrowband technologies for land mobile communications.

Marketplace

The marketplace approach to regulation has often been the preferred approach by NTIA for many emerging technologies. This has been especially true for most Government, non-military, fixed and mobile applications where "off-the-shelf" equipment is purchased. Often Government purchases of such equipment, although extensive, is still small compared with that of private industry. Standards or procedures that might be adopted by NTIA which were in opposition to, or more stringent than, that used by private industry would, in general, cost more money and have been avoided.

The opposite approach involving strong regulatory measures was taken as satellite communications emerged. By its nature, frequency allocations had to be modified to permit its use, specific interference measures had to be adopted (power flux density limits), etc.

The introduction of narrowband technologies into bands allocated to the Government Fixed and Mobile Services, requires no specific change to any existing regulation or procedure. For example, both the ACSB and NBFM equipment will meet all applicable technical standards of Chapter 5 of the NTIA Manual (1982) and can be accommodated within applicable channeling plans of Chapter 4 of the NTIA Manual. Other procedures are equally applicable. A marketplace approach is, therefore, a valid approach to be considered. Past efforts to introduce narrowband technology, for instance in transitioning from the previous 50 kHz

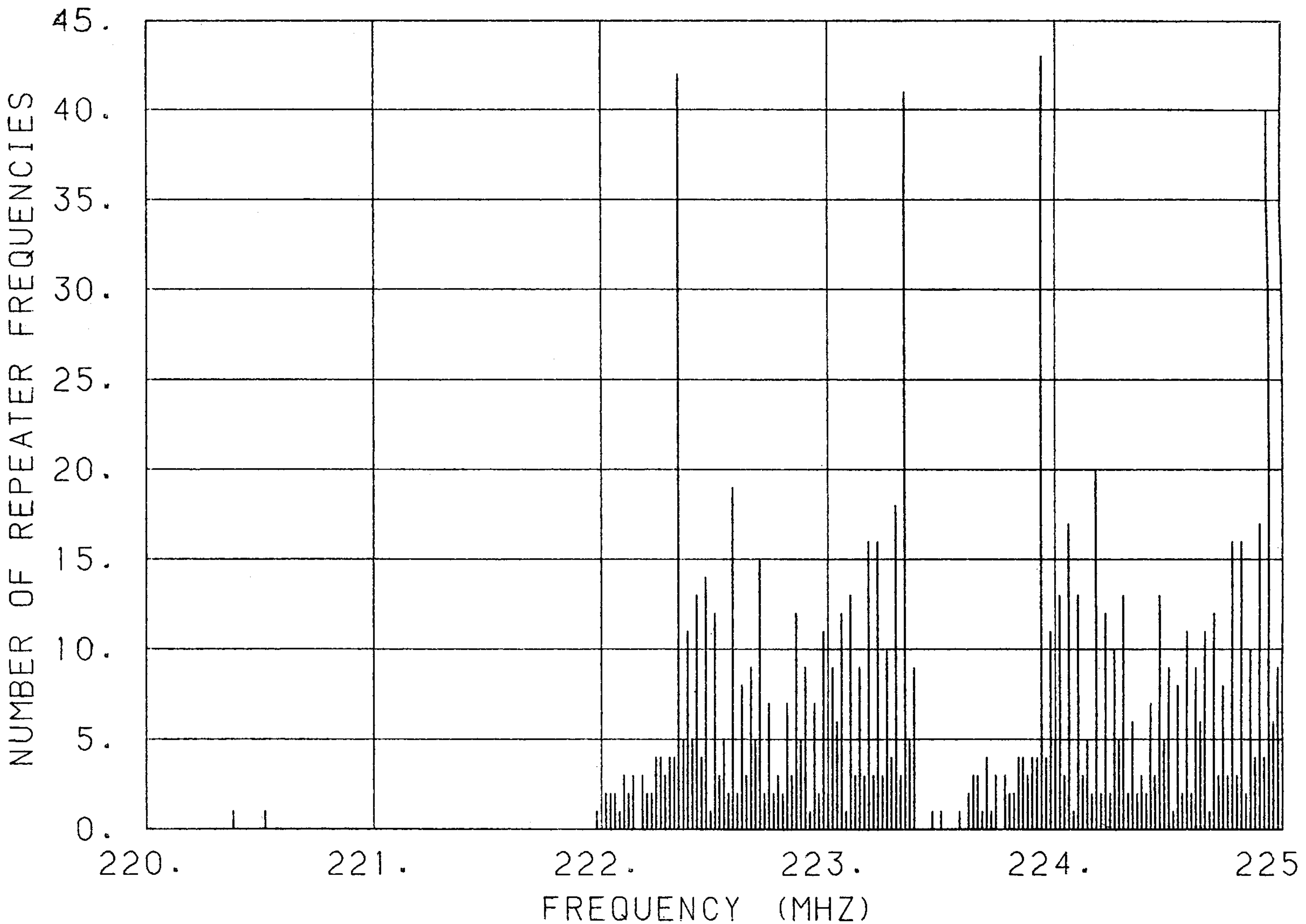

Figure 27. Repeater Assignment Distribution in the Amateur Service.

channel spacing to the current 25 kHz, was accompanied by changes to technical standards, channeling plans, etc. This was, however, only after first being adopted within the private sector by the FCC and the equipment availability and design had somewhat matured.

Strong Regulation

The potential impact to Federal agencies if a strong regulatory approach were taken is examined in the following paragraphs. It could be well argued that because of equipment design uncertainties, cost implications, and performance questions, it is far too premature to consider mandatory requirements for Federal agencies to employ narrowband technologies. The various Federal agencies have very diverse land mobile communication requirements which are in support of Congressionally or Presidentially mandated missions. Agencies involved in law enforcement such as the FBI, INS, and the Secret Service have a requirement for nationwide interoperability among units. Without interoperability, communication equipment could not easily be moved around the country in response to crisis situations. Each local area would have to be fully equipped to handle any given emergency, a very ineffective approach. In many of these applications, digital communications are being increasingly required.

Resource management activities within the Government have, in some cases, similar requirements such as the Department of Agriculture fire cache in which a quantity of radio equipment is centrally stored for use in forest fire fighting throughout the Western United States. Military base, non-tactical communications used in these bands may to a lesser extent have similar interoperability requirements. Other networks used by the Government such as paging, local dispatch, maintenance communications, executive networks, etc., may be similar to many private systems in being local, independent networks not interconnected with other networks.

Because of these diverse requirements, a general mandatory requirement to convert to a new narrowband technology would be impractical and not desirable. Even a more limited conversion requirement aimed at specific classes of system or functions would be initially impractical because of the difficulty in identifying which specific system is a suitable candidate for using narrowband technology. Further study would be necessary to develop a method and procedure to identify, at the request for frequency assignment stage, which stations are candidates.

Active Encouragement

In managing the radio spectrum allocated to the Federal Government, NTIA has a responsibility to ensure the spectrum is used efficiently. While a marketplace approach is possible with regard to evolving narrowband techniques, it is proposed that a more active Federal role could be effective but still short of mandatory regulations. General steps that NTIA could take would include: (1) removing regulations and procedures which have an inhibiting effect on introduction of narrowband technologies, (2) continuing to provide information, test results and/or application results to potential Federal agency users, (3) taking a clear and open position in support of suitable narrowband technologies, (4) committing limited NTIA funds towards furthering the technology, and (5) supporting further studies of how these narrowband technologies could be applied to other radio services and/or functions. Several specific steps are discussed below.

News Release. One method that would provide a clear message to current and potential developers and users of narrowband technologies would be the promulgation of a public news release which states NTIA's full support and endorsement of the concepts. The release could acknowledge the completion of measurements and analysis on the subject and outline the steps which NTIA plans to take as a result.

Government Leadership. Chapter 2 of the NTIA Manual (1982) establishes the overall policies and objectives of the Federal Government with respect to use of the radio spectrum. Section 2.3.5 of that chapter states, "The Government shall exercise leadership in the application of technological advances of operational procedures that will result in more efficient and effective use of the radio spectrum" (emphasis added). One method for NTIA to clearly exercise its leadership role in this area is through the competitive purchase and use of a narrowband technology land mobile system. This system would be operated on a semi-permanent basis to serve both operational communication needs as well as to serve as a demonstration to Federal agencies of its long-term operational viability. The system would serve the Annapolis and Washington NTIA offices as well as linking capability between the two. Cooperative experiments with Federal agencies would be pursued. Federal agencies, which may in the future consider purchase of such equipment, would be given "hands on" ready access to the operational and performance aspects of these radios.

A much broader scope effort aimed at establishing this leadership role would be to undertake a study, in conjunction with Department of Commerce frequency management and administrative personnel, to investigate establishing the U.S. Department of Commerce as the lead Federal agency in implementing narrowband land mobile technology. The Department of Commerce, which encompasses spectrum management and telecommunications policy as well as domestic and international trade responsibilities, is a unique candidate for the lead role in this area. Part of this study would be the identification of candidate radio stations for its use within the Department and establishment of a schedule for eventual phase-over of applicable stations. The study should fully consider the cost, performance, reliability as well as spectrum efficiency of these techniques and any adverse impact on Congressionally and Presidentially mandated Department missions.

Continued Development. Measurements and analysis completed on a commercially available ACSB radio demonstrated it can function well in many environments with 5-6.25 kHz channel separation. However, in congested environments in which significant adjacent channel interference is present, currently available adjacent channel performance may be inadequate. For existing FM radio, current industry recommendations call for a minimum of 70 dB adjacent channel selectivity (EIA, 1982), and NTIA standards call for 70 to 80 dB minimum values for various classes of radio equipment in the 162-174 MHz band. Similar values may eventually be required for narrowband technology radios such as ACSB. It has been suggested that with further development, the adjacent channel performance of ACSB technology should be capable of meaningful improvement through development of more linear transmitter power RF amplifiers and/or changes to pilot carrier processing.

Within the Federal Government, the Department of Defense has consistently maintained a lead role in funding research and development of new and innovative telecommunication systems pursuant to its national defense responsibilities. Records also show that the Department of Defense has, by far, the largest number of frequency assignments in the Government Fixed and Mobile bands between 138 and 174 MHz as summarized in TABLE 13. In view of this significant spectrum usage as well as its vast research and development experience, the DoD is in a unique position to further this narrowband technology through funding of additional research and development. Such development efforts could be aimed at improving the adjacent channel performance of the ACSB technology.

On a much broader scale, it is noted that the ACSB concept is not limited to land mobile applications but could be used to great benefit in applications such as military tactical communications, maritime and aeronautical communications and even satellite applications such as the Land Mobile Satellite Service. A brief review of frequency allocations and assignment trends between 30 and 1000 MHz indicate that approximately 40 percent is allocated and primarily used for single channel fixed and mobile applications. A modest level of funding by a Federal Department, such as the Department of Defense, aimed at investigating application of ACSB for these and other radio services could have immense impact to overall U.S. spectrum utilization, both private and Government.

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APPENDIX A

NTIA FIELD TESTS

BACKGROUND

In an effort to gain a more thorough appreciation of the operational aspects of new technologies in narrowband land mobile, NTIA conducted a series of subjective field tests. These tests were designed to make a direct comparison of a more conventional wideband FM land mobile system (Motorola MAXAR) and a relatively new narrowband amplitude compandored single sideband (ACSB) system (Sideband Technology, Inc., Pioneer 1000). Subsequent to the completion of the ACSB tests, NBFM radios were made available for similar measurements (comparing NBFM with conventional FM radios). The results of the NBFM measurements are presented in Section 4 of this report.

OBJECTIVES

The objectives of these field tests were to obtain direct experience, under operational conditions, of:

1. operational range,

2. voice quality as a function of range, and

3. behavior in an interfering environment (adjacent channel only).

APPROACH

In order to accomplish these objective testings, a subjective testing approach was used. Test facilities at NTIA, Annapolis, are limited and the field tests conducted were, consequently, limited in scope. The tests conducted were of two generic types:

1. Range Tests, and

2. Adjacent Channel Interference Tests

Each category consisted of a series of individual tests designed to explore operational characteristics in sufficient detail to draw a conclusion.

Initially, to obtain an estimation of maximum range, several automated propagation models were run to calculate the theoretical maximum communication range using system parameters listed in TABLE A-1. The results of these theoretical investigations are shown in TABLE A-2.

Subjective range tests were then conducted to attain operational range and voice quality objectives. Three test routes were selected to represent as varied a set of conditions as possible, and identical tests were conducted for FM and ACSB systems. Specific procedures, criteria, and objectives are discussed in more detail later.

TABLE A-1

FIELD TEST PARAMETERS

<u>Transceivers</u>	
GTI Pioneer 1000 ACSB	
*Power output	25 watts PEP (44 dBm)
*Sensitivity	0.3 µV for 20 dB Quieting (-117 dBm)
Frequencies	
ch 1	172.050 MHz
ch 2	172.055 MHz
ch 3	172.065 MHz
ch 4	172.075 MHz
Motorola MAXAR	
*Power output	25 watts (44 dBm)
*Sensitivity	0.35µV for 20 dB Quieting (-116 dBm)
Frequencies	0.35µV for 12 dB SINAD (-116 dBm)
ch 1	172.050 MHz
ch 2	172.080 MHz
<u>Antennas</u>	
Base:	
Type	Omni Whip
Gain	3 dBi
Height	10 meters (33 ft.)
Mobile:	
Type	Magnetic Roof Mount
Gain	0 dBi
Height	2 meters (6.5 ft.)
<u>Confidence Factors (C.F.)</u>	
Location Variability	50.0%
Time Variability	50.0%
Confidence Level	50.0%

*Manufacturer's Specifications

TABLE A-2

MAXIMUM RANGE CALCULATIONS[1]

MODEL	PATH LOSS(dB)	Max. Range (km)
TIREM[3] NLAMBDA[4]	158.6[2] 148.0[2]	20.8

[1] The propagation path loss calculated using TIREM or NLAMBDA differ slightly from the expected system loss (164 dB) obtained from the system parameters indicated in TABLE A-1. This difference is due to signal fading, cable and coupling losses that have not been included in the computer calculations.

[2] Path loss at predicted maximum range.

[3] Powell, J.R., The Terrain Integrated Rough Earth Model (TIREM), ECAC-TN-83-002, September 1983.

[4] Maiuzzo, M.A. and Frazier, W.E., A Theoretical Ground Wave Propagation Model - Nλ Model, ESD-TR-68-315, Electromagnetic Compatibility Analysis Center, Annapolis, MD, December 1968.

Additional field tests to investigate general adjacent channel interference behavior were also conducted. Although subjective in nature, observations in an actual operating environment are important aspects in the validation of laboratory measurements. Specific details of these tests are discussed in a later section.

SYSTEM DESCRIPTION

The systems used for these tests included the following.

1. Three Sideband Technology, Inc. (STI) Pioneer 1000 ACSB transceivers

   SN 100224
   SN 100305
   SN 100308

2. Two Motorola MAXAR FM transceivers

   SN 240 FGS0610
   SN 240 FGS0611

Complete technical descriptions of these transceivers can be found in other sections of this report. The systems were set up in various base and mobile configurations. In the base-station configuration, an HP6286A DC power supply was used as the power source. A cassette tape recorder was connected to the speaker output of the base station receiver so that all tests could be recorded for subsequent analysis. Specific parameters of system components are listed in TABLE A-1. Procedures for individual tests are described in the appropriate subsection.

TEST PROCEDURES

The test procedure used varied for each generic class of test (i.e., range and interference). Both categories used the mobile unit as the test transmitter and the base unit as the test receiver. The test area was confined to an approximate 25 km (15 mile) radius of NTIA, Annapolis, Maryland. To maintain consistency and validity, each test was performed at approximately the same time of day as the same test for the other system. Any conclusions or opinions were based on the subjective observations of the listener.

RANGE TESTS

The purposes of the range tests were to establish several communication zones centered about the base station and to observe strength and quality of the transmissions as a function of range. Each zone represented a degree of quality of communications: nominally good, acceptable, and poor (or non-existent). These zones were established by moving a mobile transmitter along various test routes representing varied terrain condition, and reading from a Harvard list of phonetically balanced sentences (TABLE A-3). During all tests, the base station (receiver) recorded the signals on magnetic tape.

TABLE A-3

HARVARD PHONETICALLY BALANCED SENTENCES

6 WORD SENTENCES

Lately, exercising has become increasingly popular.
They conveniently misplaced the storeroom key.
Negotiations have been discontinued this week.
No one knows what causes nightmares.
Were you embarassed after your fall?
When will you graduate from college?
Did you deliberately ruin that painting?
One fundamental difference was their age.
His expression was one of dismay.
Which candidate is considered more liberal?
Was the announcement encouraging or grim?
She observed them from a distance.
The disaster was a harsh reality.
What kind of nonsense is this?
The envelope had already been opened.

7 WORD SENTENCES

Are there more automobile accidents at intersections?
Was he unwilling to saddle your horse?
Do many corporations avoid paying income tax?
Other companies were competing for the contract.
Your carelessness finally ruined this beautiful forest.
Due to the snowstorm, visibility was minimal.
New innovations can vastly improve the procedure.
What was all the commotion about outside?
How did you ever survive that ordeal?
He publicly announced the new tax increase.
Several improvements were made in the proposal.
Everyone involved was shaken by the tragedy.
We encountered some hostility during the tour.
Only seven passengers survived the terrible crash.
Was that fabric difficult to sew with?
What were the circumstances surrounding that incident?
The landscape was particularly colorful this Fall.
The two signatures appeared to be identical.
The villagers were severly undernourished and sick.
The elderly judge presided over the courtroom.
The wastebasket was full of crumpled papers.
Relatively few people attended the afternoon sessions.
Are those leather wallets and belts handmade?
Have the congressmen returned to the session?
The demonstrators were charged with disorderly conduct.
How much do you charge for alterations?
Acting requires many long hours of rehearsals.
Why is this sleeping bag so lumpy?
What prompted the investigation of that airline?
He was preoccupied by thoughts of sailing.
The manuscript summarized many years of research.
Who remembers the consequences of that action?
In her judgement, the decision was wrong.
His enthusiasm for the sport was overwhelming.
Official welcome came from the president himself.

To determine the borders of each zone, the following criteria were established to note the two distances or ranges that separate the zones:

(1) The maximum range at which good communications is maintained (i.e., all words in each sentence are received and understood).

(2) The maximum range at which communications becomes marginal (i.e., transmission is subject to deep fading or breakup and two or more words in each of three contiguous sentences are missed, garbled, or not intelligible).

Identical tests were performed on ACSB and FM systems.

Test 1 - ACSB Range Test. Designed to test range and voice quality characteristics in a general northerly direction, this test route extends from the base station, northeast along Riva Road, and then north on Maryland Routes 178 and 32. The test route can be found on the map in Figure A-1. The general test configuration is pictorially represented by Figure A-2.

Test 2 - ACSB Range Test. This test is designed to explore range and voice quality characteristics in a general westerly direction from the base station. The test route extends northeast from the base, along Riva Road, and then west on U.S. Route 50 (see Figure A-1). General configuration is identical to Test 1.

Test 3 - ACSB Range Test. This test reveals range and voice quality characteristics in a southeasterly direction from base. The route begins at the base station and extends southwest on Riva Road and west on Route 2A-14 (see Figure A-1). The configuration is identical to that in Test 1.

Test 4 - FM Range Test. This test uses the identical route as Test 1 (see Figure A-1) and explores range and voice quality for the FM system. The general configuration is pictured in Figure A-2.

Test 5 - FM Range Test. This test reveals range and voice quality for the FM system along the same route as Test 2 (see Figure A-1) and was configured as in Test 4 (Figure A-2).

Test 6 - FM Range Test. The final range test examined range and voice quality for the FM system on the same route as Test 3 (see Figure A-1) and was configured as in Test 4 (see Figure A-2).

The results of all range tests are discussed in a later subsection.

Interference Tests

This series of tests is designed to explore some of the adjacent signal interference (ASI) characteristics of the ACSB radio and to form an operational opinion of their (ACSB) behavior in an interfering environment. Although subjective in nature, it is felt observations in an actual operating (and interfering) environment are important aspects in the validation of laboratory measurements.

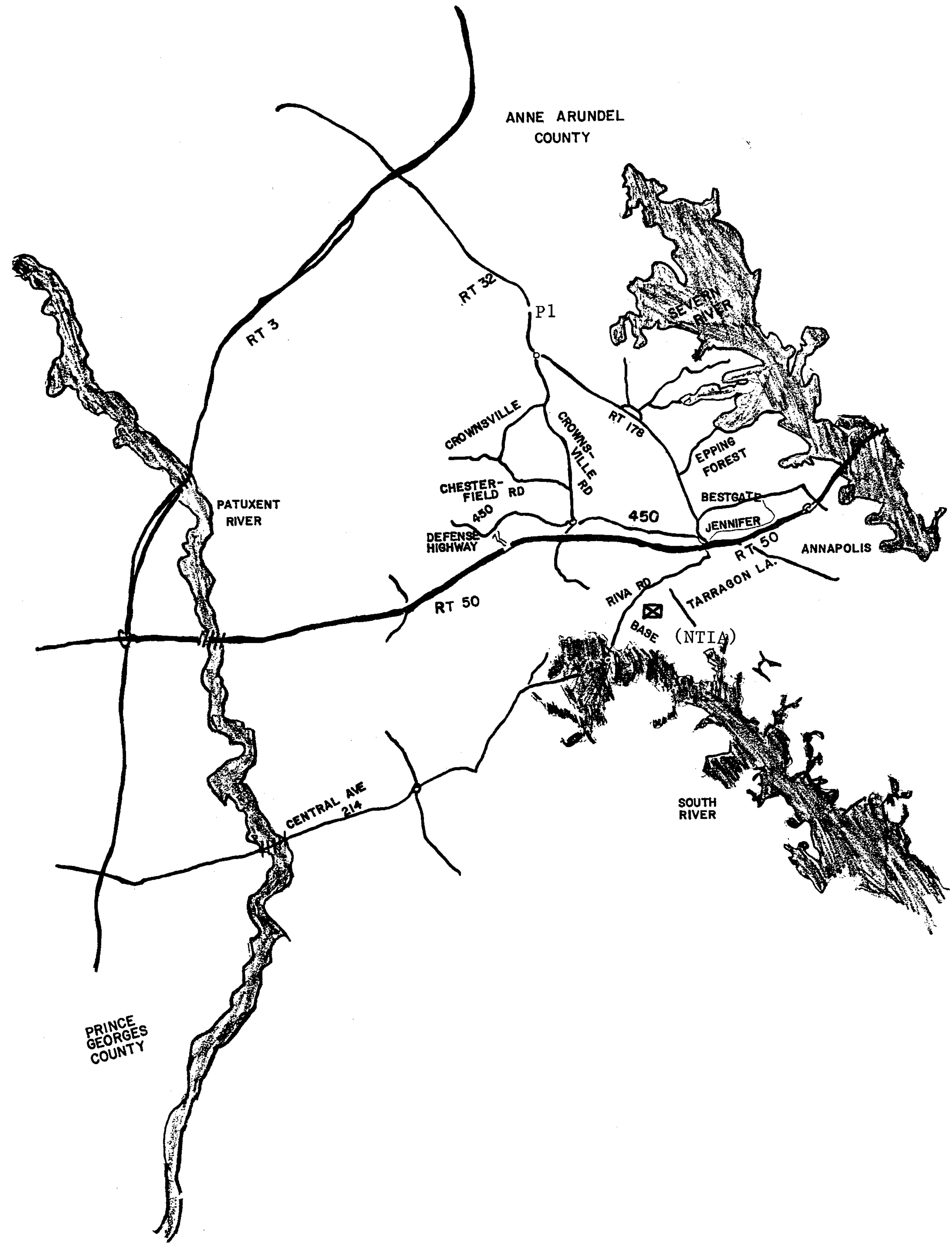


Figure A-1; Field Test Area

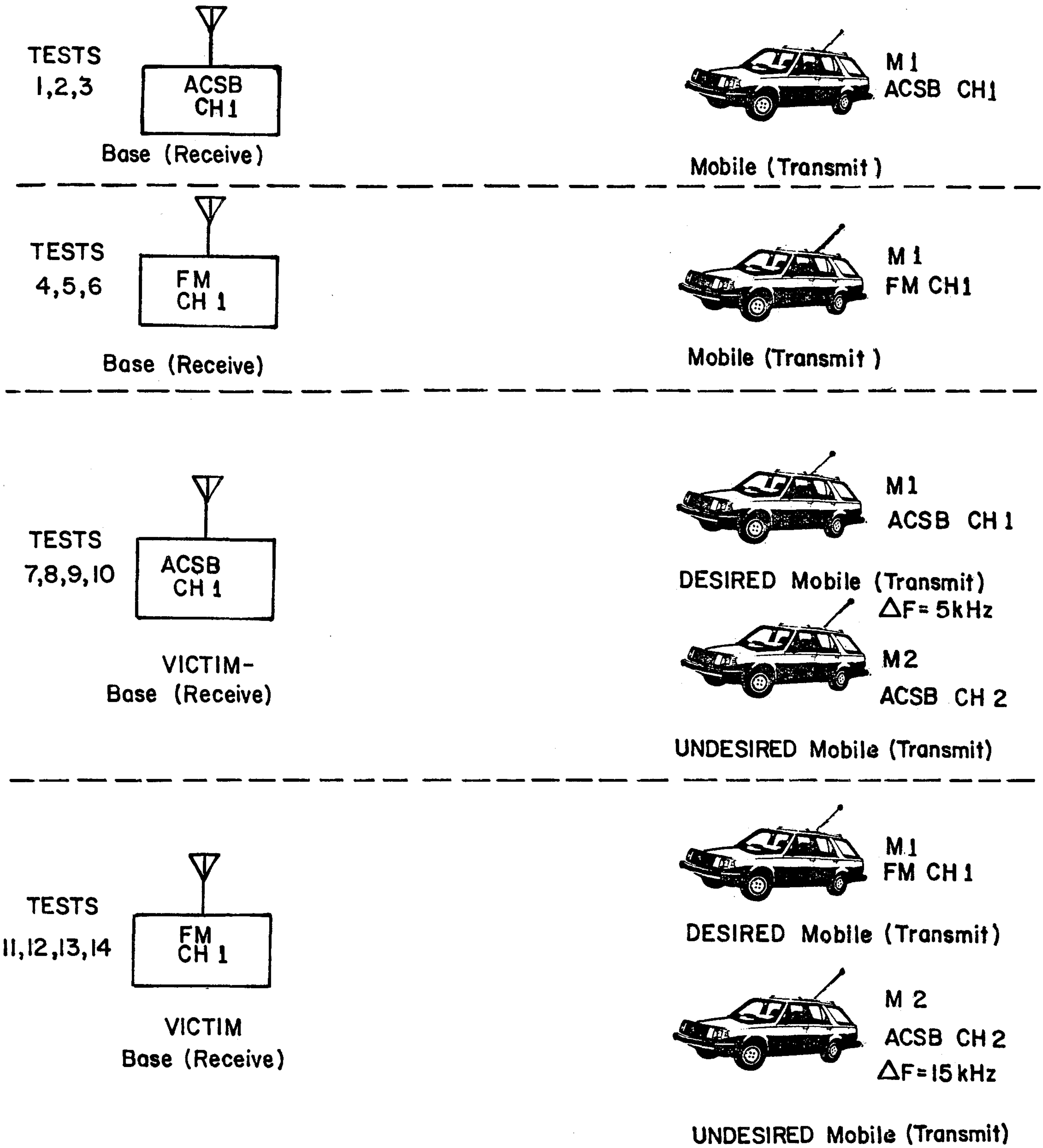


FIGURE A-2: Field Test Configuration

Due to the lack of resources, the testing was limited to two scenarios;

(1) ACSB-to-ACSB interference
Δf = 5 kHz

(2) ACSB-to-FM interference
ΔF = 15 kHz

The tests involved a victim (base station) and two mobiles, a desired mobile (M1) and an undesired mobile (M2). The desired mobile was located in a fixed position (P1; see Figure A-1) in the zone of acceptable communications (as determined by range tests).

In all tests, the desired mobile (M1) continuously transmitted (with occasional breaks) a list of phonetically balanced sentences (6-word sentences) from TABLE A-3. At the same time, the undesired mobile (M2) transmitted from the 7-word list in TABLE A-3, while traveling the various test routes described.

All ASI tests were recorded and observations (results) were made according to the degree and extent of interference. Degradation criteria were established to quantify (somewhat) observations. In general, levels of degradation are defined as:

(1) ACCEPTABLE DEGRADATION - Interference which causes a minor degradation in service and in which all or nearly all words of the desired transmission are received and understood.

(2) SEVERE DEGRADATION - Interference which causes a major disruption or degradation in service and in which two or more words in each of three continguous sentences are missed, garbled or not intelligible.

The following tests were designed to record the interaction of the desired and undesired signal at the victim receiver. The test routes for the undesired mobile (M2) varied in azimuth and distance from the base station while the desired mobile remained in a fixed position (P1).

The first series of tests explores ACSB-to-ACSB adjacent channel interference with a frequency separation (Δf) of 5 kHz.

Test 7 - ACSB-to-ACSB interference. During this test, as the desired mobile (M1) transmitted from a fixed position (P1), the undesired mobile (M2) transmitted continuously along the first test route. The route starts at the intersection of Bestgate Road and Ridgely Avenue (4.2 km (2.5 mi)) see Figure A-1) and proceeds west on Bestgate, south on Route 178 and southwest on Riva Road, ending at the base station. Test units were configured as in Figure A-2.

Test 8 - ACSB-to-ACSB Interference. The route for this test extends from the base, northeast along Riva Road, and north on Route 178, ending at Epping Forest Road (3.2 km (2 mi)). The desired mobile (M1) continued to transmit from

P1. The test configuration is diagramed in Figure A-2 and the procedures outlined earlier were followed.

Test 9 - ACSB-to-ACSB Interference. The route for Test 9 starts at the intersection of Route 450 and Crownsville Road (3.5 km (2.2 mi)), proceeds east on Route 450 to Route 178, and south on Route 178 to Riva Road, continuing southwest on Riva Road to Base. The desired mobile (M1) transmitted continuously from the fixed position P1. Test units were configured as in Test 7 (see Figure A-2).

Test 10 - ACSB-to-ACSB Interference. For this test the configuration and procedures were identical with Tests 7 through 9, except the test route varied. The route started at the base station and proceeded southwest on Riva Road to a point approximately 3.2 km (2.0 miles) from base.

The second series of tests was designed to show the effects of ACSB interfering with FM. A frequency separation of 15 kHz was used. The desired link (M1 to base FM) was fixed while the undesired or interfering mobile (M2, ACSB) traveled the same test routes as in Tests 7 through 10.

Test 11 - ACSB-to-FM Interference. This test used the identical route as Test 7, except the desired link was FM and the undesired (interferer) was ACSB as shown in Figure A-2.

Test 12 - ACSB-to-FM Interference. This used the same route as Test 8 with differences in test configuration as shown in Figure A-2.

Test 13 - ACSB-to-FM Interference. This test used the identical route as Test 9 with configuration differences noted in Figure A-2.

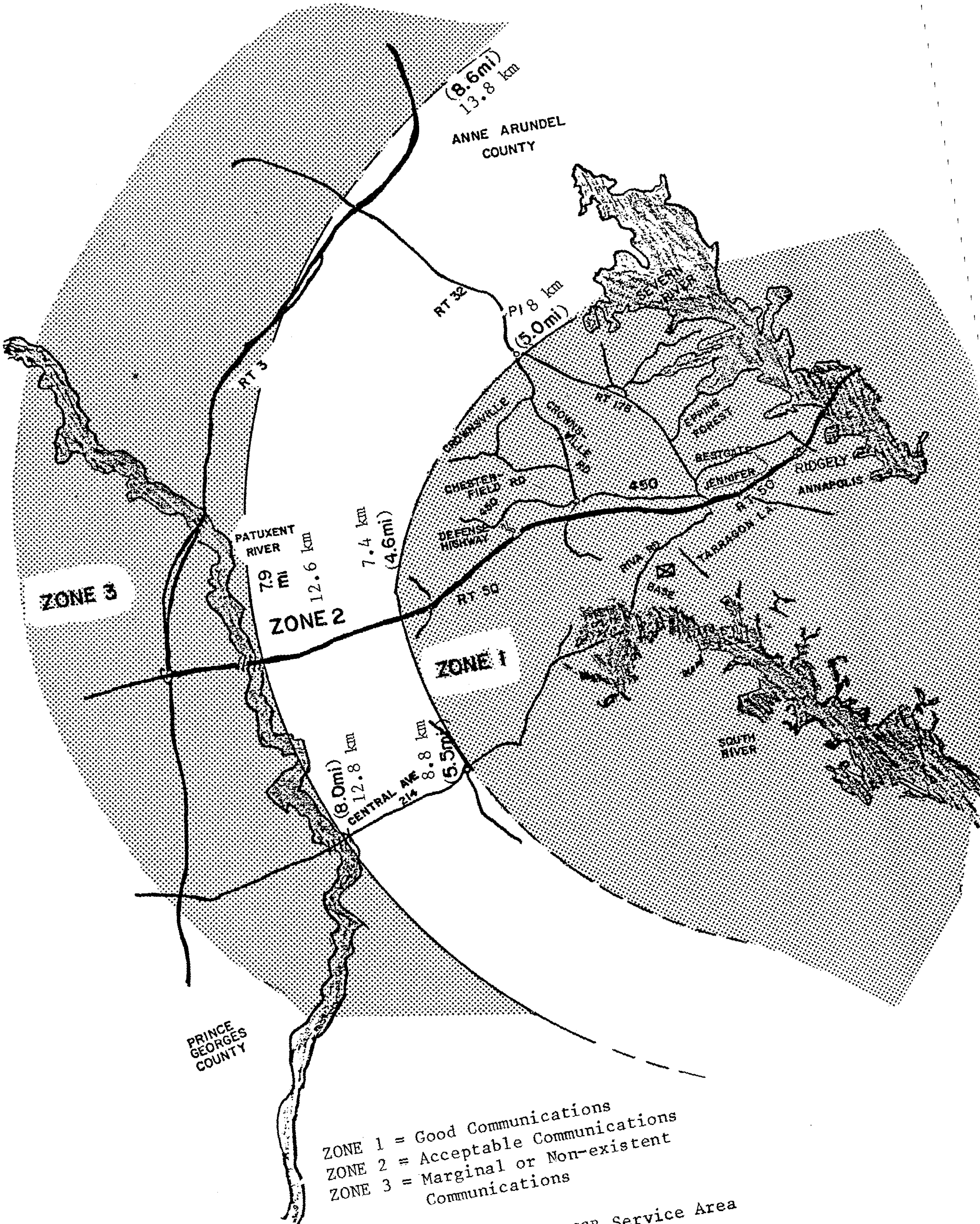
Test 14 - ACSB-to-FM Interference. The final test in the series used the same route as Test 10 with differences in configuration shown in Figure A-2.

RESULTS

Upon completion of the field tests, the recordings were analyzed and the results, in response to the objectives, are represented in the following observations:

1. ACSB Range - The maximum range at which the ACSB system maintained good communications (defined earlier) averaged 8.0 km (5.0 miles) over the three test routes. The average maximum range at which the ACSB system maintained acceptable communications was 13.1 km (8.2 miles). The actual distances (ranges) observed for the individual test routes and the service area these ranges describe are diagramed in Figure A-3.

2. ACSB Quality - Voice quality was maintained at a "very good" level in Zone 1 (good communications). The received signal was strong and clear but appeared to have a slight gravel or raspy quality. Voice recognition may pose a minor problem. In Zone 2 (acceptable



ZONE 1 = Good Communications
ZONE 2 = Acceptable Communications
ZONE 3 = Marginal or Non-existent Communications

FIGURE A-3: ACSB Service Area

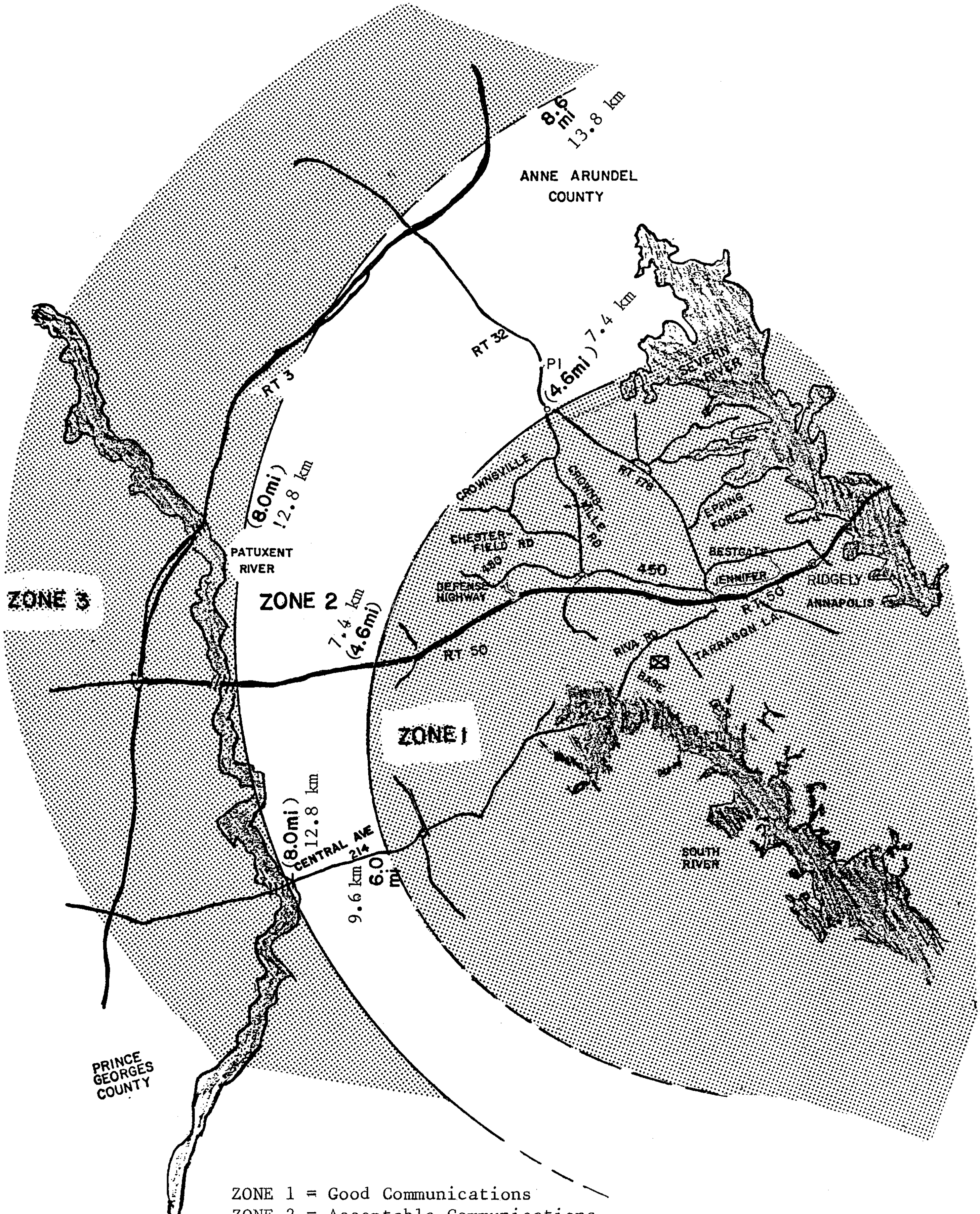
communication), the signal was subject to some rapid fading and terrain masking effects; however, messages were received and understood. Beyond the acceptable zone, transmissions were subject to deep fades, breakups, and complete loss of transmission. On a whole, the voice quality tended to degrade at a fairly constant rate over the entire range.

3. FM Range - The average maximum range for maintaining good communications (outer limit of Zone 1) for the FM system was 8.2 km (5.1 miles). To maintain acceptable communications (outer limit of Zone 2) the average maximum range was 13.1 km (8.2 miles). Distances observed for each test route and the zones that define FM service area are pictured in Figure A-4.

4. FM Quality - The FM system displayed excellent voice quality and voice recognition characteristics throughout the zone of good communications (Zone 1). Noise "pops" became apparent at an average of 5.2 km (3.2 miles) but did not become a nuisance or degrading until later. Few fades were noticed. Throughout the acceptable zone (Zone 2) voice quality remained at a good to fair level. The noise "pops" increased in intensity with range, and the transmission became subject to the same rapid fading and terrain masking as the ACSB system. Beyond the acceptable zone (into Zone 3), the FM transmission experienced virtually the same deep fades and noise interference as the ACSB system. Overall, the FM system appeared to maintain a higher degree of voice quality for a longer period. Degradation was more rapid as range approached the maximum. The ACSB system experienced more gradual degradation in voice quality as range approached the maximum.

5. ACSB-to-ACSB Interference (Δf = 5 kHz) - During the desired transmission, little or no interference was recorded while the interfering mobile was located between 1.5 km (one mile) and 3.2 km (two miles) from the base (VICTIM). In this range, the only noticeable degradation occurred during natural breaks in the desired transmission. This was in the form of noise bursts. Between 0.8 km (1/2 mile) to 1.5 km (one mile) from the base, the interfering signal became more apparent providing occasional interference bursts during the desired transmission. This interference was, however, acceptable and the desired link remained intelligible. Within a 0.8 km (1/2 mile) radius of the base station, the interfering signal became dominant, severely degrading the desired link, with a total loss of intelligence.

6. ACSB-to-FM Interference (Δf = 15 kHz) - The interfering environment for these tests was very similar to that recorded for the ACSB-to-ACSB interference tests. Acceptable degradation was noticed from about 1.2 km to 1.5 km (three-quarters to one mile) from the base station, with noise burst during breaks in desired transmission beyond one mile. Within 0.8 km to 1.2 km (1/2 to 3/4 mile) radius of the base station, degradation of the desired signal was severe with an almost total loss of the desired signal.



ZONE 1 = Good Communications
ZONE 2 = Acceptable Communications
ZONE 3 = Marginal or Non-existent Communications

Figure A-4: FM Service Area

7. Mobile-to-Mobile Interference - During both the ACSB/ACSB and the ACSB/FM interference test, it was observed that when mobiles were within 0.4 km (one-quarter mile) of each other, severe interference interactions resulted during transmission from either system.

APPENDIX B

TECHNICAL SPECTRUM EFFICIENCY FACTOR OF ACSB AND NBFM UTILIZING A 25 kHz FM REFERENCE SYSTEM*

INTRODUCTION

This appendix includes calculations of the technical spectrum efficiency factor of ACSB and NBFM referenced to FM for situations typical of U.S. Government land mobile operations. The performance parameters used in the calculations are primarily those from the ECAC measurements [NTIA, 1983]. The computerized land mobile model (PRODSIR), developed by Berry [1977], was used to simulate the communication performance of the NBFM, 25 kHz FM.

A previous in-depth study to calculate the spectral efficiency of ACSB and compare it to 25 kHz FM was completed by Herro [1981]. This previous comparison showed ACSB to have significantly greater spectral efficiency than 25 kHz FM. The majority of the measured data used in that comparison was taken from measurements by Lusignan [1980]. A variety of methods and measures have previously been utilized to calculate spectrum efficiency of land mobile environments. The past measures of spectrum efficiency for land mobile have included users/MHz [Cooper and Nettleton, 1983] and Erlangs/MHz/Mi^2 [Hatfield, 1977]. Herro chose to define spectrum efficiency in the units of mobiles/MHz/Km^2. In many of these previous calculations of spectral efficiency, mobile-to-mobile interference was the factor that determined the communication capacity. The typical communication links in Government land mobile operations consist primarily of base stations communicating back and forth to mobile stations. Consequently, in Government land mobile operations, base-to-base and base-to-mobile interference are the factors which limit the communication capacity and determine spectrum efficiency. Both of these interference situations were considered.

This appendix computes the technical efficiency factors of the two narrowband modulation technologies relative to 25 kHz FM. The method used to compute the relative spectrum efficiency was to compare for each modulation method the amount of spectrum denied to any adjoining base station (spectrum space used), under the added condition that the communications achieved be identical for all modulation methods.

MEASURE OF SPECTRUM RESOURCE USED

A useful measure of spectrum resource used is

$$\text{Spectrum resource used} = (\text{bandwidth})\cdot(\text{space})\cdot(\text{time}) \qquad \text{(B-1)}$$

*ACSB is designed to operate on a 5 kHz channel width, NBFM on a 12.5 kHz channel width and 25 kHz FM on a 25 kHz channel width.

This measure is general and applies to all telecommunication environments. It is necessary to interpret and apply it to typical land mobile Government environments. Consider first the numerator. The measure of communication achieved is successful communication between a base station and a randomly moving mobile station located in a circular reception area around the base station. For voice circuits, successful communication is characterized by an adequate intelligibility of the signal.

The denominator term is the spectrum resource used. Spectrum resource used has three coordinates: space (spatial area), bandwidth and time. The total "volume" of spectrum space used is (bandwidth) x (space) x (time). The total spectrum used is that amount of spectrum denied to others. In the land mobile environment simulation, the spectrum space denied is that spectrum volume, (bandwidth) x (space) x (time), in which other base stations cannot operate. The placement of an additional base station in the denied spectrum may cause interference to communications being carried out by the existing base station and mobiles.

The amount of denial in each of the individual spectrum coordinates needs consideration. The spatial coordinate of spectrum used is considerably scenario dependent. An operating base station may preclude the physical placement of another base station in its vicinity depending upon its and the other base stations frequency of operation. This denial results because a base station in the vicinity may cause interference to either mobile or base station receivers in the communication area around the base station. For this analysis only cochannel interference will be considered. Figure B-1 shows the spatial area denied to an additional base station. An adjoining base station, if cochannel in frequency, might cause interference to a receiver at either the base station or the mobile located in the reception area. The two separate interference cases, base-to-base and base-to-mobile, will each be considered individually.

In the computer simulation the communication channel was simulated as being occupied by one wanted transmitter and one interfering transmitter, both of which were transmitting continuously. As a result, the spectrum denied in the time coordinate is the same for all modulation types and is cancelled out in the computation of the relative spectrum efficiency of the modulation methods.

PERFORMANCE CRITERIA, S/N AND S/I

In a land mobile environment both long- and short-term fading causes signals to fluctuate randomly. In this statistical signal environment, successful communication requires that the signal-to-noise ratio (S/N) exceed a defined threshold, α, with a certain probability. This signal-to-noise ratio must be realized at the communication range, R_a, the radius of the base station's service area. This is shown in Figure B-2. Mathematically, the criteria for successful communication is

$$P(S/N > \alpha) = 90\% \text{ at } r = R_a \qquad \text{(B-2)}$$

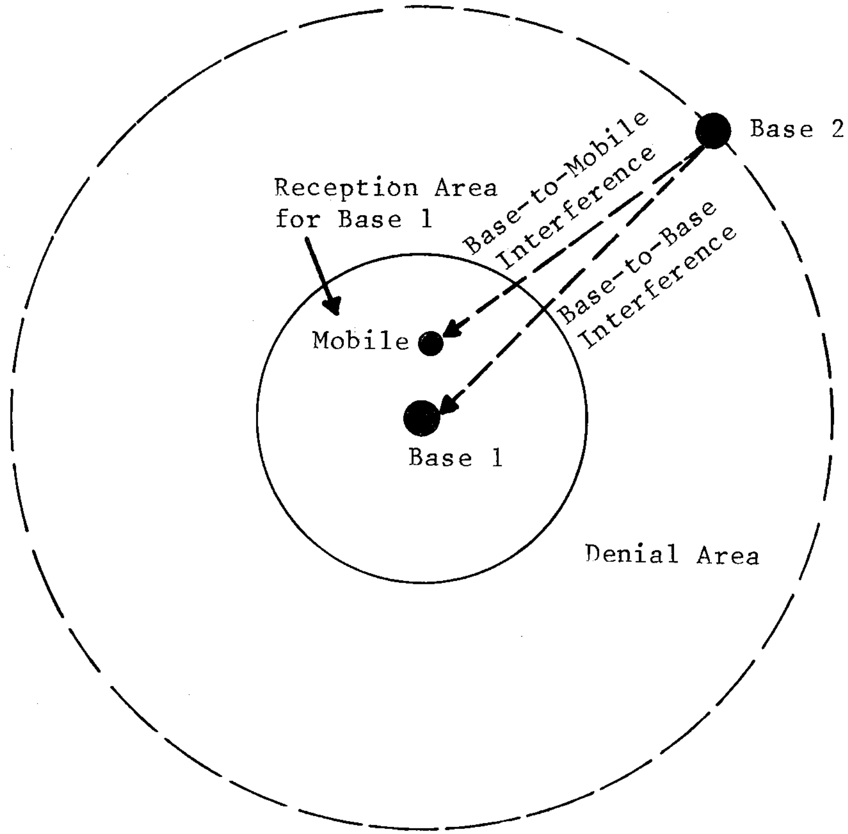


Figure B-1. Denial Areas for Base Station 1. Another Base Station (Base 2) Depending upon Operations may cause Interference to Either the Mobile or Base Station 1. It is therefore Spatially Denied from being Placed in the Circular Area around Base Station 1.

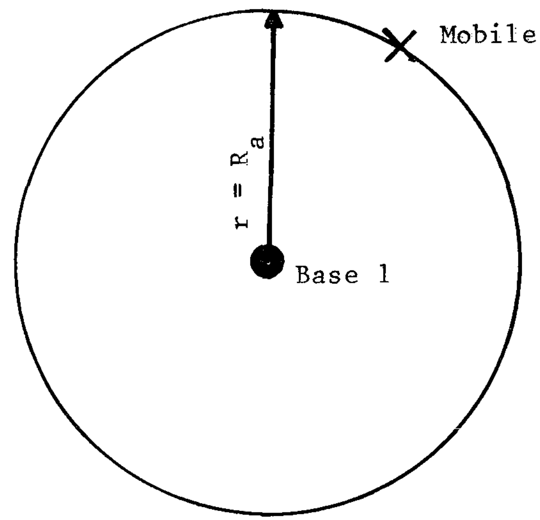


Figure B-2. The Communication Range or System Range is the Distance from a Base Station where the Probability of Receiving Better than a Specific Minimum S/N Value is 90%. The mobile, at radius R_a is at the Communication Range of Base 1.

where

S, N = signal and noise power

α = S/N threshold for successful communication without interference

The ECAC measurements without fast fading [NTIA, 1983], was used as the basis for the receiver performance threshold of ACSB. The acceptable signal-to-noise ratio for ACSB is 10.4 dB. Similarly, from Juroshek [1979], for 25 kHz FM modulation and a 3-kHz peak deviation, the acceptable S/N for FM is 8.5 dB. The assumption was made that NBFM would require approximately the same S/N ratio.

When interfering signals are present, the criteria of successful communication is that throughout the reception area of the base station the probability that the S/I exceeds a threshold value, β, is 90 percent. Mathematically this can be written as

$$P(S/I > \beta) = 90\% \text{ in the reception area} \qquad \text{(B-3)}$$

where

S, I = Signal and interference power

β = S/I threshold for successful communication with interference

The threshold or protection ratio, β, for acceptable performance for ACSB modulation in ACSB interferences is +8.1 dB. This value also is from the ECAC measurement program [NTIA, 1983]. The threshold or protection ratio for a 25 kHz signal in FM interference, obtained from Juroshek [1979] is 5 dB. The assumption was made that NBFM would require approximately the same S/I ratio.

Slow fading is taken into account in the propagation model of the PRODSIR simulation model. Fast fading causes rapid fluctuations in signal strength which is compensated for by increasing the S/N and S/I thresholds required to achieve acceptable performance. When both signal and interference undergo Rayleigh fading, 9 dB must be added to the stable S/N and S/I ratios to yield 90 percent probability of successful communication. Bond and Meyer [1957], have determined the statistics of P(S/I) when the S and I are Rayleigh fading and it is from their work that the 9 dB was obtained. Also, Hagn [1980] states that for VHF the Rayleigh fade margin is in the range 6-10 dB.

The effects of fading will be considered to affect the ACSB and FM similarly and a 9 dB fade margin is added to each S/N and S/I protection ratio. TABLE B-1 includes the protection ratios with fast fading.

TABLE B-1

THRESHOLD (PROTECTION RATIO) FOR SUCCESSFUL COMMUNICATION INCLUDING FADING ALLOWANCES

	ACSB	NBFM and 25 kHz FM
S/N (dB)	19.4	17.5
S/I (dB)	17.1 (ACSB vs ACSB)	14 (NBFM vs NBFM 25 kHz FM vs 25 kHz FM)

STATISTICAL LAND MOBILE (PRODSIR)

The computer model used to represent the land mobile environments was PRODSIR. PRODSIR is a procedure for computing the probability distribution of the signal to interference ratio in radio environments. The independent variables in the S/I equation are assumed to be random variables. PRODSIR combines and transforms input pdfs to produce the pdfs of signal power, interference power, noise power and the probability distributions of signal-to-interference ratio and signal-to-noise ratio. The following describes certain parameters used in this analysis.

In the PRODISR model the mean basic transmission loss is represented by the equation

$$L\ (\text{mean}) = A + B \log\ (\text{path length}) \qquad (B-4)$$

At 172 MHz, utilizing antenna heights (30-meter base and 2-meter mobile) the mean loss was approximated by

$$L\ (\text{mean}) = 78 + 40 \log\ (D)\ (\text{base-to-base}) \qquad (B-5)$$

$$L\ (\text{mean}) = 93 + 40 \log\ (D)\ (\text{base-to-mobile})$$

D = distance in kilometers

L (mean) = loss in dB

In the PRODSIR model, the transmission loss is represented as being normal in dB about these mean values, with a standard deviation of 5 dB. The transmitter power for both base and mobile had a mean value and a normal distribution about this mean with a standard deviation of 3 dB. The background noise was normally distributed about a mean with a standard deviation of 4.5 dB.

COMMUNICATION RANGE

A procedure was devised to make the communication ranges for the ACSB, NBFM and 25 kHz FM the same. In this procedure, the PRODSIR model was first used to determine the communication range for an FM transmitter with 25 watts power. This range was found to be 4.75 Km. The PRODSIR model was then used with typical ACSB parameters. The transmitted power for the ACSB transmitter was progressively changed until the ACSB had the same communication ranges, 4.75 Km as the two FM transmitters. The ACSB transmitter required 15.8 watts to achieve this same communication range.

The probability of successful communication $P(S/N > 19.4)$ for NBFM and 25 kHz FM modulation plotted as a function of service distance D is shown in Figure B-3. A similar plot for ACSB with $P(S/N > 17.5)$ is shown in Figure B-4. Note in both figures that when $D=R_a$ = 4.75km, the $P(S/N > \alpha)$ = 90 percent.

CASE I - BASE-TO-BASE INTERFERENCE

The scenario for this situation is shown in Figure B-5. A mobile transmitter, M, is communicating with the base station 1. This mobile moves randomly in the reception area and its location is uniformly distributed spatially in the reception area with radius 4.75km. The interference is from base station 2, a distance D=BB away. The PRODSIR model was used to calculate the radius BB, distance between base stations, which yields

$$P(S/I > \beta) = 90 \text{ percent in the reception area} \qquad \text{(B-6)}$$

where S is the power of the desired signal from the randomly located mobile and I is the power of the interfering signal from base station 2. In this scenario, the receiver is at the base station B1. The parameters and PRODSIR results for each modulation are shown in TABLE B-2. The parameters used in the calculations are the same as the NTIA measurement program [Appendix A], except that for this efficiency calculation the base station antenna height was 30 meters.

CASE II - BASE-TO-MOBILE INTERFERENCE

The interference situation for this case is shown in Figure B-6. The desired signals to the mobile is from base station 1 and the interference, I is from base station 2. As in Case I, the mobile is moving randomly in the reception area. The interference is along the path BM. In this scenario, the receiver is located at the moving mobile. The probability density function for the interference path length used in the PRODSIR program was altered to account for the receiver not being at the origin O. The PRODSIR model was used to determine the radius BB, distance between base stations, which yields $P(S/I > \beta)$ = 90 percent in the reception area.

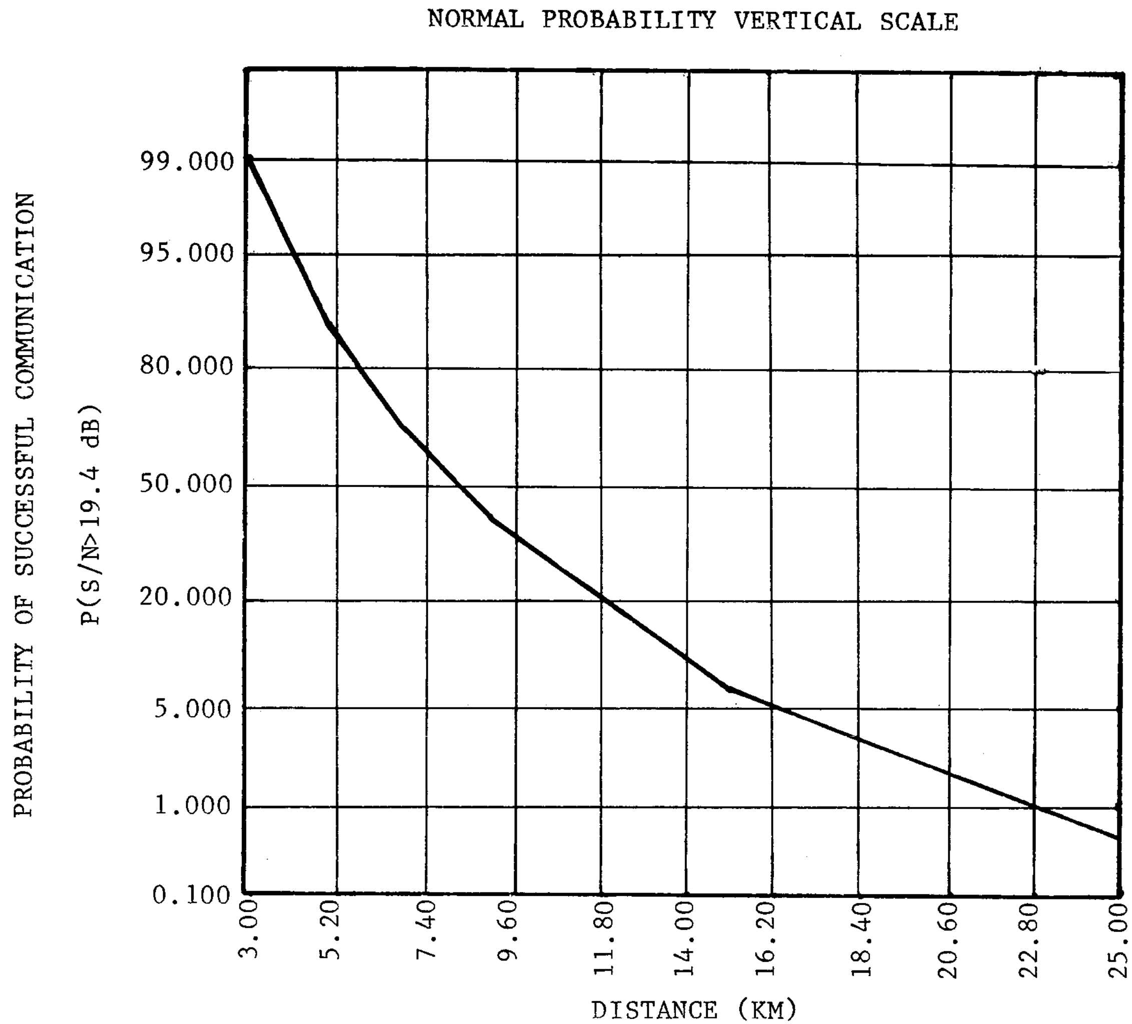


Figure B-3. Probability of Successful Communication for FM Modulation. The Required S/N for Successful Communication is 19.4 dB. The Transmitter Power is 25 Watts. At a Distance of 4.75 km the Probability is 90%.

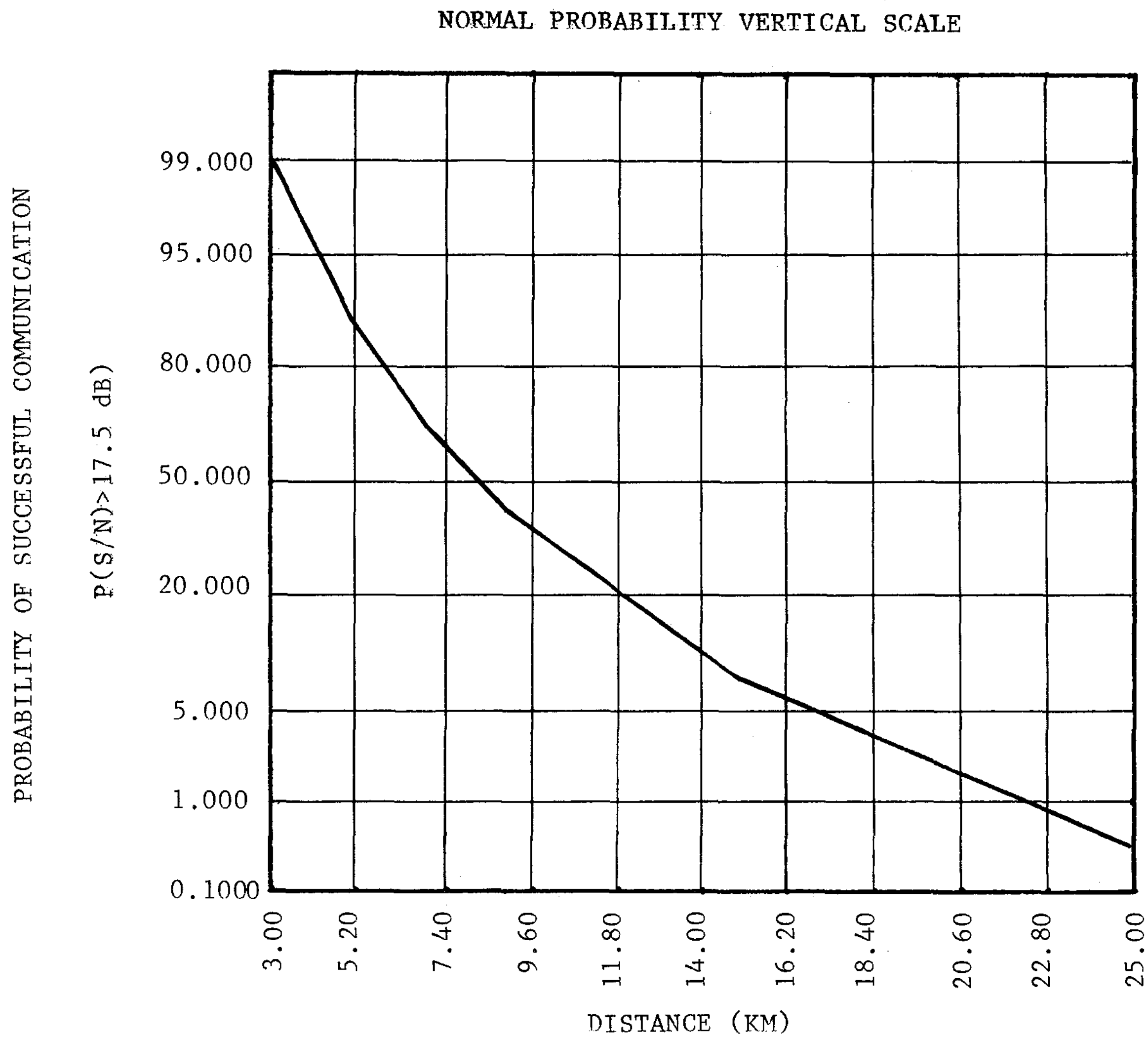


Figure B-4. Probability of Successful Communication for ACSB Modulation. The Required S/N for Successful Communication is 17.5 dB. The Transmitter Power is 15.8 Watts. At a distance of 4.75 km the Probability is 90%.

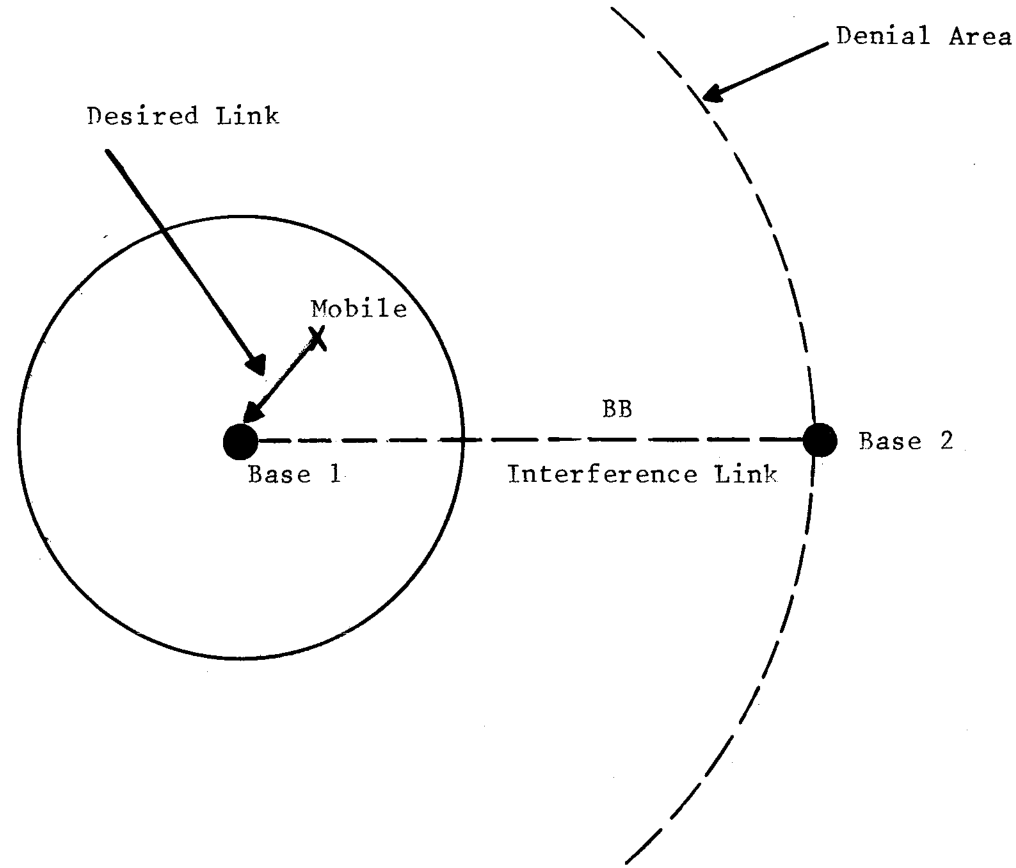


Figure B-5. Denial Area for Base 1 for the Case of Base-to-Base Interference From Base 2 to a Receiver at Base 1. The Denial Area is $\pi(BB)^2$.

TABLE B-2

INPUT PARAMETERS AND PRODSIR GENERATED CRITERIA FOR THE CASE WHEN BASE-TO-BASE INTERFERENCE DETERMINES THE DENIAL RADIUS BB.

	NBFM 25 kHz FM	ACSB
Base Transmitter Power	25 watts	15.8 watts
Base Antenna Gain	3 dBi	3 dBi
Mobile Transmitter Power	25 watts	15.8 watts
Mobile Antenna Gain	0 dBi	0 dBi
Base-Mobile Propagation	A = 93	A = 93
Base-Base Propagation	A = 78	A = 78
S/I Protection Ratio,	14 dB	17.1 dB
Communication Range, R	4.75 km	4.75 km
Interference Denial Range, BB	40 km	47.3 km
Mean Signal	-94.5 dBW	-96.5 dBW
Mean Interference	-122.3 dB	-127.2 dBW
Mean S/I	27.7 dB	30.7 dB
Interference Denial Area $\pi(BB)^2$	5027 km^2	7028.6 km^2

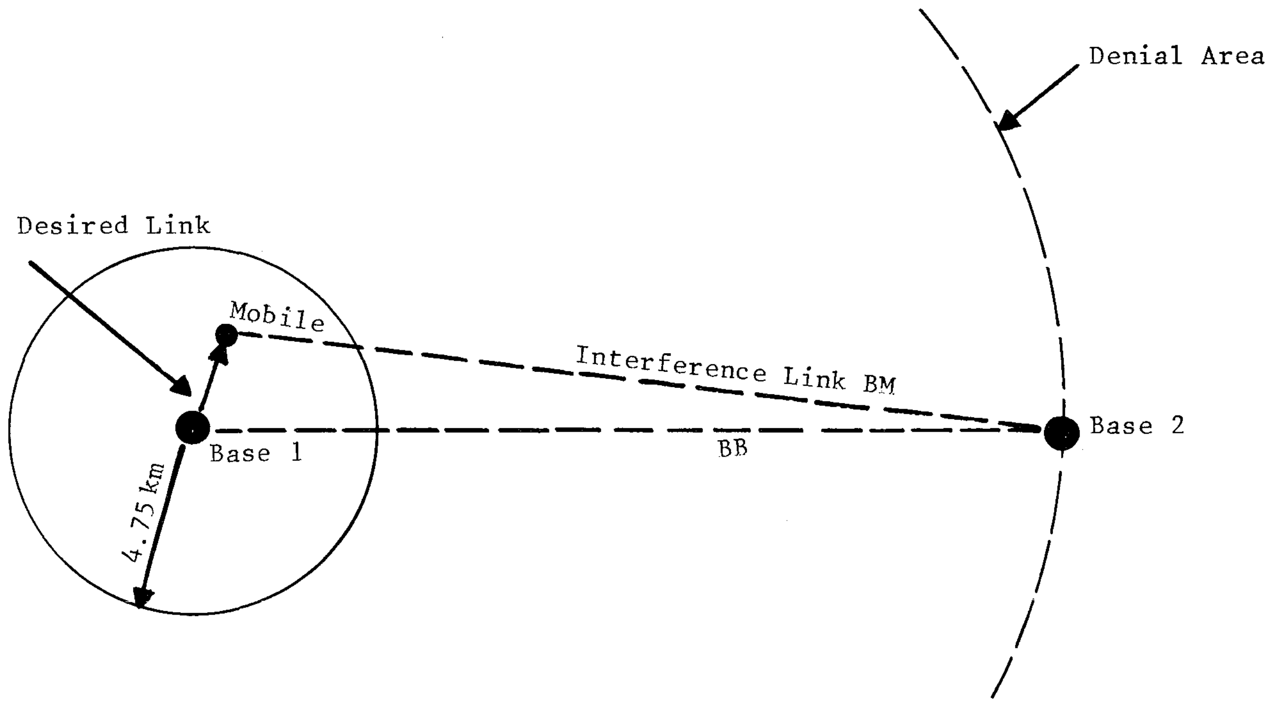


Figure B-6. Denial Area for Base 1 for the Case of Interference from Base B_2 to a Mobile Receiver. The Denial Area is $\pi(BB)^2$.

TABLE B-3 includes the results for this base-to-mobile interference condition.

TECHNICAL SPECTRUM EFFICIENCY FACTOR

The spectrum resource used, from equation (B-1) is

$$\text{Spectrum resource used} = (\text{bandwidth})\ (\text{space})\ (\text{time}) \qquad (B\text{-}7)$$

In all of the cases considered, the communication range was 4.75 Km. Consequently, for all cases, the systems accomplish the same mission. Therefore, from equation (B-7) the TSEF are

$$\text{TSEF} = \frac{\text{resource used (25 kHz FM)}}{\text{resource used (ACSB)}} \qquad (B\text{-}8)$$

and

$$\text{TSEF} = \frac{\text{resource used (25 kHz FM)}}{\text{resource used (NBFM)}}$$

TABLE B-4

SPATIAL DENIAL AREA (km^2)

Modulation / Interference Condition	ACSB	NBFM	FM
Base-to-Base	7029	5027	5027
Base-to-Mobile	907	706.5	706.5

The TABLE B-4 lists the Spatial Denial Area for each of the modulations (FM, NBFM and ACSB). The approximation is made that NBFM and FM have the same spatial denial areas. This assumes that NBFM and FM have similar performance characteristics (i.e., S/N ratios and cochannel S/I ratios). The bandwidths were determined as a function of the adjacent signal protection ratios (See TABLE B-5).

The technical spectrum efficiency factors of the modulations as referenced to 25 kHz FM can be obtained by using Equation (B-8) and the data in TABLES B-4 and B-5. The resulting TSEF's are listed in TABLE B-6.

TABLE B-3

INPUT PARAMETERS AND PRODSIR GENERATED CRITERIA FOR THE CASE WHEN BASE-TO-MOBILE INTERFERENCE DETERMINES THE DENIAL RADIUS BB.

	NBFM 25 kHz FM	ACSB
Base Transmitter Power	25 watts	15.8 watts
Base Antenna Gain	3 dBi	3 dBi
Mobile Transmitter Power	25 watts	15.8 watts
Mobile Antenna Gain	0 dBi	0 dBi
Base-Mobile Propagation	A = 93	A = 93
S/I Protection Ratio,	14 dB	17.1 dB
Communication Range, R	4.75 km	4.75 km
Interference Denial Range, BB	15 km	17 km
Mean Signal	-94.5 dBW	-96.5 dBW
Mean Interference	-123.0 dBW	-127.2 dBW
Mean S/I	28.5 dB	30.7 dB
Interference Denial Area $\pi(BB)^2$	706.5 km^2	907 km^2

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APPENDIX C

LOCATION OF ACSB LICENSES

TABLE C-1

LOCATION OF ACSB LICENSES BY STATES

Alabama	3	Nebraska	0
Alaska	0	Nevada	3
Arizona	0	New Hampshire	2
Arkansas	7	New Jersey	7
California	73	New Mexico	0
Colorado	5	New York	25
Connecticut	1	North Carolina	0
Delaware	0	North Dakota	0
D.C.	1	Ohio	2
Florida	14	Oklahoma	6
Georgia	9	Oregon	17
Hawaii	0	Pennsylvania	5
Idaho	1	Puerto Rico	1
Illinois	20	Rhode Island	0
Indiana	6	South Carolina	1
Iowa	2	South Dakota	0
Kansas	0	Tennessee	1
Kentucky	3	Texas	63
Louisiana	27	Utah	0
Maine	1	Vermont	0
Maryland	16	Virginia	8
Massachusetts	9	Washington	12
Michigan	12	West Virginia	2
Minnesota	3	Wisconsin	4
Mississippi	1	Wyoming	1
Missouri	1	CONUS	8
Montana	1		

TABLE C-2

LOCATION OF ACSB LICENSES
BY MAJOR METROPOLITAN AREAS

1.	New York/N.E New Jersey	1
2.	Los Angeles	7
3.	Chicago/N.W. Indiana	2
4.	Philadelphia/Camden	1
5.	Detroit	0
6.	San Francisco/Oakland	1
7.	Boston	1
8.	DC/Maryland/N. Virginia	11
9.	Pittsburgh	1
10.	Cleveland	0
11.	Miami	1
12.	Houston	10
13.	Dallas	0

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

This report examines the use of Amplitude Compandored Single Sideband (ACSB) and/or 12.5 kHz FM (NBFM) as possible solutions to the spectrum congestion in the Government Land Mobile Service in the VHF bands. These narrowband modulation techniques are investigated by looking into three different aspects of the problem: operation and use, spectrum efficiency and implementation. In each aspect, the different capabilities and deficiencies of the NBFM and ACSB are identified and compared with the conventional 25 kHz FM presently used in the VHF band. A discussion is made of the laboratory and field measurements on the ACSB and NBFM radios. These measurements were made by the Department of Defense Electromagnetic Compatibility Analysis Center, the Department of Agriculture, the FCC, and the Department of Commerce NTIA. A discussion is made of several implementation schemes and spectrum management strategies that the Government agencies might adopt in order to implement these narrowband modulation techniques.

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

Amplitude Compandored Single Sideband (ACSB); Land Mobile Radio
12.5 kHz FM (NBFM); 25 kHz FM

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