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**COMPARISON OF AM AND NARROW-BAND FM
UHF COMMUNICATION SYSTEMS
APPENDIX D
LABORATORY STUDIES AND INVESTIGATIONS**

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COMPARISON OF AM AND NARROW-BAND FM UHF COMMUNICATION SYSTEMS

APPENDIX D LABORATORY STUDIES AND INVESTIGATIONS

H. R. Johannessen and W. E. W. Howe

February 18, 1949

Approved by:

R. B. Meyer, Head Communication Branch
L. A. Gebhard, Superintendent, Radio Division II



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CAPTAIN F. R. FURTH, USN, DIRECTOR
WASHINGTON, D.C.

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ABSTRACT

By means of an investigation under laboratory conditions, engineering data have been obtained on the respective performance of amplitude-modulated and narrow-band frequency-modulated ultra-high-frequency communication systems, the latter system employing a frequency deviation of ± 7 kilocycles. Models TDZ transmitters and RDZ receivers were used in this undertaking, and operational conditions were simulated in the laboratory by special circuit arrangements. Greater range of communication is provided by the a-m system; however, at shorter ranges, the f-m system yields the greater receiver output signal-to-noise ratio. During co-channel operation, the performance of the a-m system is preferable. Under conditions ordinarily experienced on Naval craft, the f-m system is the more satisfactory during adjacent-channel operation. Neither system is affected by intense radar noise, at the point of reception. High level spark noise, however, impairs the performance of both systems, the f-m system being the more adversely affected. Neither system has an outstanding operational advantage over the other.

PROBLEM STATUS

This report concludes the work on the laboratory phase of the comparison of modulation systems. Separate reports on other phases of the investigation are being rendered.

AUTHORIZATION

NRL Problem No. R01-12R (BuShips No. S-1388)

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COMPARISON OF AM AND NARROW-BAND FM
UHF COMMUNICATION SYSTEMS
APPENDIX D
LABORATORY STUDIES AND INVESTIGATIONS

INTRODUCTION

This report treats the laboratory phase of an investigation to compare Amplitude-Modulated and Narrow-Band Frequency-Modulated Ultra-High-Frequency Radiotelephone Communication Systems, and is an appendix to a final summary report on the subject. Other aspects of the comparison are now covered or will be covered in a series of appendices published as separate reports.

Appendix A of the summary report¹ will discuss the background of the investigation, the choice of equipments used in this study, the selection of the deviation frequency used in the f-m communication equipments employed in the comparison, and other similar matters. Various theoretical considerations having bearing on the question will be made the subject of another report.² The characteristics of the a-m and f-m communication equipments employed in this work are covered in a separate report.³ Other reports^{4,5} describe the shipboard and airborne phases of the investigative work.

The project was carried out on a co-operative basis with representatives of various British Armed Services and the U. S. Navy participating.

¹E. Toth and J. D. Wallace, "Comparison of Amplitude-Modulated and Narrow Band Frequency-Modulated Ultra-High-Frequency Communication Systems," Final Summary Report, including Appendix A, NRL Report No. R-3230, to be published.

²R. M. Maiden, "Comparison of Amplitude-Modulated and Narrow Band Frequency-Modulated Ultra-High-Frequency Communication Systems," Appendix B, Theoretical Considerations, NRL Report No. R-3231, to be published.

³W. E. W. Howe and A. R. Rumble, "Comparison of Amplitude-Modulated and Narrow Band Frequency-Modulated Ultra-High-Frequency Communication Systems," Appendix C, Design and Performance Characteristics of Equipments Employed, NRL Report No. R-3232, 11 March 1948.

⁴D. McClenon, "Comparison of Amplitude-Modulated and Narrow Band Frequency-Modulated Ultra-High-Frequency Communication Systems," Appendix E, Shipboard Studies and Investigations, NRL Report No. R-3234, 8 March 1948.

⁵F. J. Hollweck, "Comparison of Amplitude-Modulated and Narrow Band Frequency-Modulated Ultra-High-Frequency Communication Systems," Appendix F, Airborne Studies and Investigations, NRL Report No. R-3235, 3 June 1948.

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Standard Navy Model TDZ Transmitters and Model RDZ Receivers were used as the terminal units of the a-m communication system. Similar equipments, which were modified to function on frequency-modulation, served as the terminal units of the f-m communication system. Hereafter in this report the communication systems formed by means of these transmitters and their respective receivers are referred to as the "a-m communication system" or as the "f-m communication system," as appropriate.

Attention is invited to the fact that comparison of the two systems was made with equipments which were identical with only two exceptions; namely, in regard to the transmitter modulating circuits and the receiver demodulating circuits. The a-m transmitter employed conventional final amplifier stage "plate-circuit" modulation. The f-m transmitter used a crystal-controlled master-oscillator, phase-modulated in accordance with the integrated waveform of the intelligence to be transmitted to provide a frequency-modulated output. The a-m receiver used a conventional diode detector, while the f-m receiver employed a ratio detector. Thus the two communication systems were similar and differed only in the respects necessary to allow functioning with the required forms of modulation. The similarity of the equipments thus eliminated many unknown factors which would otherwise have entered into the comparison. The transmitters were rated at 30 watts output and the nominal sensitivity of the receivers was 5 microvolts. The nominal audio band transmitted by both systems was from 350 to 3500 cycles. The frequency deviation of the f-m system was ± 7 kilocycles maximum.

GENERAL CONSIDERATIONS

In a comparison of these communication systems, two major operational conditions required examination.

1. Single-Signal Operation. Covered under this heading are the characteristics when only one signal is present in a communication system, the signal being in the nature of a carrier wave which is modulated with the intelligence to be transmitted. Range of communication is the most important aspect of single-signal operation. Range is established by transmitter power output, receiver sensitivity, the nature of the antenna systems employed, wave propagation characteristics, and other factors.

2. Multiple-Signal Operation. Included in this category is the performance of the system when more than one signal is present. Under this condition the reception of one of the signals is sought to the exclusion of the others, hence this signal is called the "desired" signal and the other signals would be classed as "undersired" ones. The desired signal in all instances would be a carrier wave which is modulated with the intelligence to be transmitted. The undesired signals may be either similar in character to the desired signal or in the nature of interference such as impulse noise or random noise. When multiple-signal operation is limited to the presence of only two signals, at least three different conditions of operation require investigation.

(a) Operation where one desired and one undesired signal are present, both signals being in the form of carrier waves at the same channel frequency, and both signals being similarly modulated with intelligence, but where the intelligence of each signal is different. Capture, heterodyne beat note interference, distortion and masking of the desired signal are among the effects encountered. This condition is hereafter referred to as "co-channel operation."

(b) Operation where one desired signal and one undesired signal are present and both are in the form of carrier waves at frequencies one or more channels removed from each other. Both signals in this case are similarly modulated with intelligence, but the nature

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of the intelligence carried by each of the signals differs. The effects of cross-modulation, depression of receiver signal output level and increase in receiver output noise level are usually present. This condition of operation is hereafter referred to as "adjacent-channel operation."

(c) Operation where one desired signal and one undesired signal are present, the desired signal being in the form of a carrier wave modulated with intelligence, and the undesired signal being in the form of an interfering noise. The interference may be of any type, such as that caused by sparking electrical contacts or by various electronic equipments such as radar. The principal effect encountered is impairment of receiver output signal-to-noise ratio.

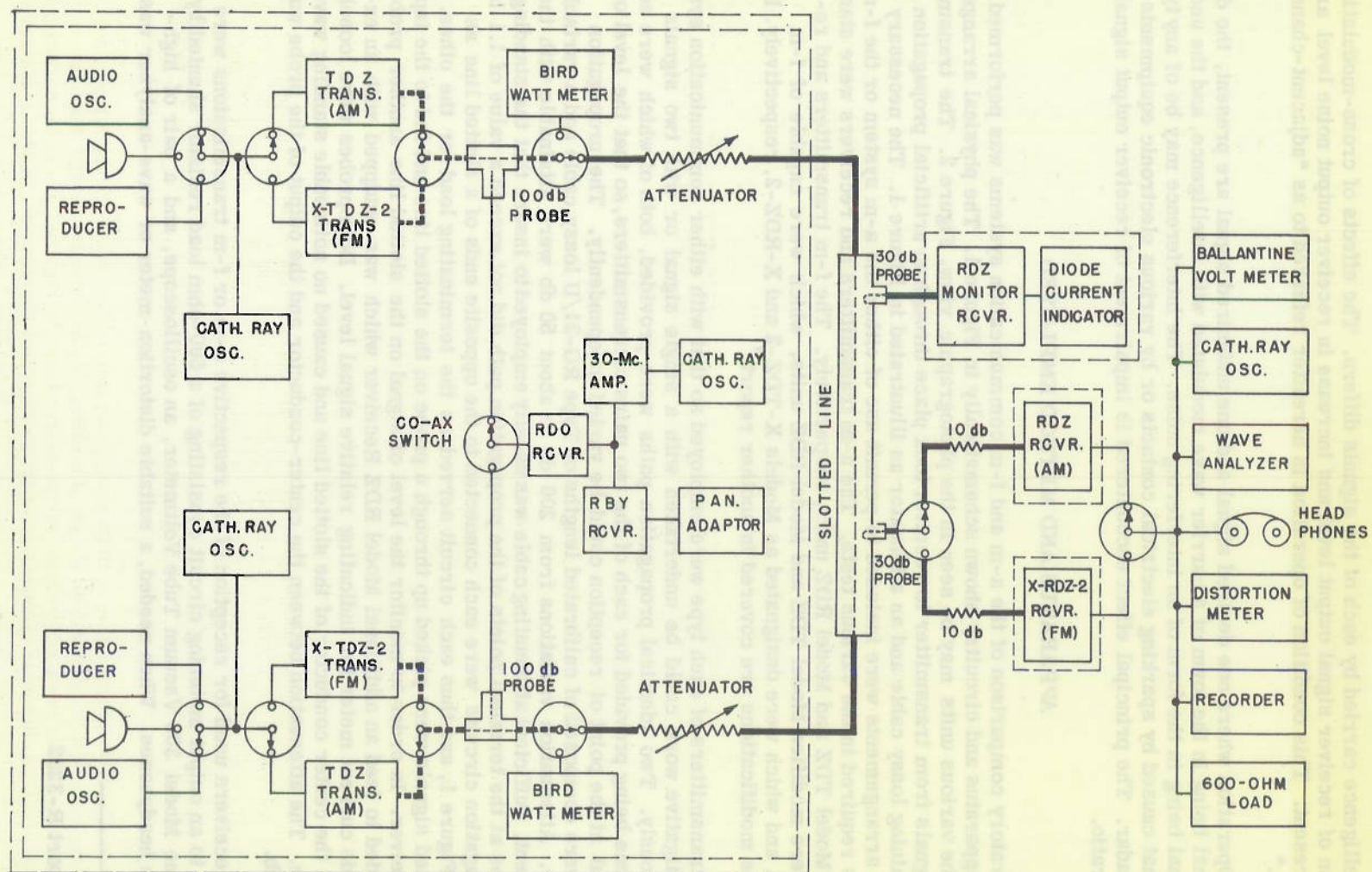
APPARATUS AND METHOD EMPLOYED

Laboratory comparison of the a-m and f-m communication systems was performed with the apparatus and circuitry shown schematically in Figure 1. The physical arrangement of the various units may be seen in the photographic view, Figure 2. The transmission of signals from transmitter to receiver took place through an artificial propagation path containing lossy cable and an attenuator as illustrated in Figure 1. The necessary switching arrangements were included to permit use of either the a-m system or the f-m system as required in the various tests. The a-m transmitters and receivers were standard Navy Model TDZ and Model RDZ units, respectively. The f-m transmitters and receivers were modified Model TDZ and Model RDZ units, which were capable of f-m operation, and which were designated as Models X-TDZ-2 and X-RDZ-2, respectively. Details of the modifications are covered in another report.⁶

Two transmitters of each type were employed so that with either communication system investigative work could be undertaken with a single signal or with two signals simultaneously. Two identical propagation paths were provided, both of which were adjustable, one being provided for each of the two pairs of transmitters, so that the level of each signal at the point of reception could be varied independently. The propagation circuits were composed of calibrated lengths of Type RG-21/U lossy cable and a variable attenuator. Attenuation variations from 200 db to about 50 db were attainable with the arrangement. Sufficient attenuating cable was usually employed to insure that the standing-wave ratios at the terminal points of the propagation path did not exceed a value of 1.1 to 1. The propagation circuits were each connected to the opposite ends of a slotted line as shown in Figure 1, and thus each circuit served as the terminating load for the other. Transmitted signals were picked up through a probe on the slotted line and fed to the input of the receiver. In order to monitor the level of signal on the slotted line another probe was provided to feed an additional Model RDZ Receiver which was equipped with an external diode current meter for indicating relative signal level. Both probes were loosely coupled to the center conductor of the slotted line and caused no noticeable standing waves on the line. The attenuation between the center-conductor and the output of the probe was about 30 db.

The receivers used for reception of the respective a-m or f-m transmissions were connected to an output metering circuit consisting of a 600-ohm load resistor shunted by a Ballantine Model 300 Vacuum Tube Voltmeter, an oscilloscope, and a pair of high-impedance headphones. When needed, a suitable distortion-meter or wave-analyzer was

⁶ NRL Report R-3232



NOTE: R-F CONNECTIONS SHOWN BY HEAVY LINES, AND WERE FORMED WITH RG-21/U ATTENUATING CABLE; CONNECTIONS SHOWN BY BROKEN HEAVY LINES EMPLOYED RG-8/U CABLE.

Fig. 1 - Block diagram of circuit used in a-m/f-m comparison

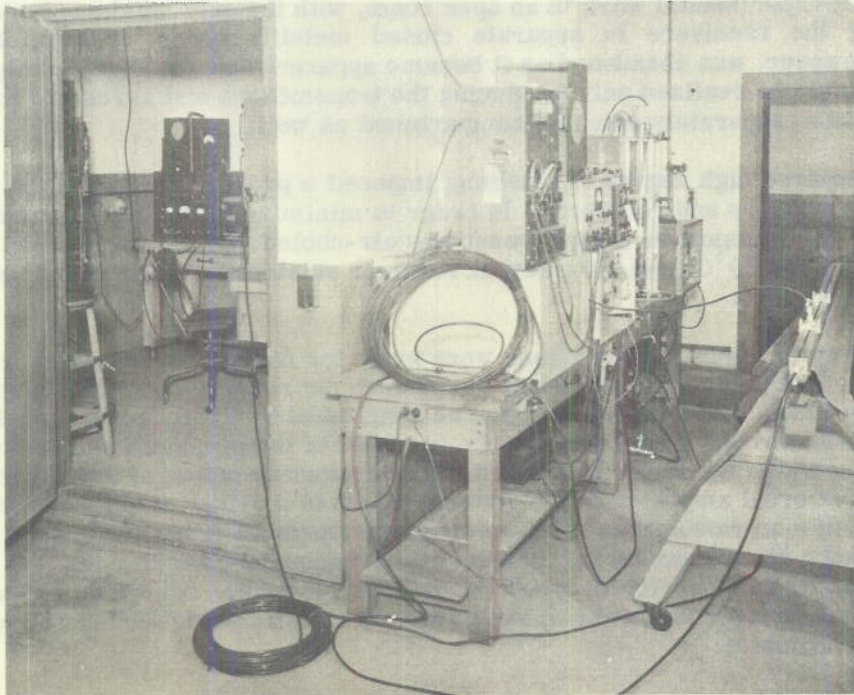


Fig. 2 - View of arrangement of apparatus used in a-m/f-m comparison

also placed across the load. All of these shunt devices were of high impedance and had negligible loading effect in comparison with that of the 600-ohm resistor.

In certain measurements involving adjacent-channel operation, the attenuation of the probe on slotted line was so great that the level of the undesired signal could not be raised to the required value. In these cases, it was necessary to substitute a Type UG-28/U "T" fitting for the slotted line and probe. The connection of the three 50-ohm lines at the "T" fitting naturally produced a mismatch. In most cases sufficient attenuating cable was used in each of the three lines to the fitting so that the mismatch caused no appreciable effect on the performance of the transmitters and receivers. In a few cases, however, where a strong adjacent-channel signal was required, the attenuation between the "T" fitting and the receiver was of necessity reduced to a low value and consequently for those few cases the accuracy of the attenuation reading was somewhat compromised.

Each of the receivers was mounted inside separate metallic boxes which served as additional shields. Audio and power leads were adequately filtered so that radio-frequency leakage was negligible. A high degree of shielding was imperative, especially at low receiver input levels, to insure that no signal entered the receiver through means other than the accurately calibrated propagation path. The efficacy of the shielding was determined by two methods. One means was to short-circuit the receiver antenna receptacle and observed the change in receiver diode current as measured on a microammeter when a nearby transmitter was energized. Additionally, with the receiver input terminal normally connected to the propagation circuit, a weak signal was applied while apparatus capable of radiating or reflecting radio-frequency energy was varied in position. When no noticeable variation due to radio-frequency leakage was observed during the course of

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these checks, the receivers were considered adequately shielded. An attempt was made to carry out experimental work in an open room, with the only shielding being provided by placing the receivers in separate closed metallic boxes as described. This attempt, however, was abandoned as it became apparent that the required high degree of shielding could be realized only by placing the transmitters and certain of the auxiliary apparatus in a separately shielded compartment as well.

The required high degree of shielding imposed a problem in ventilation and cooling for the transmitters and receivers. In order to minimize tube failures and tuned circuit variations, the transmitter compartment was air-cooled and was maintained at a temperature of about 20°C, and the external receiver shields were perforated and fitted with ventilating blowers.

As shown in Figure 1, provisions were made for modulating transmitters with continuous tone from an audio oscillator, live speech, or recorded program material from a reproducer. Modulation monitoring was accomplished by lightly coupling a Navy Type RDO Receiver through a capacitive probe to either of the propagation circuits near the transmitting end of the line. The intermediate-frequency output of this receiver was fed through an external amplifier to the vertical plates of a 5-inch oscilloscope for visual monitoring of a-m modulation. The receiver intermediate-frequency output was also impressed upon a Navy Type RBY-1 Receiver with Panoramic Adaptor for f-m deviation observations by the "carrier-dropout" method, as elsewhere described.⁷ Provisions were made for measuring transmitter output power with a Bird Model 750-2 "Termaline" radio-frequency Wattmeter.

By means of the apparatus and circuitry described it was possible to simulate in the laboratory most of operational effects and conditions, such as varying distance between transmitter and receiver or the effects of co-channel or adjacent-channel operation. Also the effect of noise could be studied by introducing the output of a noise generator instead of a transmitter into the propagation circuit. In fact almost any operational effect could be simulated by this arrangement except the influence of wave propagation variations.

All of the investigative work was performed at or near a channel frequency of 328.2 megacycles. This frequency was selected because previous investigations showed that the equipments used were free of extraneous responses at this channel frequency.⁸ The performance characteristics of the transmitters and receivers were thoroughly investigated and standardized prior to use.⁹ It was possible to select receivers in pairs, each pair consisting of one a-m and one f-m receiver of very similar characteristics. For comparative tests, standardized pairs of receivers were generally used. In the case of the transmitters, recourse was not made to this procedure as the significant characteristics, carrier power output and degree of modulation, could be measured and adjusted as required at any time during the course of the work.

Tone modulation was used where accurate measurements of such quantities as audio signal level and signal-to-noise ratio were desired. Speech modulation was used in determining the intelligibility of the systems during various simulated operational conditions.

⁷ NRL Report R-3232

⁸ A. W. Walters, "Interference Analysis of 100 Primary Communication Channels, 225-400 Megacycles," NRL Report No. R-2967, 6 December 1946.

⁹ NRL Report R-3232

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When using tone modulation, a level of 100 percent peak was employed for a-m transmission and a deviation of ± 7 kilocycles maximum was generally used during f-m transmission. Hereafter in this report these modulating conditions are referred to as "full-modulation" or "full-deviation," respectively. The 7-kilocycle value of deviation for f-m transmissions was chosen as proper for use in this investigation, to be indicated in another report.¹⁰ When speech modulation was transmitted, adjustments were maintained so that ordinary peaks of speech, disregarding occasional extreme peaks, would produce 100 percent modulation in a-m transmission or ± 7 kilocycles deviation in the f-m case. According to studies of transmitter speech modulation, the average modulation or deviation is approximately 30 percent of that occurring during voice peaks for acceptable distortion. Since this is only an approximate figure, a value of 31.6 percent has been adopted in this report, as it provides a convenient figure when expressed in decibels. Thus during speech modulation of a transmitter, the average modulation is considered to be 10 db below that of the modulation peaks. The ratio between the average receiver output speech level and the noise level is designated as the speech-to-noise ratio in this report. It follows from the above discussion that to obtain a given speech-to-noise ratio, 10 db should be subtracted from the steady tone modulated signal-to-noise ratio, where the steady tone has a peak level equal to the ordinary peaks of speech.

Signal-to-noise and signal-to-interference ratios provide convenient figures of merit for communication system comparison purposes. Whenever reference is made in this report to signal-to-interference ratio the interference may be any kind of extraneous component in the output of the receiver, such as cross-modulation. It should be understood that the actual meaning of these ratios as used in this report is not precisely that indicated by the terms employed in the designation of each. In most cases what is meant by the term signal-to-noise ratio is actually signal-plus-noise-to-noise ratio; and signal-to-interference ratio really refers to signal-plus-interference-plus-noise-to-interference-plus-noise ratio. Since the longer expressions are unwieldy the shorter ones have been used in this report, except where specifically indicated otherwise. While it would be possible under tone modulation conditions to measure the "true" signal-to-noise ratio by filtering out the noise when measuring the signal level, the extra complication is ordinarily not warranted. At the ratios usually encountered the difference between the "true" signal-to-noise ratio and the signal-plus-noise-to-noise ratio is small. The difference is 0.04 db at a signal-to-noise ratio of 20 db, 0.4 db at a 10-db ratio, and increases similarly for correspondingly smaller ratios. However, in a few instances the "true" signal-to-noise ratios were determined in those cases which were significant to the matter under consideration. Where this was done specific mention of the fact is made.

In this report receiver radio-frequency input levels are generally indicated as being a stated number of decibels below 30 watts, which is the rated power output of both the f-m and a-m transmitters. For convenience in translating these values into microvolts, a conversion graph, Figure 3, is included. The microvolt values obtained from the chart are only approximate since a 50-ohm value of receiver input resistance was assumed, and the actual receiver input impedance will differ somewhat from this value.

RANGE

INTRODUCTION

In comparing the a-m and f-m systems, information is needed as to whether there is a significant difference in the range of transmissions provided by these systems. Accordingly, comparative range data were obtained under laboratory conditions in the form of

¹⁰NRL Report R-3230

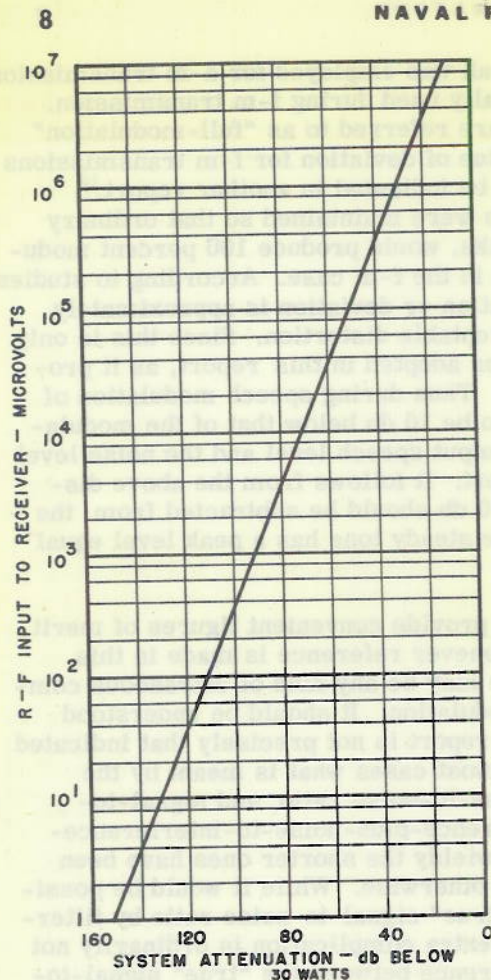


Fig. 3 - Receiver input conversion graph

conditions for the transmitter. Thus it was possible to measure the transmitter power when operating into the wattmeter and to use this value as an index of the power entering the propagation path after switching the transmitter output from the wattmeter to the propagating circuit.

During range comparisons it was seldom practical to adjust the a-m and f-m transmitters to exactly the same value of carrier output power, but the results were corrected to conform to the condition of equal unmodulated transmitter output. Initially, equality of carrier power was established to within about 2 watts after which the same values of power were maintained throughout a particular range run. An observation was made as to the ratio of the carrier levels of the two transmitters at the slotted line by means of the monitor receiver to insure that this ratio was consistent with that obtained from the output of each of the two transmitters. This step was taken to provide an additional check on the overall performance of the test circuit arrangement.

In the a-m transmitting equipment the carrier power level decreased with increasing degree of modulation. This made the application of another correction necessary in order

receiver output signal-to-noise ratios prevailing under conditions of equal received signal strengths. Such data were obtained over a wide range of receiver input signal levels. Additionally, studies were made as to the comparative intelligibility of the two systems as a function of received signal level. Range is the most important aspect of single-signal operation.

METHOD OF INVESTIGATION

Simulation of range variation was affected by adjusting the attenuation in the propagating path of the circuit arrangement illustrated in Figure 1. Attenuation was adjusted to vary the receiver signal input level in discrete steps ranging from 160 to 115 db below 30 watts, or from about 0.4 to 90 microvolts. Signal-to-noise ratios of the receiver output were measured on a Ballantine Model 300 Vacuum Tube Voltmeter. The decibel relationship of voltmeter readings with transmitter modulation and without transmitter modulation, but with the carrier still present in the latter instance, was recorded as the receiver output signal-to-noise ratio. For range studies only one pair of transmitters, that is one a-m and one f-m unit, and the associated propagation path were utilized. The output signals of the a-m and f-m transmitters were directed to their respective receivers alternately over a common propagating path, thus insuring equal transmission conditions for each.

A Bird Model 750-2 "Termaline" radio-frequency Wattmeter was employed to measure transmitter output power after first determining that the wattmeter and the propagating path produced equal loading

to compare the two systems on the basis of equal unmodulated carrier powers. Since the a-m transmitter output power was essentially unchanged from the unmodulated to the fully modulated condition, it is evident that the carrier power level under full tone-modulation conditions fell to two-thirds the unmodulated value. Therefore, when a signal-to-noise ratio value as a function of attenuation was observed during full tone modulation, an attenuation correction of 1.7 db was applied in favor of the a-m system. To apply a similar correction during voice modulation, the factor employed was 0.1 db. This was based on the assumption that voice modulation, where voice peaks produce 100 percent modulation, can be considered as the equivalent of a steady percentage of modulation 10 db below the level prevailing with full tone modulation.

Range comparisons were made at or near a channel frequency of 328.2 megacycles. Before this work was started, transmitter and receiver crystals were paired in frequency so as to produce a difference frequency closely approaching 15.100 megacycles, the intermediate-frequency of both the a-m and f-m receivers and the center-frequency of the f-m receiver discriminator. The corresponding transmitter and receiver crystals were selected so as to produce the above-mentioned difference frequency within the limits of ± 5 kilocycles in the case of the f-m system and within ± 20 kilocycles in the a-m system. It may be noted that the indicated tolerances for maximum allowable frequency difference were not the same for the two communication systems. Actually the f-m system requires that greater accuracy of frequency alignment be maintained between the transmitter and the receiver resonant frequencies than does the a-m system, if the signal-to-noise results observed on the f-m system are not to be compromised by operation at an intermediate frequency too far removed from the discriminator center-frequency. When the respective tolerances are held within the above mentioned limits errors in signal-to-noise data are minimized.

The range trials were conducted in the following manner. In the case of tone-modulated transmission, the transmitter was fully modulated or deviated with a 1000-cycle tone signal and the attenuation in the propagation path was reduced until the signal-to-noise ratio of the receiver output failed to increase materially. Under such conditions the receiver output in terms of signal-to-noise ratio would be approximately 35 db, and the receiver audio-gain control was then adjusted to obtain an output of 6 milliwatts. This value was used as the starting point for a range trial. Thereafter the attenuation was increased in steps and receiver output signal-to-noise data were observed at each value of attenuation. At each step of increasing attenuation, the receiver audio output level was readjusted to a value of 6 milliwatts by means of the audio-gain control, as necessary. It should be noted since this gain control follows the final detector that these adjustments involved no change in the signal and the noise levels present at the final detector. This procedure was continued until the signal-to-noise ratio became poor. From the results thus obtained it was possible to determine the output signal-to-noise ratios of both of the communication systems as a function of the attenuation in the propagation path between transmitters and receivers. Thus these procedures simulated the effect of varying the distance between transmitter and receiver in a conventional radio communication circuit, with the exception that the influences of wave propagation variations were excluded.

A similar procedure was followed in voice modulation studies. Adjustments were maintained so that voice peaks produced full transmitter modulation or deviation. The transmitters were modulated with speech transcriptions consisting of word lists and the output of the receivers were recorded on Brush Model BK-401 Recorder-Reproducers for analysis. Harvard Psycho-Acoustic Laboratory word lists were employed, these lists consisting of monosyllabic words. Usually fifty words were transmitted in a particular test, different word lists being used in each individual test. The recorded output of each receiver was later reproduced before a group of auditors who copied as many of the words as were understandable. From this information the intelligibility rating of either system under the particular test conditions was established.

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For voice modulation of the transmitters, similar Brush Recorder-Reproducers were used to provide transcribed voice program material. It is realized that the use of these units introduced a certain quantity of hum and distortion, however these effects would exercise a similar influence on either communication system and therefore would not appreciably detract from the validity of the comparison of the two systems. The voice recordings used to modulate the transmitters were made using a selected voice, which preliminary listening tests had shown to be highly intelligible. A high-fidelity microphone and the full audio-frequency range of the Brush Recorder-Reproducer were utilized in making the transcriptions. The audio band included in the transcribed material was therefore considerably greater than that provided by either communication system, which is nominally from 350 to 3500 cycles.

A reference tone at a frequency of 1000 cycles was also placed on the recordings at discrete intervals, the purpose being to facilitate the adjustment of transmitter modulation level in a manner to provide full modulation or deviation on voice peaks. Tone-signal peak levels were so chosen as to be the approximate equal of speech peak levels. A Weston Model 862 Volume Unit Indicator was used in the equalization of tone and voice peaks, the tone level being adjusted to a value 10 db above that indicated by the meter when used to read the level of speech. Tests showed that over a ten-second interval five or six peaks of speech occurred which were slightly above the peak level of the reference tone, as measured by a peak-clipping amplifier. This means of equalizing tone-signal peaks and speech peaks was as satisfactory as could be readily established.

The various methods and corrective procedures were used also in other phases of the comparative study of the two communication systems. Minor departures took place in some instances, and whenever this was done mention of the fact is made. On some occasions variations were purposely made from the normal practices to ascertain the effect of certain influences, and in such cases the pertinent details are provided.

For range trials the following conditions of transmitter and receiver controls and adjustments were employed:

Transmitter AGC - "OFF."

Receiver AVC - "ON," for a-m receiver; "OFF" for f-m receiver.

Receiver R-F Gain - "MAXIMUM" at all times.

Receiver I-F - "NARROW."

Receiver A-F - "NARROW."

Receiver Noise Limiter, Silencer and Output Meter Multi-switch - "OFF."

While the above indicated Receiver AVC conditions were employed during the range trials, it was subsequently noted that for both the a-m and f-m systems, signal-to-noise ratios were not appreciably changed whether AVC was "ON" or "OFF." To insure maximum performance from the f-m receiver, the discriminator was adjusted for optimum alignment and symmetry before each range trial.

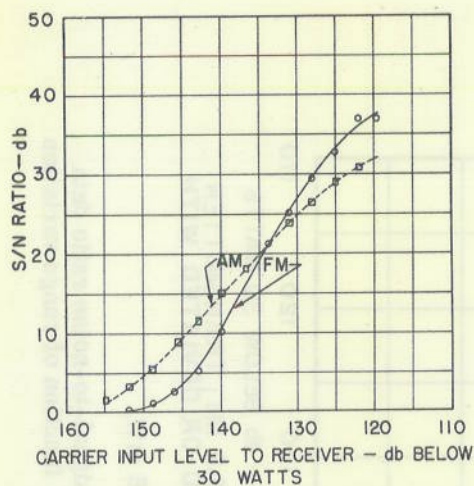
RESULTS

Tone-Modulation Studies

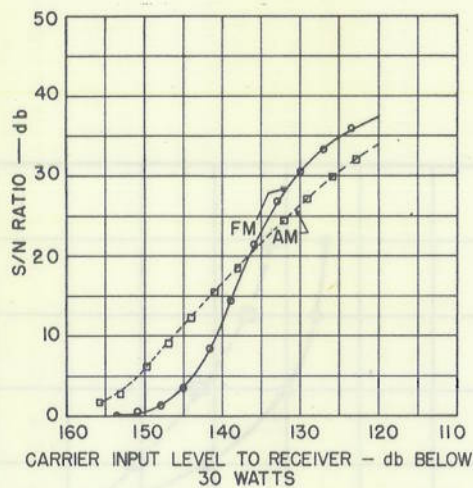
Comparative data for communication range of the two systems are shown in Figure 4, all of the curves being obtained with 1000-cycle tone modulation. The several graphs in Figure 4 present data obtained during successive repetitions of the same test at various

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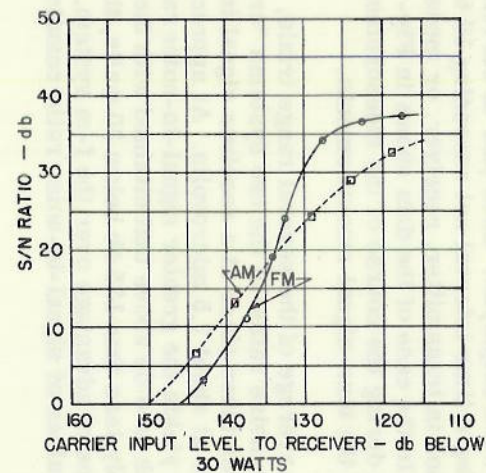
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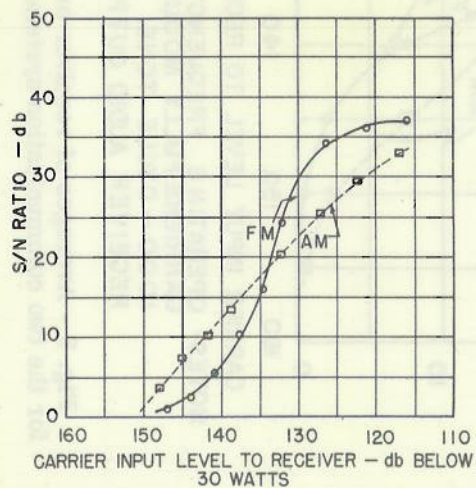
A - Range characteristics



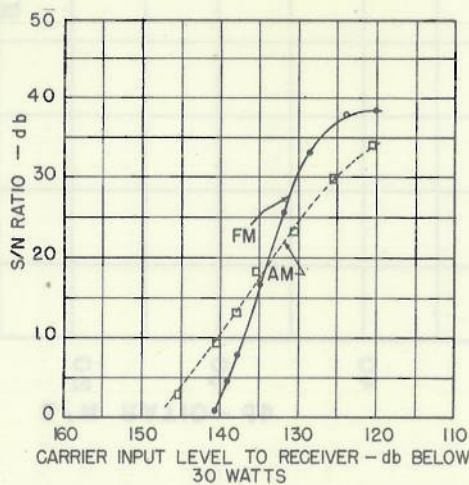
B - Range characteristics



C - Range characteristics



D - Range characteristics



E - Range characteristics

Fig. 4 - Receiver output signal-to-noise ratio data for the two communication systems as a function of range variation

Notes: Operating frequency:
328.2 Mc; transmitter carriers
fully modulated or deviated with
1000-cycle tone; receiver audio
output: 6 mW

times. In some cases different pairs of receivers were employed. Each pair of curves except those included in Figure 4E were taken during a time interval not exceeding 10 to 15 minutes and thus inconsistencies due to variations in transmitter, receiver, or measuring equipment characteristics were minimized. In the case of the data shown in Figure 4E a period of approximately one hour elapsed during the course of the measurements, as an intelligibility test was carried out along with the tone-signal measurements.

Figure 4, as well as Figure 5 which shows the average of the several range trials, indicate that the observed receiver output signal-to-noise ratios of the two systems "cross-over" at a value of approximately 20 db. Cross-over takes place at a receiver signal input level of approximately 135 db below 30 watts, or at about 7.5 microvolts. At appreciably higher receiver input levels the f-m system yields the greater signal-to-noise ratio, which in some instances may reach a value as much as 8 db above that attained with the a-m system. At receiver input levels of appreciably less than 135 db below 30 watts, the a-m system displays approximately the same degree of advantage over the f-m system. The decrease in slope of the curves at the higher values of signal-to-noise ratio results in part from the influence of receiver hum.

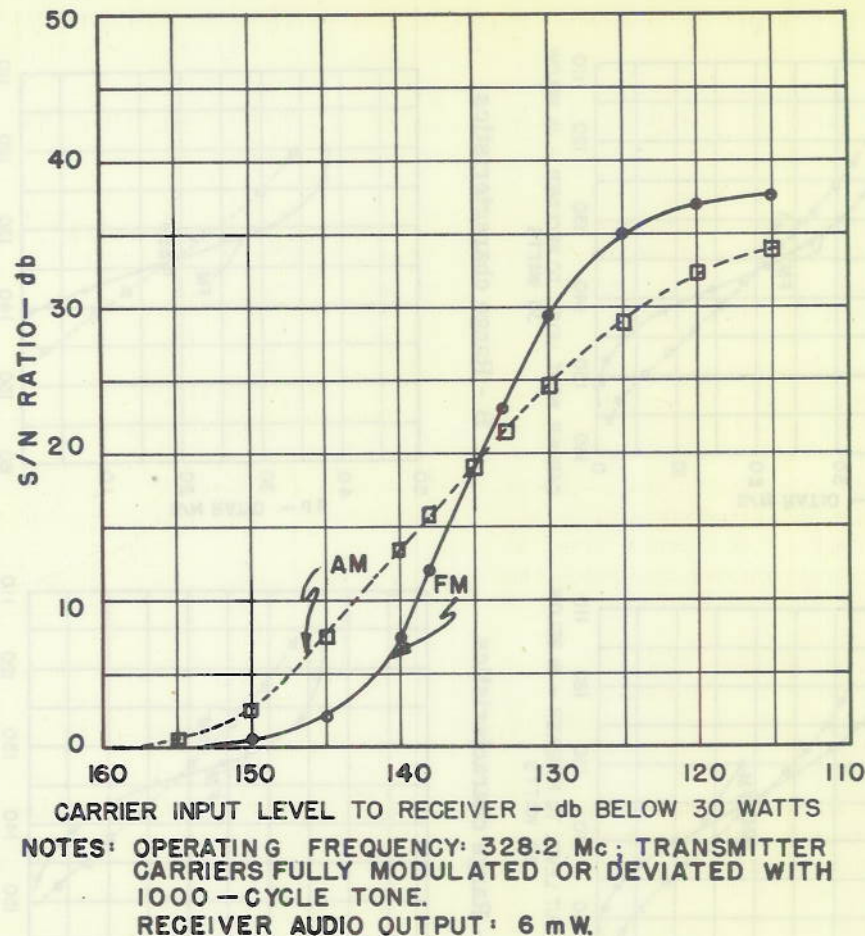
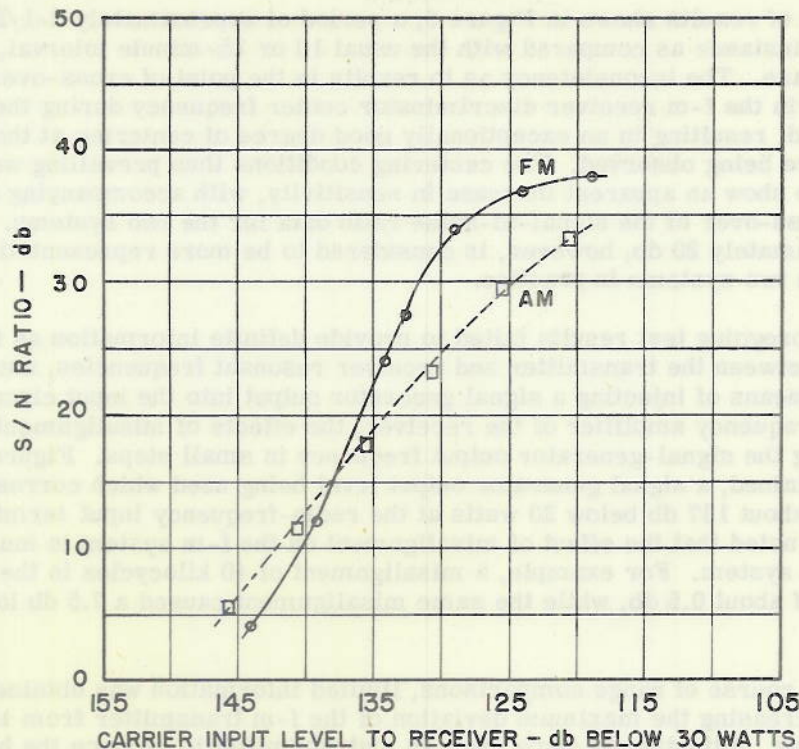


Fig. 5 - Averages of receiver output signal-to-noise ratio data for the two communication systems as a function of range variation



NOTES: TRANSMITTER FREQUENCY INCREASED
14 kc; CHANNEL FREQUENCY 328.2 Mc;
TRANSMITTER CARRIERS FULLY MODULATED OR
DEVIATED WITH 1000-CYCLE TONE.
RECEIVER AUDIO OUTPUT: 6 mW.

Fig. 6 - Receiver output signal-to-noise ratio data for the two communication systems with a 14-kilocycle increase in transmitter frequency

Data were also taken under conditions where the carrier frequencies of both transmitters were purposely increased by 14 kilocycles while the receiver resonant frequencies remained unchanged, in order to ascertain the effect of a small frequency misalignment upon the respective range characteristics of two communication systems. The term "receiver resonant frequency" as used in this report refers to the frequency to which the receiver is tuned; that is, the center frequency of the receiver radio-frequency pass band of the various circuits preceding the final detector. The results are shown in Figure 6. It is noted that cross-over occurs at a receiver output signal-to-noise ratio of approximately 16 db. It would ordinarily be anticipated that such a misalignment between the transmitter output and the receiver resonant frequencies would cause an increase rather than a decrease in signal-to-noise ratio value for the point of cross-over, as compared with that obtained with closer frequency alignment, and which has already been found to occur at approximately 20 db. In an effort to explain this inconsistency, the results in Figure 6 were compared with those in Figure 5 on the basis that the a-m curves which should be little affected by misalignment remain the same for both cases. It is noted that the f-m results differed somewhat in the two cases. Further consideration indicated that an assumed increase in the f-m receiver sensitivity could account for the inconsistency. Apart from the purposeful increase in transmitted frequency, the principal difference in experimental procedure used in the two cases lay in the elapsed time between the initial centering of the f-m receiver discriminator and the completion of the test. As intelligibility data were also obtained along with

the observation of results shown in Figure 6, a period of approximately 2-1/2 hours had elapsed in this instance as compared with the usual 10 or 15-minute interval, or 1-hour period in one case. The inconsistency as to results in the point of cross-over is believed due to drifting in the f-m receiver discriminator center frequency during the fairly lengthy operating period, resulting in an exceptionally good degree of centering at the time the data in Figure 6 were being observed. The centering conditions thus prevailing would cause the f-m receiver to show an apparent increase in sensitivity, with accompanying depression in the point of cross-over of the signal-to-noise ratio data for the two systems. A cross-over point of approximately 20 db, however, is considered to be more representative of the performance of the two systems in practice.

Since the foregoing test results failed to provide definite information as the effect of misalignment between the transmitter and receiver resonant frequencies, another procedure was used. By means of injecting a signal generator output into the input circuit of the intermediate-frequency amplifier of the receiver, the effects of misalignment may be simulated by varying the signal-generator output frequency in small steps. Figure 7 shows the results thus obtained, a signal generator output level being used which corresponded to a signal level of about 137 db below 30 watts at the radio-frequency input terminal of the receiver. It is noted that the effect of misalignment on the f-m system is much greater than in the a-m system. For example, a misalignment of 40 kilocycles in the a-m system caused a loss of about 0.5 db, while the same misalignment caused a 7.5 db loss in the f-m system.

During the course of range comparisons, limited information was obtained regarding the effect of increasing the maximum deviation of the f-m transmitter from ± 7 kilocycles to ± 15 kilocycles. Adjustments were made in the transmitter to produce the higher value of deviation. Range curves similar to those illustrated in Figures 4 and 5 were made and

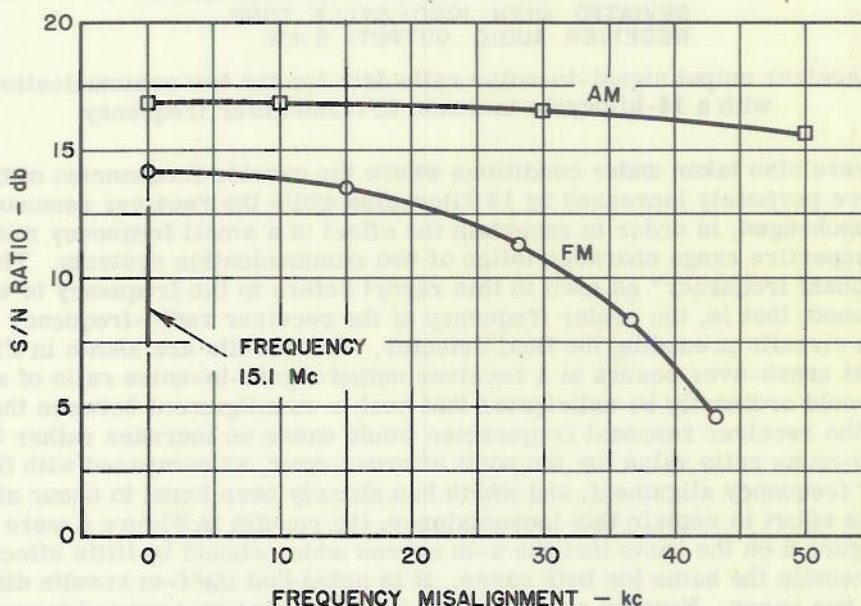
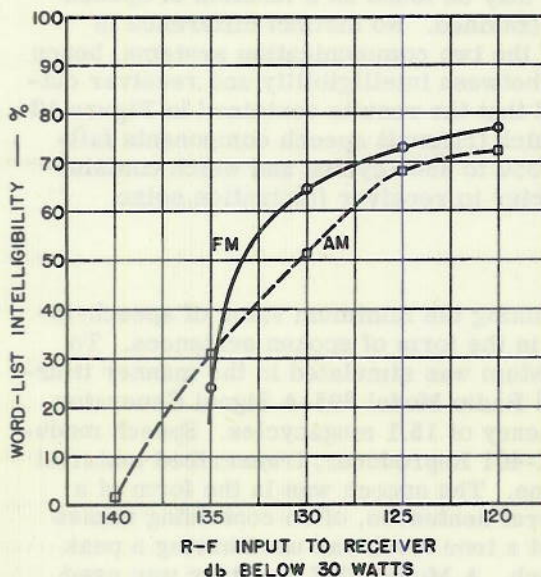


Fig. 7 - Effect of misalignments between transmitter output and receiver resonant frequencies upon receiver output signal-to-noise ratio

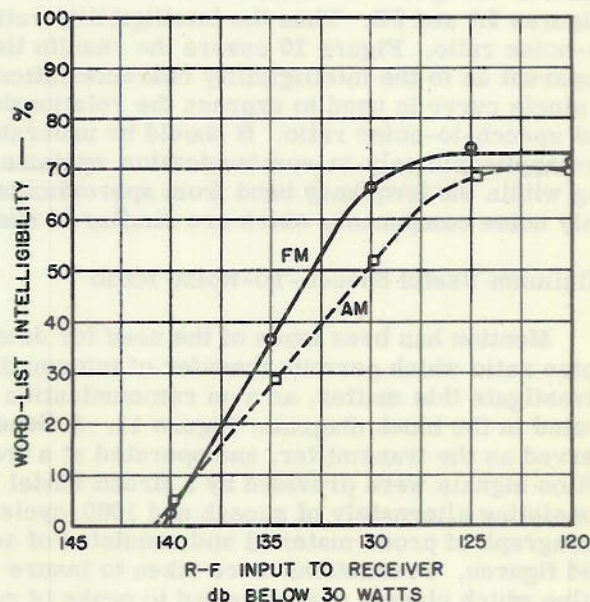
are shown in Figure 8. It is noted that cross-over occurred at a signal-to-noise ratio of approximately 14 db rather than at 20 db, the value noted at 7 kilocycles deviation. A decrease in the value of cross-over by approximately such a factor would normally be anticipated. Efforts to obtain similar data at deviations appreciably greater than 15 kilocycles were not successful, as it was found that the transmitter would not satisfactorily function at these values of deviation frequency. Only in the single instance covered in this paragraph was use made of a deviation frequency other than 7 kilocycles during the course of this work.

Voice-Modulation Studies

The comparative word-list intelligibility of the two communication systems as a function of attenuation in the propagation path is shown in Figure 9. The curves indicate the average of results obtained by a group of 17 auditors. Data are included for two similar analyses. Data presented in Figures 4E and 6 show tone-modulated signal-to-noise ratios prevailing during the conditions under which the intelligibility results given in Figures 9A and 9B, respectively, were obtained.



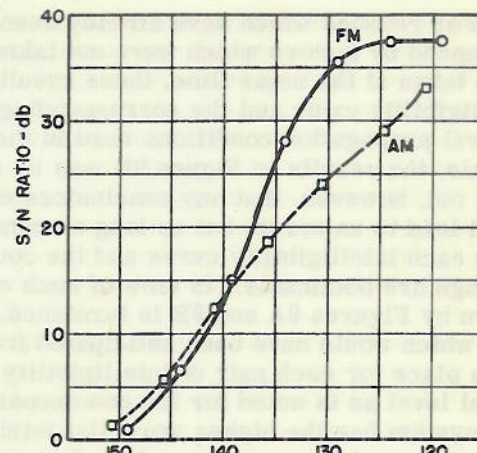
A



B

Notes: Operating frequency: 328.2 Mc; voice modulation used; transmitter carriers fully modulated or deviated by voice peaks

Fig. 9 - Intelligibility data for the two communication systems as a function of range variation



CARRIER INPUT LEVEL TO RECEIVER - db BELOW 30 WATTS

NOTES:

OPERATING FREQUENCY: 328.2 Mc.

DEVIATION OF F-M TRANSMITTER INCREASED TO 15kc.

TRANSMITTER CARRIERS FULLY MODULATED OR FULLY DEVIATED AT 15kc WITH 1000-CYCLE TONE.

RECEIVER AUDIO OUTPUT: 6mW.

Fig. 8 - Effect of increasing deviation of f-m transmitter on relative range characteristics

For reasons which have already been covered, the data in Figure 6 were most likely influenced by factors which were not taken into account, and since the data in Figure 9B were taken at the same time, these results also were similarly affected. However, as an intelligibility value and the corresponding signal-to-noise ratio value for any one of the several propagation conditions used in the test were taken over comparatively short intervals, the results in Figure 9B may be utilized for certain purposes. It is desired to point out, however, that any conclusions drawn by direct comparison of Figures 9A and 9B could lead to an error, but as long as consideration is restricted to deductions possible from each intelligibility curve and the counterpart tone signal-to-noise ratio curve, valid findings are obtainable. In view of such circumstances, a discussion of the results actually shown by Figures 9A and 9B is furnished. It is noted that each curve is of the general nature which would have been anticipated from its counterpart tone-signal curve. Cross-over takes place for each pair of intelligibility curves at essentially the same receiver input signal level as is noted for the counterpart pair of tone-signal curves. Above cross-over the f-m system has the higher word-list intelligibility; below cross-over the intelligibility of both systems becomes poor. Actual transfer of information in the form of spoken sentences, however, can take place at signal-to-noise ratios considerably below that required to permit a listener to identify an appreciable number of words in a word list. This matter was made the subject of a separate investigation and will be treated subsequently.

Referring again to Figures 4E, 6, 9A, and 9B, it is possible from the data in each intelligibility curve and from those in the counterpart signal-to-noise ratio curves to determine both the intelligibility of received speech as a function of receiver output speech-to-noise ratio and also whether any intelligibility difference exists between the two communication systems at similar values of speech-to-noise ratio. First, however, signal-to-noise ratios must be converted into speech-to-noise ratios, and this may be accomplished by deducting 10 db from the former ratio to obtain the latter one. In this manner the speech-to-noise ratio can be found at any point along the curves shown in Figures 9A and 9B. Thus the intelligibility rating may be found as a function of speech-to-noise ratio. Figure 10 covers the results thus obtained. No distinct difference is apparent as to the intelligibility characteristics of the two communication systems, hence a single curve is used to express the relationship between intelligibility and receiver output speech-to-noise ratio. It should be understood that the results contained in Figure 10 are applicable only to communication systems which transmit speech components falling within the frequency band from approximately 350 to 3500 cycles and which contain only noise components which are similar in character to receiver fluctuation noise.

Minimum Useful Speech-To-Noise Ratio

Mention has been made of the need for determining the minimum value of speech-to-noise ratio which permits transfer of information in the form of spoken sentences. To investigate this matter, an a-m communication system was simulated in the manner illustrated in the block diagram, Figure 11. A General Radio Model 805-A Signal Generator served as the transmitter, and operated at a frequency of 15.1 megacycles. Speech modulation signals were provided by a Brush Model BK-401 Reproducer, transcribed material consisting alternately of speech and 1000-cycle tone. The speech was in the form of a paragraph of prose material and consisted of several sentences, often containing names and figures. Precautions were taken to insure that a tone level was used having a peak value which closely corresponded to peaks of speech. A Model RDZ receiver was used for reception purposes, the signal generator being fed into the intermediate-frequency circuit of the receiver at grid resistor R-115 of the type 6F4 mixer tube, V-106. The output of the receiver was fed into a Ballantine Model 300 Vacuum Tube Voltmeter, a General Radio Type 736-A Wave Analyzer and a Navy Type 49587 Loud-speaker. The two measuring instruments were used in determining signal-to-noise ratios and the loud-speaker was used to project the speech signals to listeners. This arrangement permitted

Fig. 10 - Intelligibility of received signals as a function of receiver output speech-to-noise ratio

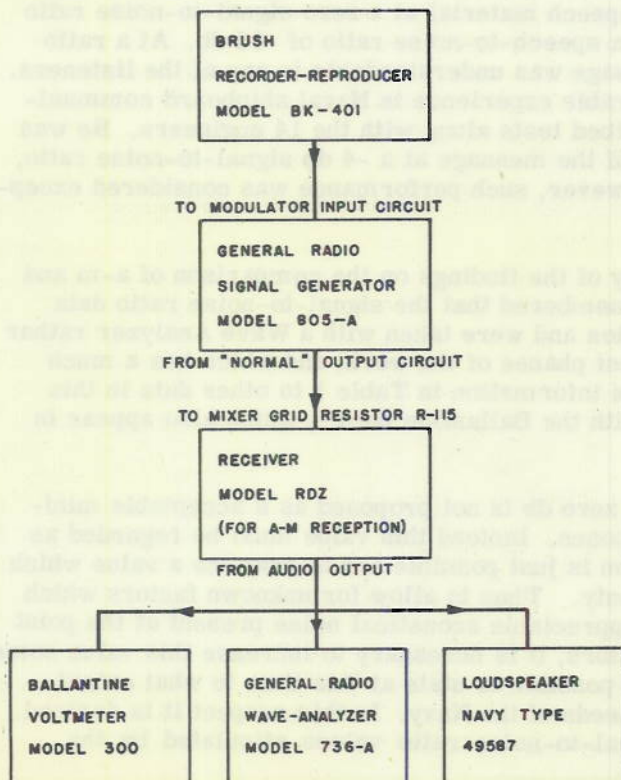
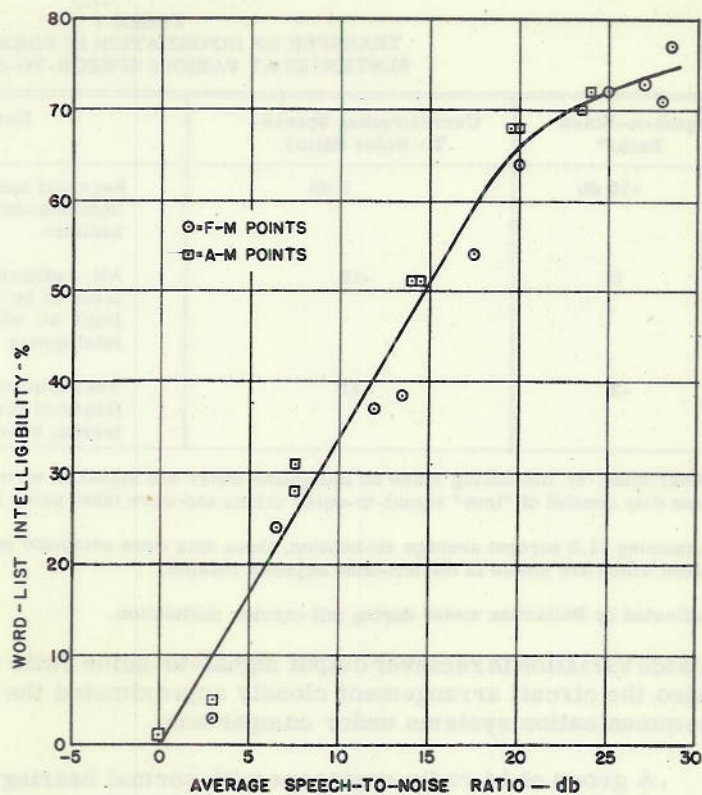


Fig. 11 - Simulated a-m communication system

TABLE 1
TRANSFER OF INFORMATION IN FORM OF SPOKEN
SENTENCES AT VARIOUS SPEECH-TO-NOISE RATIOS

Signal-to-Noise Ratio*	Corresponding Speech-To-Noise Ratio†	Results	Signal-Plus-Noise-To-Noise Ratio‡
+10 db	0 db	Received speech completely understandable to all 14 auditors	+11 db
0	-10	All auditors consider this level to be about the lower limit at which transfer of intelligence can take place	+5
-2	-12	The auditors do not consider this level as capable of transferring information	+4

*Determined by measuring noise on Ballantine meter and signal on wave analyzer during full carrier modulation; these data consist of "true" signal-to-noise values and were taken using 1000-cycle tone modulation.

†Assuming 31.6 percent average modulation, these data were computed by deducting 10 db from the signal-to-noise values which are shown in the left-hand adjacent column.

‡Indicated by Ballantine meter during full carrier modulation.

a wide variation in receiver output signal-to-noise ratio which could be adjusted as required. Also the circuit arrangement closely approximated the audio characteristics of the two communication systems under comparison.

A group of 14 radio engineers with normal hearing served as auditors on a series of tests conducted with the simulated communication system. Table 1 lists the results obtained. All observers were able to understand the speech material at a zero signal-to-noise ratio as determined by the Wave Analyzer, or at a speech-to-noise ratio of -10 db. At a ratio 2 db lower however, very little of the message was understandable to any of the listeners. A former Navy radio operator with considerable experience in Naval shipboard communications also participated in the above described tests along with the 14 engineers. He was able to receive a good portion of the sense of the message at a -4 db signal-to-noise ratio, or at a speech-to-noise ratio of -14 db. However, such performance was considered exceptional.

In the application of these results to any of the findings on the comparison of a-m and f-m communication systems, it must be remembered that the signal-to-noise ratio data cited above were "true" signal-to-noise ratios and were taken with a Wave Analyzer rather than by the Ballantine Voltmeter used in most phases of the work, and which has a much broader frequency response. In applying the information in Table 1 to other data in this report, signal-to-noise readings obtained with the Ballantine meter, which also appear in Table 1 should therefore be used.

A "true" signal-to-noise ratio value of zero db is not proposed as a acceptable minimum standard for Navy communication purposes. Instead this value must be regarded as an absolute low limit at which communication is just possible and in practice a value which could be tolerated as a transient condition only. Thus to allow for unknown factors which may have influenced the tests, the effect of appreciable acoustical noise present at the point of reception and fatigue on the part of operators, it is necessary to increase this value somewhat to provide a factor of safety. It is not possible to state at this time to what extent this value should be increased to meet the needs of the Navy. In this respect it is desired to state that the minimum acceptable signal-to-noise ratio values stipulated by the

Admiralty Signals Establishment and the Royal Aircraft Establishment for reliable communication correspond to fully modulated tone signal-to-noise ratios of +20 and +16 db, respectively.

SUMMARY

During single-signal operation, whenever the receiver input signal level is of the value which provides a receiver output signal-to-noise ratio of approximately 20 db, the performance of the a-m and f-m systems are the same, both with respect to receiver output signal-to-noise ratio and the intelligibility of reception. At appreciably higher values of receiver input signal level, the f-m system yields the more favorable signal-to-noise ratio and intelligibility. At appreciably lower values of receiver input signal level the a-m system excels in the same respects. It follows from these statements that greater range would be obtainable from the a-m system, the various factors which influence range being made equal.

At the same values of receiver output signal-to-noise ratio, the two systems have equal word-list intelligibilities.

It is possible to transfer information in the form of spoken sentences at a "true" signal-to-noise ratio as low as zero db, which corresponds to a speech-to-noise ratio of -10 db; however, such a figure is not proposed as an acceptable minimum standard for Navy communication purposes.

In the f-m system a considerably higher degree of frequency alignment between transmitter and receiver must be maintained than is necessary in the a-m system in order to prevent undue impairment of receiver output signal-to-noise ratio.

CO-CHANNEL OPERATION

INTRODUCTION

The performance of a communication system during co-channel operation is largely governed by the effect of the unwanted signal upon the receiver. During co-channel operation four principal effects may be experienced when two signals on the same channel frequency are received simultaneously; these are capture, heterodyne beat-note interference, distortion, and masking. These effects are applicable to the reception of both amplitude-modulated and frequency-modulated signals. All four effects detract from the net intelligibility of a received signal.

Capture is the term applied to the reduction in level of, or in some instances the elimination of, a desired signal output due to the presence of another signal of comparable or greater intensity on the same channel. Heterodyne beat-note interference refers to the new frequencies which appear in the receiver output as a result of the presence of two signals having a frequency difference falling within the audio band passed by the receiver and audible to the listener. Distortion refers to changes in wave-form of the intelligence on the desired signal due to the presence of the other. Masking is the term used to refer to the distracting effect caused by the mere presence of the intelligence on the undesired signal and the influence is largely independent of distortion and heterodyne interference effects. Thus, even if the other effects did not exist, the masking of one signal by another would affect intelligibility. Although certain of the four effects could be considered separately, it is usually necessary to take into account the combined influence of all of them if the result upon the intelligibility of a received signal is to be determined. Of principal interest is the net result of the several effects upon reception, as follows:

- (1) The influence of an undesired signal upon the intelligibility of the desired signal, and
- (2) The influence upon the ability to detect the presence of a signal when another much stronger signal is also present.

The latter consideration is of operational significance, for the mere knowledge of an attempt on the part of a remote craft to enter a communication net is desirable. In such an event even though the signal is too weak to be understandable in the presence of a stronger signal, the knowledge of the existence of the weaker signal would make it possible for those in control of communications to silence the stronger signal for a time sufficient to ascertain if the weaker signal was of importance.

METHOD OF INVESTIGATION

Co-channel operational investigations were performed making use of a desired signal and one undesired signal, both of which were on a channel frequency of 328.2 megacycles. This was also the receiver resonant frequency. Only one undesired signal was employed in order to prevent undue complications of the study. The arrangement shown in Figure 1 was employed in these tests and use was made of both propagation paths rather than only one of them, as was the case in the range trials. Both of the transmitters, that is, either the two a-m equipments or the two f-m units, depending on which form of modulation was being studied, were in simultaneous operation. One transmitter provided the desired signal, the other the undesired. Adjustments of the transmitter and receiver controls were identical to those used in the range trials except that both the a-m and f-m receivers were operated with AVC "ON." Since the a-m system distortion was less with AVC "ON" although capture was increased, and the f-m system performance was improved when using AVC "ON," all data were taken in this condition. The attenuation in each branch of the system was taken into account together with the necessary corrections in transmitter power output data, as already treated in the discussion of range studies, to ascertain the input level at the receiver for each of the two signals. The attenuation of each signal, desired or undesired, was adjusted as required to provide the signal conditions necessary for the various tests.

Voice intelligibility of the a-m and f-m communication systems was determined in the following manner. The transmitter which provided the desired signal was modulated by voice transcriptions consisting of standard word lists. The transmitter producing the undesired signal was modulated by voice transcriptions of continuous prose. The level of transmitter modulation was adjusted so that voice peaks in the transcribed program material would produce full modulation or deviation. The same voice, which previous studies had shown to be highly intelligible, was used in making both transcriptions. For the purpose of this analysis the transmitter crystals were chosen so as to produce heterodyne beat-note frequencies not too different in both the a-m and f-m systems.

Equality was attained to within 500 cycles in a particular comparative test, and the prevailing heterodyne beat-note frequencies usually fell between 2300 and 3700 cycles. The beat-note frequency was purposely placed in the audio frequency range since it was evident that with the present crystal tolerances, audio-frequency products of this nature would often be experienced in co-channel operation. When making intelligibility comparisons, the desired signal input levels to the receivers in both the a-m and f-m systems were adjusted to provide a receiver output signal-to-noise ratio of 27 db, or a 17-db speech-to-noise ratio, in the absence of the undesired signal. This procedure required slightly different receiver input signal levels for the two communication systems, but the desired signal level was in

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all cases between the limits of 132 and 126 db below 30 watts, or in the region between 10 and 20 microvolts. The undesired signal input level was adjusted in steps of 4 db so as to vary the ratio of undesired-to-desired signal levels from -20 to -4 db. At each undesired-to-desired signal ratio a list of 50 words was transmitted on one communication system, this procedure being repeated using another list on the other system. Recordings of the output of the receivers were made of the whole series of tests. These recordings were later reproduced in sequence to a group of auditors for analysis.

In addition to investigating comparative voice intelligibility of the systems, studies were made to determine ability to detect the presence of a signal when another signal was also being received. This was performed by a procedure similar to that described above, but with desired signal strengths yielding approximately 12 and 38 db signal-to-noise ratios in the absence of the other signal, and for interfering signal levels ranging from 10 db below the level of the signal under observation to 70 db above that level. In all cases, the signal under observation was voice modulated to the same level as indicated in the previous paragraph, while the other signal was unmodulated. Recordings were made of the receiver outputs for evaluation.

Additionally, the capture characteristics of the receivers used in the two communication systems were investigated. The same circuit arrangement was employed, the transmitter furnishing the desired signal being fully modulated with 1000-cycle tone. The undesired signal carrier was unmodulated. The level of the desired signal input to the receiver was held constant and the level of the undesired signal was varied over wide limits. Tests of this nature were made at several values of desired signal level. In order to determine the degree of capture, the 1000-cycle audio component of the receiver output was measured. When making such measurements, a 1000-cycle filter of very narrow band-width was used on the output of the receiver in order to reject the heterodyne beat-note products. Transmitter crystals were selected to produce beat-notes which did not coincide with the pass-range of the filter. The filter also served to reduce metered noise to a negligible value and thus any comparatively low receiver output readings, which were noted under certain test conditions, were not greatly affected.

RESULTS

System Intelligibility

Figures 12A and 12B show results obtained from an intelligibility study during co-channel operation under conditions in which either system would have provided a desired signal speech-to-noise ratio of 17 db in the absence of the undesired signal. Figure 12A shows the average of the results of ten observers, while Figure 12B indicates the maximum and minimum values obtained by any individual in the group of listeners. In Figure 12A it is seen that the a-m system intelligibility averages were greater than those for the f-m system under similar conditions. When the undesired-to-desired signal ratios approached -12db the intelligibility of both systems suffered appreciably and when the signal ratio reached a value of -4 db, the intelligibility of both systems became quite poor.

To illustrate that the average values shown in Figure 12A are consistent with the extreme variations observed, the data in Figure 12B are included, showing the maxima and minima of the results for the several listeners. Over the greater portion of the signal ratio range studied, the spread between the two a-m curves occupies a region higher in intelligibility than that between the two f-m curves.

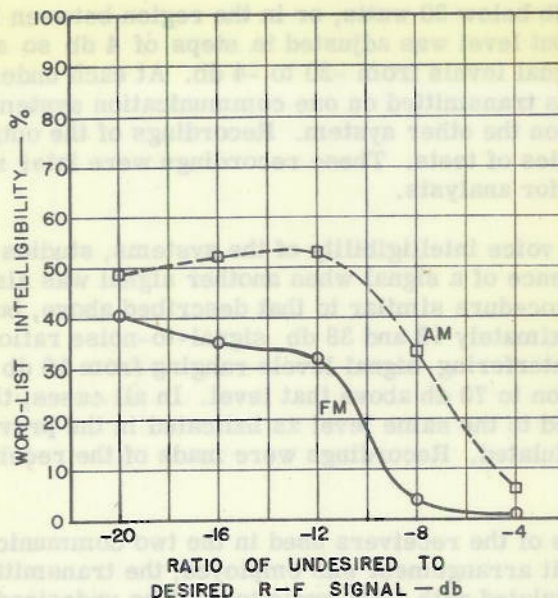
The observers noted that heterodyne beat-note interference in the a-m system was a serious detriment to the intelligibility of received signals. However, the "swishing" present

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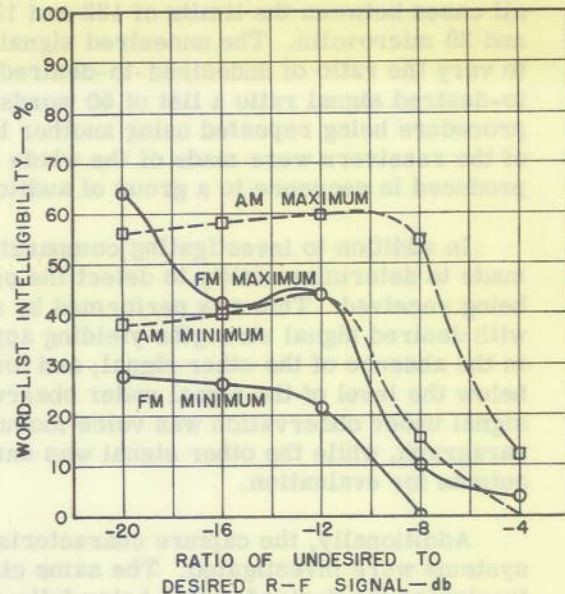
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A - Average results
of ten auditors



B - Extreme variation in
results of the ten auditors

Notes: Speech-to-noise ratio produced by the desired signal in absence of undesired signal: 17 db

Heterodyne beat-note frequency ranged between 2300 and 3700 cycles during course of tests.

Operating frequency: 328.2 Mc.

Fig. 12 - Word-list intelligibility of the two communication systems during co-channel operation

in the f-m receiver output in addition to beat-notes present between words, was an equal if not greater detriment to the intelligibility of the f-m system.

The foregoing discussion considered the intelligibility of the two systems; that is, the ability to recognize and understand individual words from a word list. Since intelligence may be extracted from complete sentences under co-channel operating conditions where it is not possible to identify an appreciable number of words in a word-list, additional observations were made. It was found possible to discern either the complete meaning, or portions of spoken sentences under conditions where the level of the undesired signal, which in this case was also speech modulated with prose material but of a different context, was appreciably greater than that of the desired signal. This was possible in either communication system, for some part of the sense of a message could be obtained unless undesired-to-desired signal input levels of about 8 db or more prevailed. When an 8-db or greater input signal ratio was present, neither communication system was capable of transferring useful information. Distortion of the desired signal by the stronger signal was believed to be the principal cause of failure to extract meaningful information from the message at such signal levels. Thus it is evident that both systems are capable of transferring actual intelligence when sent in the form of spoken sentences at greater adverse signal ratios than would be inferred from the intelligibility data shown in Figure 12A.

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Under the desired signal level conditions employed in Figure 12A, reference to Figure 10 indicates that either system would have shown an intelligibility of approximately 58 percent, had the undesired signal been absent. At undesired-to-desired signal ratios up to -12 db, the a-m system has an intelligibility not too different from 58 percent, as indicated in Figure 12A, and thus the signal ratio must be more adverse than -12 db to materially influence the intelligibility of this system. The f-m system intelligibility, however, was affected when the undesired-to-desired signal ratio was of a level corresponding to -20 db. Thus it is further illustrated that the a-m system has the better intelligibility under similar co-channel operational conditions.

Weak Signal Detection

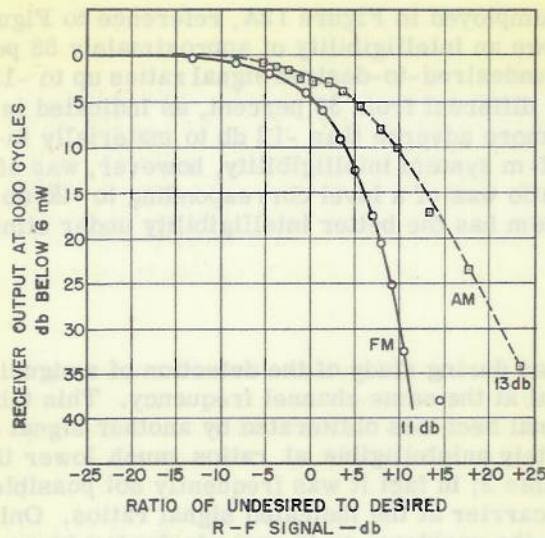
The data presented in Table 2 were obtained during study of the detection of a signal in the presence of another much stronger signal at the same channel frequency. This table lists the ratio of signal levels at which one signal becomes obliterated by another signal of higher level. Both systems had become completely unintelligible at ratios much lower than values indicated in the right hand column of Table 2; in fact it was frequently not possible to detect the presence of modulation on either carrier at the indicated signal ratios. Only through heterodyne beat-note products between the carriers, or in some instances by received "swish" during f-m reception, was discernment of the weaker signal possible. Determination of the exact point of obliteration of the weaker signal was not possible, thus the data presented are accurate to about 3 or 4 db. Examination of the information in Table 2 indicates that the point of obliteration is largely dependent upon the ratio of input signal levels, and that the absolute output level of the receiver has only a secondary influence. It is also evident that neither system offers any significant advantage over the other insofar as this aspect of co-channel operation is concerned.

Capture Characteristics

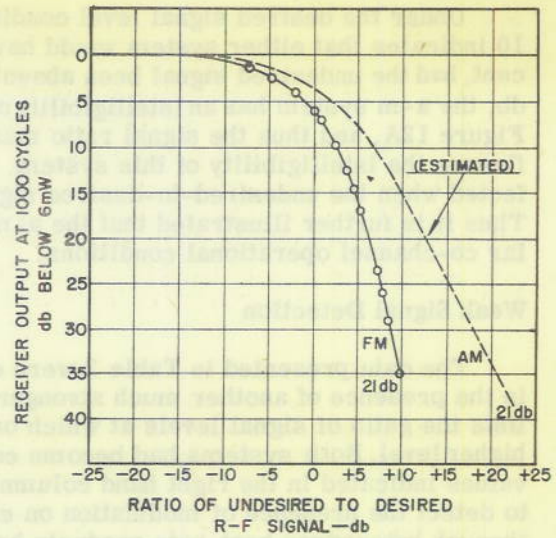
Capture effects were studied, and the findings are presented in Figures 13A, 13B, and 13C. The data contained in these illustrations are similar, differing only with respect to the values of receiver output signal-to-noise ratio obtainable in the absence of the undesired signal. Notes and figures appended to the curves indicate these differences. The degree of capture is indicated by the depression of the curves from the zero-db ordinate. A greater degree of capture is exhibited by the f-m system, a result which was anticipated from the

TABLE 2
DETECTION OF WEAK SIGNALS IN PRESENCE OF
ANOTHER OF MUCH HIGHER LEVEL

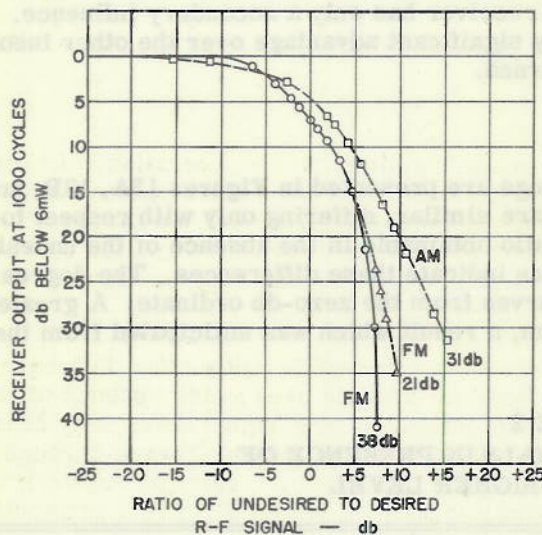
Communication System	Receiver Output Signal-to-Noise Ratio of Weak Signal in Absence of Stronger Signal (db)	Ratio of Stronger-to-Weaker Signal Level Necessary to Obliterate Weaker Signal (db)
a-m	13	62
a-m	38	69
f-m	12	60
f-m	38	68



A - Low desired signal level



B - Medium desired signal level



C - High desired signal level

Notes: db values associated with each curve show signal-to-noise ratio produced by desired signal in absence of undesired signal.

Operating frequency: 328.2 Mc; transmitter carriers furnishing the desired signal were fully modulated or deviated with 1000-cycle tone.

Undesired signal carrier was unmodulated.

Estimated a-m curve, Figure 13B, was established by interpolation between 13 db and 31 db curves shown on Figures 13A and 13C, respectively.

Fig. 13 - Capture characteristics at several values of receiver input signal level

results of previous investigations in this field. The curves also reveal that capture is principally dependent upon the ratio of the undesired and desired signal strengths, although the absolute value of the desired signal strength has some influence.

SUMMARY

During co-channel operation, the word-list intelligibility of the a-m system is not greatly affected when the undesired signal level is 12 db or more below that of the desired signal. In the f-m system, however, the intelligibility became somewhat impaired when the undesired signal level was 20 db below that of the desired signal. For increasingly more adverse undesired-to-desired signal ratios, the intelligibility in both systems diminished, and became quite poor when the undesired signal level reached a value 4 db below that of the desired signal. For comparable co-channel operational conditions, the intelligibility of the a-m system is the higher.

Information in the form of spoken sentences may be transferred at more adverse signal level ratios than by means of word lists. Ability to extract the meaning from such messages is not completely lost unless the undesired signal level is about 8 db above that of the desired signal. This is equally applicable to both communication systems.

Neither system offers an advantage over the other for detecting the presence of a signal when another signal of much higher level is also present on the same channel frequency.

The degree of capture in the f-m system exceeds that of the a-m system, a finding which is consistent with the results of other investigations.

ADJACENT-CHANNEL OPERATION

INTRODUCTION

The performance of a communication system during simultaneous operation with both an on-channel and an off-channel signal is largely governed by the receiver performance characteristics. The effect of a signal which has a frequency different from that at which the receiver is resonant is dependent upon various factors, such as the difference between the signal and the receiver resonant frequencies, the level of the off-resonant signal, and the level of the resonant signal when present.

When an off-resonant signal is comparatively strong and sufficiently close in frequency to the resonant frequency of the receiver, the signal is detected even in the absence of any other signal. This effect is solely dependent on the over-all single-signal selectivity characteristic of the receiver, and the result is referred to in this report as "break-through." In the case of the Models RDZ and X-RDZ-2 Receivers used in this investigation, the single-signal selectivity is chiefly that of the intermediate-frequency amplifier, as the contribution of the preselector to the over-all selectivity is negligible.

When both an off-resonant and a resonant signal are received simultaneously, an effect commonly known as "cross-modulation" may result. Cross-modulation consists of imposition of the adjacent-channel signal modulation upon the receiver resonant signal carrier. This mixing of the two signals is largely the result of nonlinearity in the plate characteristics of the first tube of the receiver. Cross-modulation may occur in conjunction with break-through, or it may occur considerably outside the region of break-through. Cross-modulation is usually negligible in an f-m system.

Another effect of adjacent-channel operation is depression of resonant signal output due to the presence of the other signal. This effect is similar to capture in co-channel

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operation. Often, however, the resonant signal output is reduced by an off-channel signal outside the over-all single-signal selectivity characteristic of the receiver. Such reduction in over-all receiver gain caused by an adjacent-channel carrier can be attributed to capture effects in an early amplifier stage of the receiver.

A further effect is the appearance of noise components due to the presence of an adjacent-channel carrier which results in a depreciation of the signal-to-noise ratio of the received signal on the resonant frequency.

An additional effect, spurious response of the receiver to an adjacent-channel signal, may take place. As spurious response aspects have no bearing on comparison of the a-m and f-m communication systems, operating frequencies were so chosen as to exclude such an influence during adjacent-channel operation.

In this discussion the signal having a frequency the same as the receiver resonant frequency is referred to as the "desired" signal. The signal at a frequency differing from the receiver resonant frequency is called the "undesired" signal.

Prior to performing the tests it was necessary to establish the minimum attenuation which would ordinarily exist between the respective undesired signal transmitting and the desired signal receiving antennas during adjacent-channel operation. The closest spacing which would commonly be encountered on shipboard would be with the two dipole antennas mounted collinearly, with a spacing of 4 feet between centers. The attenuation between two dipoles so disposed in free space has been found to be approximately 30 db in the case of Navy Type 66147 antennas. Therefore a receiver input of 30 db below the nominal transmitter output of 30 watts was considered as the maximum value of undesired signal which should be used in this work. In addition, for an adjacent-channel operating condition somewhat less severe, a signal 36 db below 30 watts was also employed. This latter value was approximately the worst condition encountered during the sea trials which were made as a part of this investigation.¹¹ These two values of receiver input signal level correspond to approximately 1.2 volts and 0.6 volts, respectively.

METHOD OF INVESTIGATION

The general circuit arrangement and apparatus shown in Figure 1 was used for the investigation of adjacent-channel operation except that the slotted line was omitted and the two transmitters and the receiver were connected together through a "T" fitting, Type UG-28/U. This was necessary in order to reduce the total attenuation of the undesired signal to 30 db. The standing waves introduced by connecting the three 50-ohm transmission lines to the "T" fitting were kept to the minimum value possible at the terminal points of the propagation path by including at least 10 db of attenuation in each of the three Type RG-21/U cables to the "T" fitting wherever possible. In some cases, however, it was necessary to reduce the attenuation between the "T" fitting and the receiver to a value less than 10 db in order to obtain a sufficiently low total attenuation for the purpose of the test involved. The increase in standing wave ratios, thus caused, unavoidably reduced the accuracy of the attenuation measurements by a maximum of about 3 db.

As in the case of co-channel operation, and for the same reason, only two signals were used in the adjacent-channel tests. The receiver was always resonant to the frequency of the desired signal. The other signal employed was of a somewhat different frequency and was usually of considerably higher level than that of the desired signal.

¹¹ NRL Report R-3234

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Model X-TDZ-2 transmitters were used for producing both the desired and undesired signals. This was possible since the Model X-TDZ-2 transmitter is provided with means for producing either f-m or a-m transmissions.

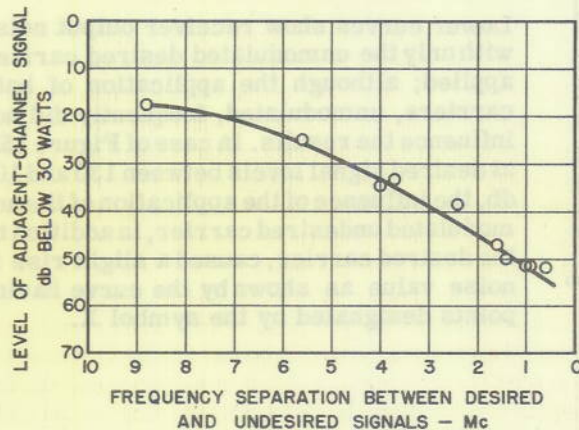
In order to minimize the effects of extraneous emissions and spurious responses, a frequency of 328.2 megacycles was chosen initially for comparative tests of the two communication systems. For the adjacent-channel investigations, however, a frequency of 329.0 megacycles was used as the frequency of the desired signal in order to attain a better selection of crystals for the transmitter providing undesired signals. During the adjacent-channel tests no effects were observed which were attributable to extraneous emissions or spurious receiver responses.

Adjustments of transmitter and receiver controls were, in general, the same as used for co-channel operation. The data presented herewith are mostly for the receiver AVC "ON" condition. Observations were also made with the AVC "OFF" but no significant differences were noted. Various series of data were observed with an undesired signal input to the receiver of 30 db below 30 watts, other series at 36 db below 30 watts, for previously indicated reasons. Tests were made at several frequency spacings between the desired and undesired signals and differing resonant signal input levels to the receiver. Other observations were made with the power level and frequency of the off-channel signal varied to maintain a fixed amount of cross-modulation. Tests were made with both tone and voice modulation and recordings of the receiver output under various test conditions were made. In some of the tests, standard word lists were employed in order to evaluate intelligibility of the two systems under various conditions.

Since break-through may occur simultaneously with cross-modulation, it was necessary to check for both effects. This was done by removing the desired carrier and checking the receiver output for the presence of any modulation components from the undesired carrier. This procedure was followed to insure that the accuracy of cross-modulation data were not compromised by break-through.

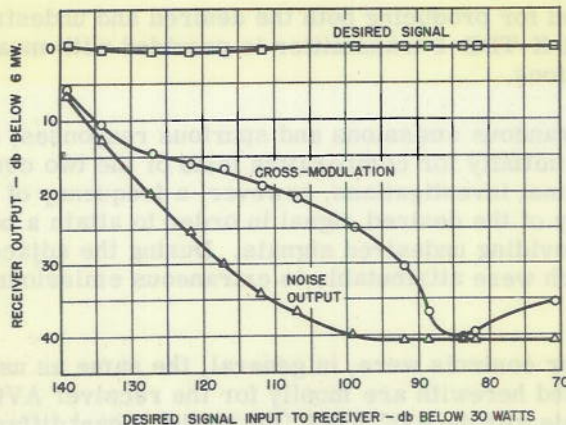
ADJACENT-CHANNEL OPERATION—A-M COMMUNICATION SYSTEM

The results of the adjacent-channel tests are shown in Figures 14 to 20 inclusive. The data, which fall into several categories, were obtained under conditions where break-through was not an appreciable influence. Figure 14 is a conventional cross-modulation characteristic

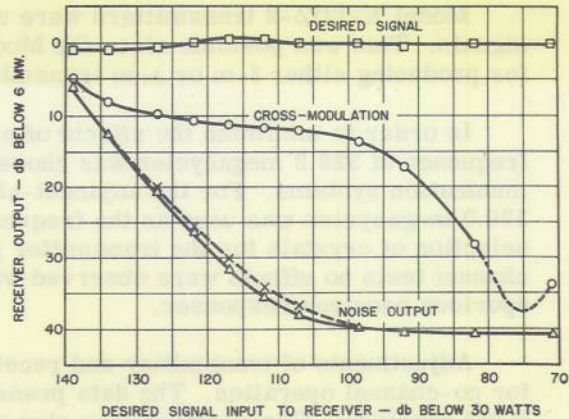


Notes: Curve shows level of undesired carrier required to produce 6 db of cross-modulation. Desired signal frequency: 329 Mc; desired carrier level was 127 db below 30 watts and produced a receiver output signal-to-noise ratio of 20 db in absence of the undesired signal. Frequency of undesired signal was below that of desired signal. Full transmitter modulation with 1000-cycle tone was used in obtaining above data. Receiver AVC "ON."

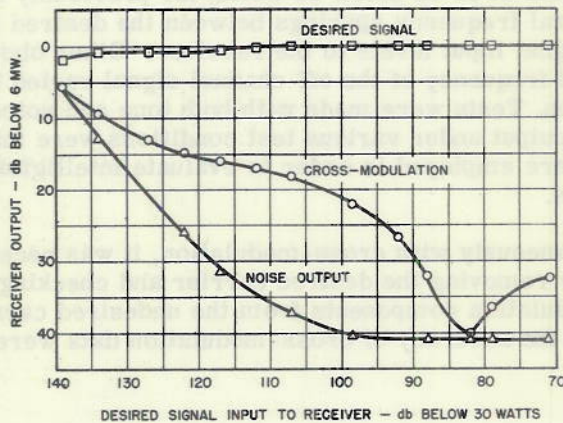
Fig. 14 - Relation of undesired signal level to frequency separation for 6 db cross-modulation



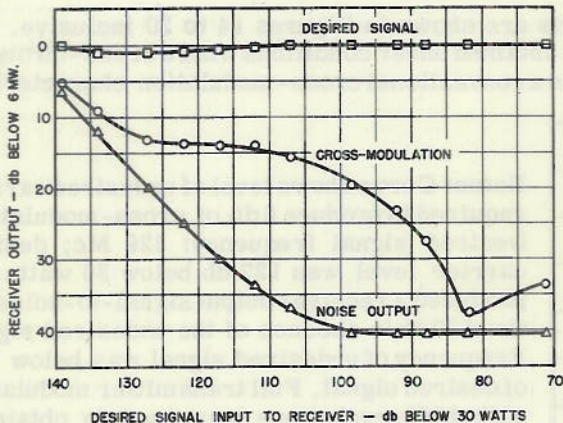
A - Frequency separation: 4 Mc



D - Frequency separation: 2.4 Mc



B - Frequency separation: 3.57 Mc



C - Frequency separation: 2.88 Mc

Notes: Desired signal frequency 329 Mc; receiver AVC "ON;" receiver output maintained at 6 mW in absence of undesired signal throughout test by adjustment of audio gain control.

The zero db ordinate represents the receiver desired signal output in the absence of the undesired signal.

Uppermost curves show receiver output from desired carrier, fully modulated with 1000-cycle tone, in presence of undesired carrier, unmodulated.

Middle curves show receiver cross-modulation output due to undesired signal, fully modulated with 1000-cycle tone, with an unmodulated desired carrier.

Lower curves show receiver output noise with only the unmodulated desired carrier applied; although the application of both carriers, unmodulated, frequently did not influence the results. In case of Figure 15D, at desired signal levels between 130 and 100 db, the influence of the application of the unmodulated undesired carrier, in addition to the desired carrier, caused a slight rise in noise value as shown by the curve having points designated by the symbol X.

Fig. 15 - Cross-modulation data at frequencies below the desired signal frequency with an undesired signal level of 30 db below 30 watts

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Notes: Desired signal frequency 329 Mc; receiver AVC "ON;" receiver output maintained at 6 mW in absence of undesired signal throughout test by adjustment of audio gain control.

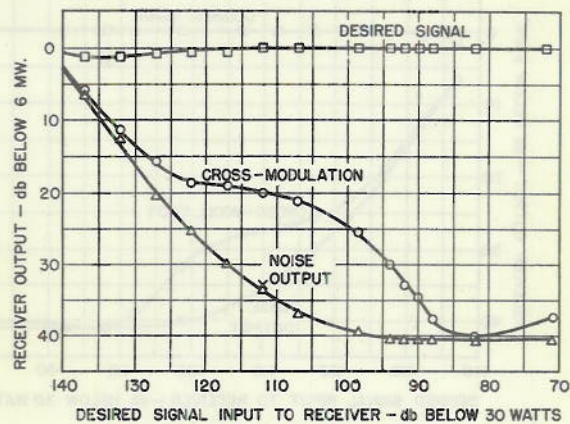
The zero db ordinate represents the receiver desired signal output in the absence of the undesired signal.

Uppermost curves show receiver output from desired carrier, fully modulated with 1000-cycle tone, in presence of undesired carrier, unmodulated.

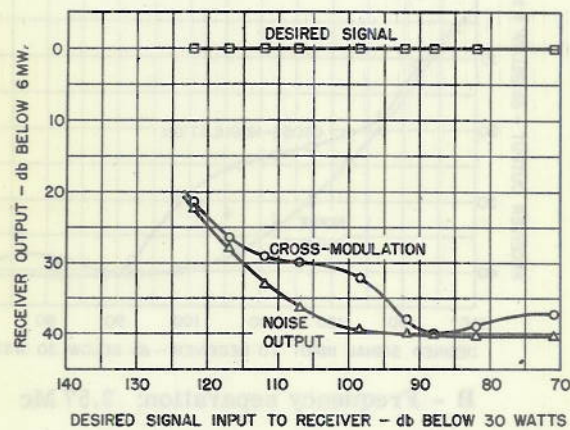
Middle curves show receiver cross-modulation output due to undesired signal, fully modulated with 1000-cycle tone, with an unmodulated desired carrier.

Lower curves show receiver output noise with only the unmodulated desired carrier applied; although the application of both carriers, unmodulated, ordinarily did not influence the results.

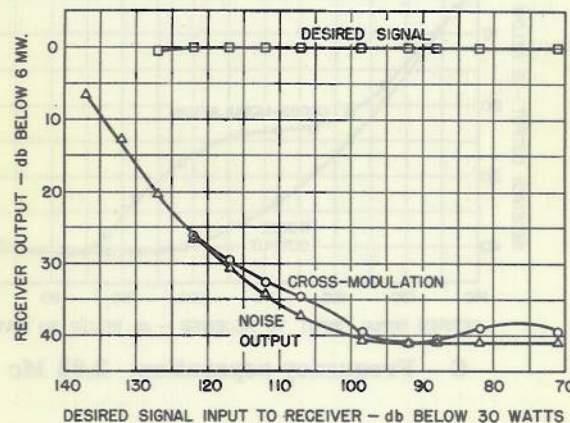
Fig. 16 - Cross-modulation data at frequencies above the desired signal frequency with an undesired signal level of 30 db below 30 watts



A - Frequency separation: 2.4 Mc

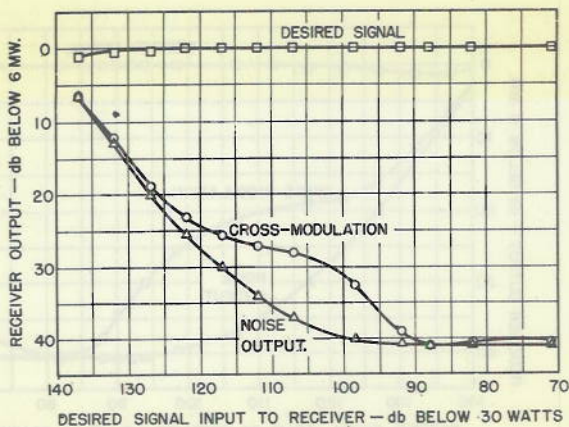


B - Frequency separation: 3.2 Mc

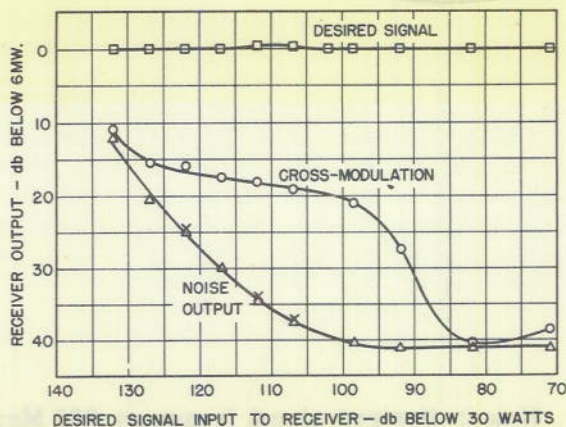


C - Frequency separation: 4 Mc

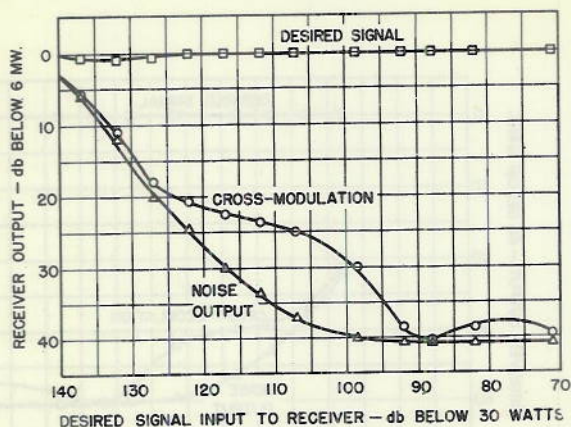
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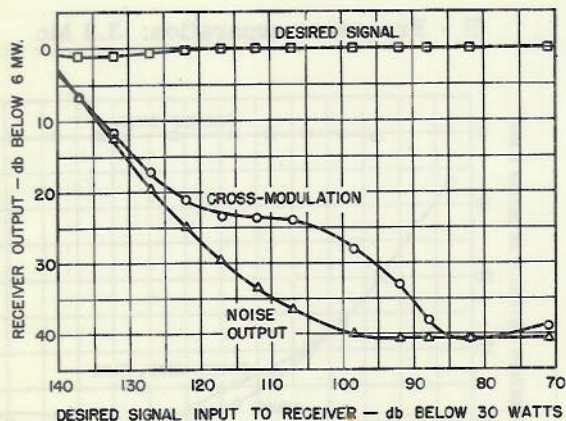
A - Frequency separation: 4 Mc



D - Frequency separation: 2.4 Mc



B - Frequency separation: 3.57 Mc



C - Frequency separation: 2.88 Mc

Notes: Desired signal frequency 329 Mc; receiver AVC "ON;" receiver output maintained at 6 mW in absence of undesired signal throughout test by adjustment of audio gain control.

The zero db ordinate represents the receiver desired signal output in the absence of the undesired signal.

Uppermost curves show receiver output from desired carrier, fully modulated with 1000-cycle tone, in presence of undesired carrier, unmodulated.

Middle curves show receiver cross-modulation output due to undesired signal, fully modulated with 1000-cycle tone, with an unmodulated desired carrier.

Lower curves show receiver output noise with only the unmodulated desired carrier applied; although the application of both carriers, unmodulated, ordinarily did not influence the results.

Fig. 17 - Cross-modulation data at frequencies below the desired signal frequency with an undesired signal level of 36 db below 30 watts

curve obtained on the low-frequency side of receiver resonance and is based on 1000-cycle tone measurements. This curve shows the undesired signal level at various frequencies which produces 6 db of cross-modulation, under the desired signal level conditions indicated. By the expression "6 db of cross-modulation" is meant the condition where the receiver cross-modulation-output-to-noise ratio has the db value indicated. The cross-modulation output consists of 1000-cycle tone with which the undesired carrier is modulated and which appears in the receiver output. The noise value is that prevailing with only the unmodulated desired carrier being impressed upon the receiver. The curve stops at a frequency spacing of 0.6 megacycles due to the fact that at closer spacings break-through occurred along with cross-modulation and hence the latter quantity could not be measured individually.

Figures 15, 16, and 17 show cross-modulation and depression as a function of desired signal level with the undesired signal to the receiver being held constant.¹² The ordinate distance between the uppermost curve and the zero-db ordinate shows the extent of desired signal depression. The ordinate distance between the lower curve and the uppermost curve is the signal-to-noise ratio of the desired signal in the presence of the undesired unmodulated carrier. The remaining curve in each figure shows cross-modulation and its relation to the receiver output noise and the desired signal output level. The ordinate distance between the cross-modulation curve and the uppermost curve is the signal-to-interference ratio of the desired signal. The magnitude of the cross-modulation output-to-noise ratio is the ordinate distance between the cross-modulation curve and the bottom curve.

Examination of the curves of Figures 15 through 17 shows that cross-modulation-output-to-noise ratios start from a comparatively low value at the weaker desired signal levels and increase gradually with the level of the desired signal. A maximum is reached between 110 and 100 db below 30 watts of desired signal input level. Over this range the cross-modulation remains fairly constant. As the desired signal level is further increased, however, the cross-modulation decreases sharply and reaches a minimum at a desired signal level near 80 db below 30 watts; from there the cross-modulation-outputs again rise as the desired signal level is increased still further. Such a minimum is the result of the varying curvature with grid bias of the plate current characteristic of the tube or tubes in which cross-modulation occurs.

For undesired signal frequencies above resonance, the cross-modulation outputs follow the same general trend as for those below resonance, but are not of similar magnitude. This asymmetry results principally from the band-pass response characteristic of the preselector circuits ahead of the first radio-frequency amplifier, which at this particular desired signal frequency is not exactly centered relative to the other selective circuits of the receiver.

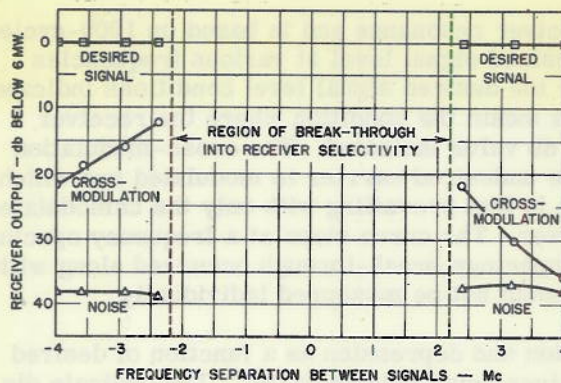
Of value in showing an over-all picture of cross-modulation effects are the results contained in Figures 18 and 19. These data which were extracted from the results appearing in Figures 15, 16 and 17, show how cross-modulation varies with frequency for certain combinations of levels of the desired and undesired signals. In Figure 18A data are shown regarding the condition under which maximum cross-modulation output resulted from any of the several combinations of desired and undesired signal levels used. The difference in cross-modulation output on the two sides of the receiver resonant frequency is again illustrated.

The curves shown in Figures 18 and 19 indicate an increase in cross-modulation output as the undesired signal frequency approaches the resonant frequency of the receiver. For

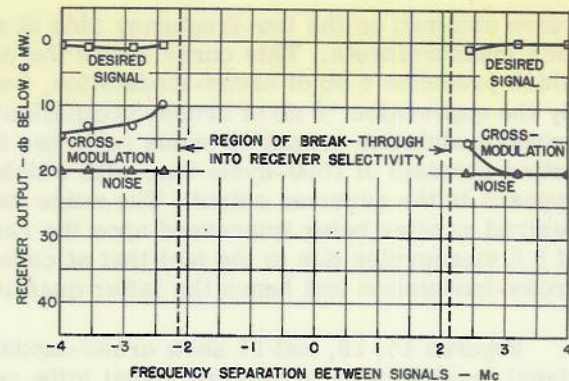
¹²It is desired to point out that the abscissa scales are shown on a relative basis, and thus do not indicate absolute signal levels. If 8 db were added to the values appearing along the abscissa, a more correct indication of the absolute signal level would be represented.

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A - Desired signal level:
105 db below 30 watts



B - Desired signal level:
123 db below 30 watts

Notes: Desired signal frequency: 329 Mc; receiver AVC "ON;" receiver output maintained at 6 mW in absence of undesired signal by adjustment of audio gain control.

The zero db ordinate represents the receiver desired signal output in the absence of the undesired signal.

Uppermost curves show receiver output from desired signal, fully modulated with 1000-cycle tone, in presence of unmodulated undesired carrier.

Middle curves show receiver cross-modulation output due to undesired carrier, fully modulated with 1000-cycle tone, and an unmodulated desired carrier.

Lower curves show receiver output noise with only the unmodulated desired carrier applied although the application of both carriers unmodulated usually did not influence the results.

The signal level combinations of Figure 18A produced maximum cross-modulation output.

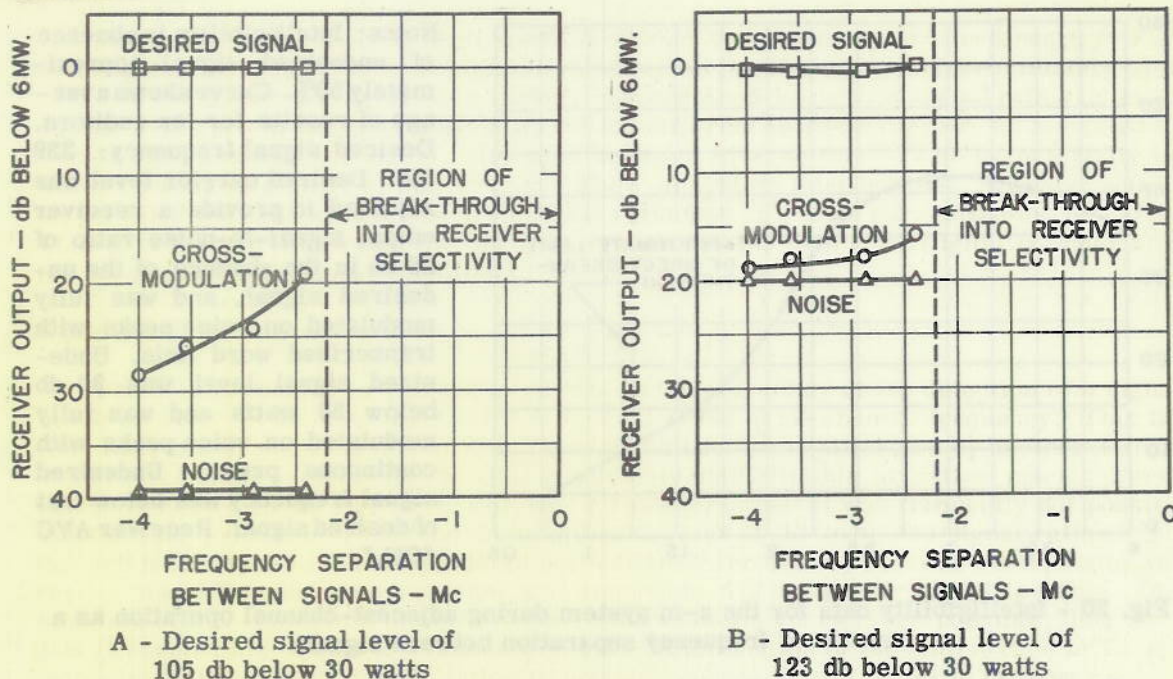
Fig. 18 - Cross-modulation data as a function of frequency separation between signals for an undesired signal level of 30 db below 30 watts

example, in Figure 18A a 38-db value of signal-to-noise ratio in the absence of the undesired signal depreciates to a 22-db signal-to-interference ratio when the off-channel signal is 4 megacycles below the receiver resonant frequency, and to a 13.5-db signal-to-interference ratio at 2.5 megacycles below resonance. On the high-frequency side of resonance, cross-modulation effects are considerably less, but still appreciable.

The data in Figure 14 are as consistent with those in the other illustrations of cross-modulation results as can be expected considering the fact that different receivers were used. The differences amount to only 1 or 2 db.

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Notes: Desired signal frequency: 329 Mc; receiver AVC "ON;" receiver output maintained at 6 mW in absence of undesired signal by adjustment of audio gain control.

The zero db ordinate represents the receiver desired signal output in the absence of the undesired signal.

Uppermost curves show receiver output from desired signal, fully modulated with 1000-cycle tone, in presence of unmodulated undesired carrier.

Middle curves show receiver cross-modulation output due to undesired carrier, fully modulated with 1000-cycle tone, and an unmodulated desired carrier.

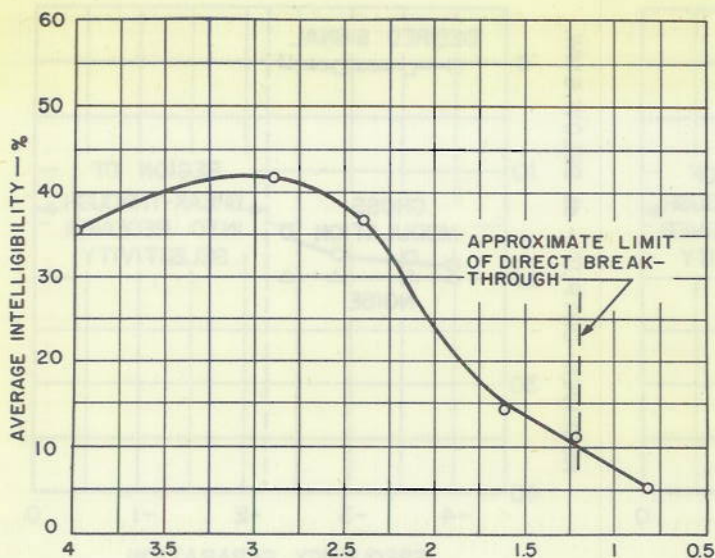
Lower curves show receiver output noise with only the unmodulated desired carrier applied although the application of both carriers unmodulated, usually did not influence the results.

Fig. 19 - Cross-modulation data as a function of frequency separation between signals for an undesired signal level of 36 db below 30 watts

Voice intelligibility studies were also undertaken during adjacent-channel operation. The desired signal was modulated with word lists, while the undesired signal was modulated with continuous prose. Transcriptions were used in the modulation of both transmitters, the program material having been prepared in advance using the same voice. The results of the intelligibility analysis are shown in Figure 20. As seen from the curve, the intelligibility was seriously affected when the frequency difference between the undesired and desired signals was appreciably less than 2.5 megacycles and became very poor when the separation was as low as 1 megacycle.

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Notes: Intelligibility in absence of undesired signal approximately 50%. Curve shows average of results for ten auditors. Desired signal frequency: 329 Mc. Desired carrier level was adjusted to provide a receiver output signal-to-noise ratio of 25 db in the absence of the undesired signal, and was fully modulated on voice peaks with transcribed word lists. Undesired signal level was 30 db below 30 watts and was fully modulated on voice peaks with continuous prose. Undesired signal frequency was below that of desired signal. Receiver AVC "ON."

Fig. 20 - Intelligibility data for the a-m system during adjacent-channel operation as a function of frequency separation between signals

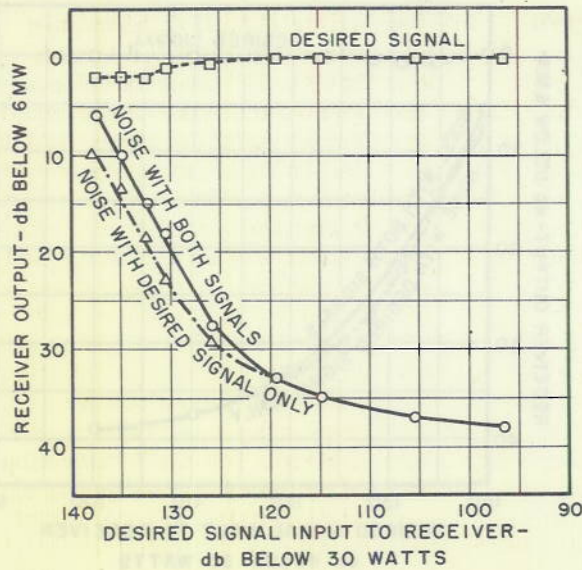
From Figure 10 it is noted that the intelligibility of the desired signal under the conditions employed in Figure 20 would have been about 50 percent had the undesired signal been absent. Even at the higher frequency spacings employed in Figure 20 the intelligibility results are somewhat below 50 percent, hence it is concluded that with the undesired-to-desired signal ratios of the value employed, the intelligibility was to some extent impaired even at frequency spacings as great as 4 megacycles. It is desired to point out however, that some doubt exists as to the accuracy of the intelligibility rating shown at 4 megacycles frequency spacing.

Qualitative observations during the intelligibility tests yielded certain additional information. When the desired signal was modulated with prose rather than word-lists, other test conditions remaining the same, it was found that received signals from the desired carrier were understandable unless the level of cross-modulation output exceeded the desired signal output, as when a high level of a undesired signal modulation coincided with a low level of desired signal modulation. Even when the level of cross-modulation exceeded that of the desired signal output, a portion of the intelligence could still be extracted from the latter.

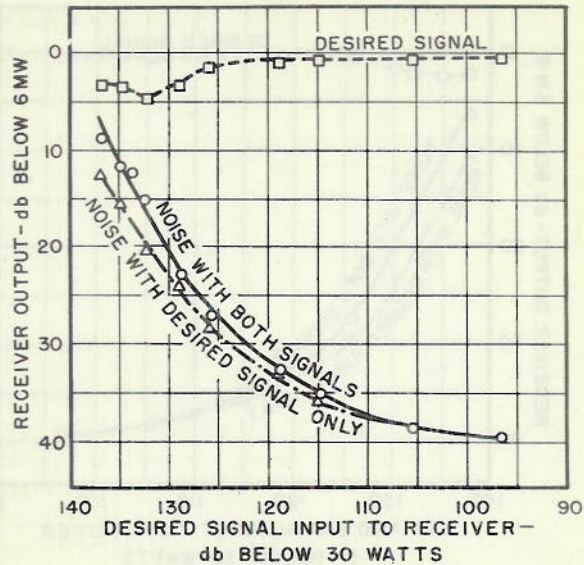
The foregoing results were applicable to the case where break-through effects had no appreciable influence. Certain additional observations were made under conditions where break-through was encountered, with the following findings. With undesired signal levels of 30 and 36 db below 30 watts, 100 percent tone-modulated, a trace of modulation break-through sufficient to be detected audibly but not great enough to be measured, was noted with an undesired signal frequency 2.4 megacycles off receiver resonance. With an undesired signal level of 36 db below 30 watts and a frequency 1.6 megacycles below receiver resonance, the signal-to-noise ratio of receiver break-through output was 20 db. During similar tests with voice modulated signals at a level of 30 db below 30 watts, slight break-through was audibly discernible at undesired signal frequencies 0.8, 1.2, and 1.6 megacycles below resonance, but in no case was it greater than an equivalent signal-to-noise ratio of 3 to 5 db.

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A - Frequency separation: 2.4 Mc



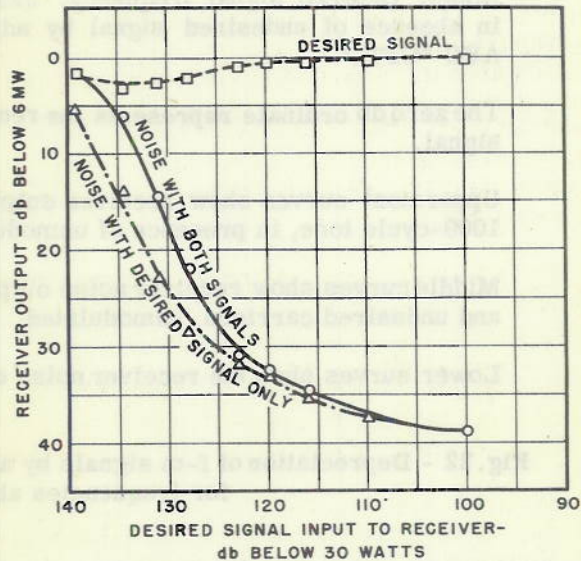
B - Frequency separation: 1.6 Mc

Notes: Desired signal frequency: 329 Mc; receiver output maintained at 6 mW in absence of undesired signal by adjustment of audio gain control; receiver AVC "OFF." The zero db ordinate represents the receiver output in the absence of the undesired signal.

Uppermost curves show receiver output from desired signal fully deviated with 1000-cycle tone, in presence of unmodulated undesired carrier.

Middle curves show receiver noise output due to simultaneous presence of desired and undesired carriers, unmodulated.

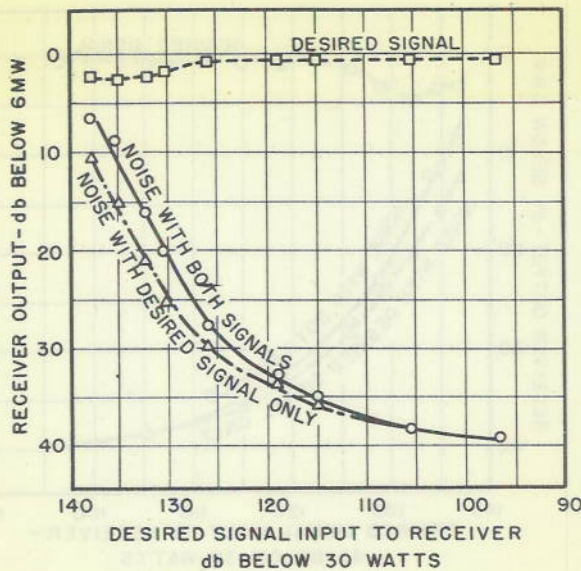
Lower curves show the receiver noise output with only the desired carrier applied.



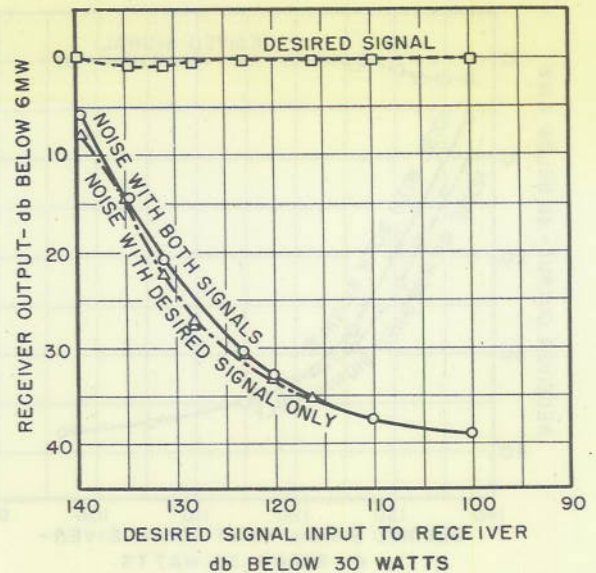
C - Frequency separation: 1.2 Mc

Fig. 21 - Depreciation of f-m signals by an undesired carrier at 30 db below 30 watts for frequencies below the desired signal

The two series of measurements above, that is break-through results with tone modulation and with voice modulation, were conducted with different receivers. The discrepancy between the points at which break-through occurred may be attributed to differences in receiver selectivity in the region of the extreme skirts of the over-all single-signal characteristics.



A - Frequency separation: 1.6 Mc



B - Frequency separation: 2.4 Mc

Notes: Desired signal frequency: 329 Mc; receiver output maintained at 6 mW in absence of undesired signal by adjustment of audio gain control; receiver AVC "OFF."

The zero db ordinate represents the receiver output in the absence of the undesired signal.

Uppermost curves show receiver output from desired signal fully deviated with 1000-cycle tone, in presence of unmodulated undesired carrier.

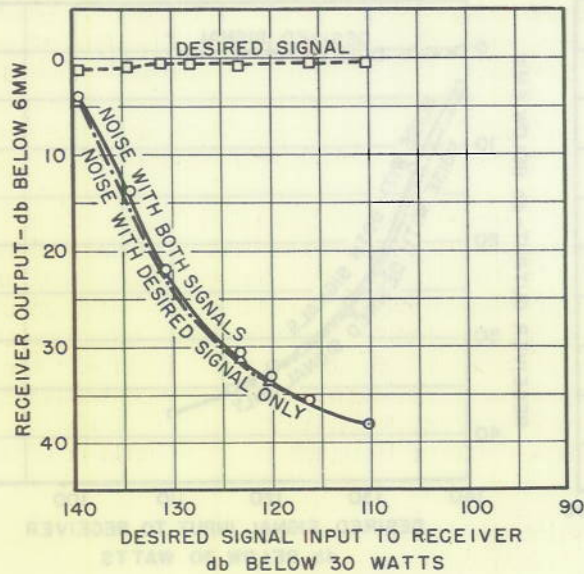
Middle curves show receiver noise output due to simultaneous presence of desired and undesired carriers, unmodulated.

Lower curves show the receiver noise output with only the desired carrier applied.

Fig. 22 - Depreciation of f-m signals by an undesired carrier of 30 db below 30 watts for frequencies above the desired signal

ADJACENT-CHANNEL OPERATION - F-M COMMUNICATION SYSTEM

The results of these tests under conditions where break-through is not a factor are shown in Figures 21 to 26. These data fall into several categories. Figures 21 to 24, inclusive, show measurements based on tone modulation and are the counterpart of data previously described for the a-m system, shown in Figures 15, 16, and 17. The departure of the uppermost curve from the zero db ordinate is a measure of the depression of the desired signal due to the presence of the undesired signal. The ordinate distance between the uppermost and middle curves gives the signal-to-noise ratio of the desired signal with the undesired signal present. The ordinate distance between the middle and lower curve is a measure of the increase in receiver noise due to the presence of the undesired signal. The ordinate distance between the lower curve and the zero db ordinate indicates the signal-to-noise ratio of the desired signal in the absence of the undesired signal.



A - Frequency separation: 2.4 Mc

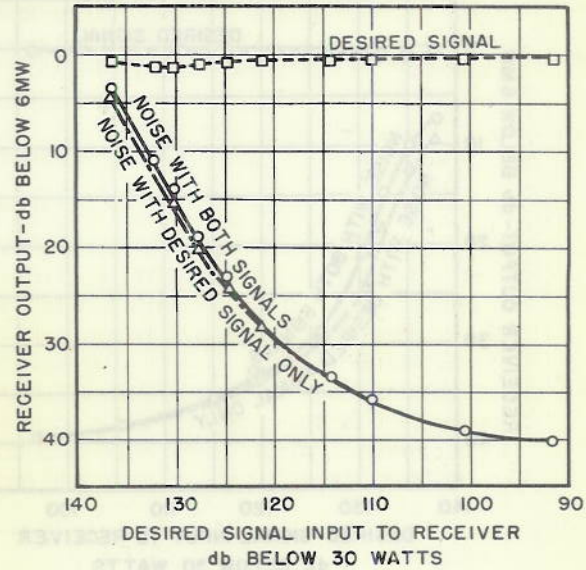
Notes: Desired signal frequency: 329 Mc; receiver output maintained at 6 mW in absence of undesired signal by adjustment of audio gain control; receiver AVC "OFF."

The zero db ordinate represents the receiver output in the absence of the undesired signal.

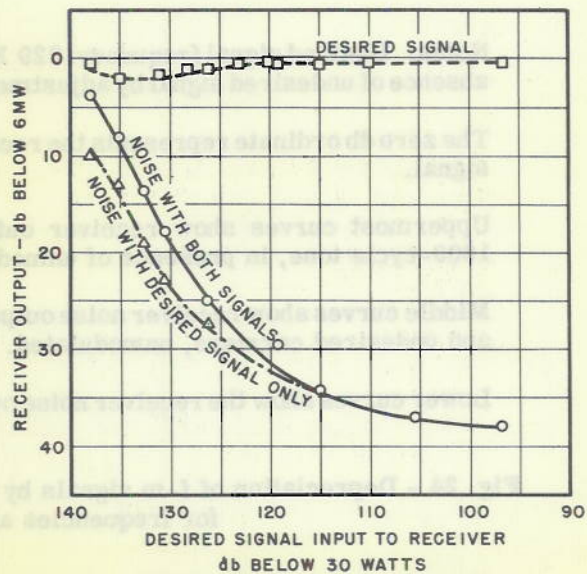
Uppermost curves show receiver output from desired signal fully deviated with 1000-cycle tone, in presence of unmodulated undesired carrier.

Middle curves show receiver noise output due to simultaneous presence of desired and undesired carriers, unmodulated.

Lower curves show the receiver noise output with only the desired carrier applied.

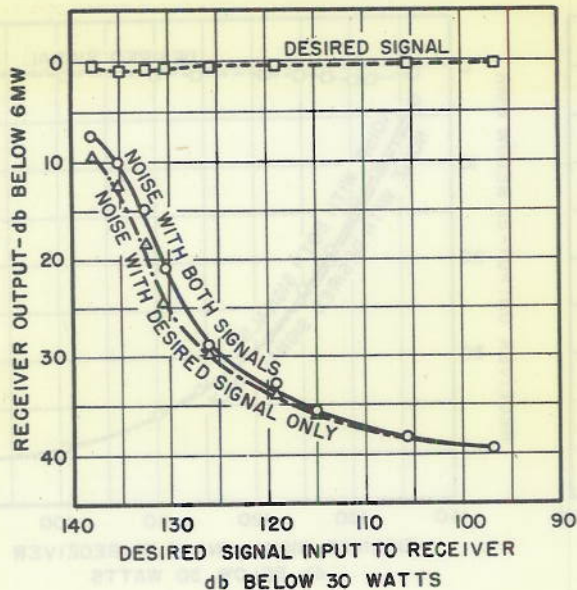


B - Frequency separation: 1.6 Mc

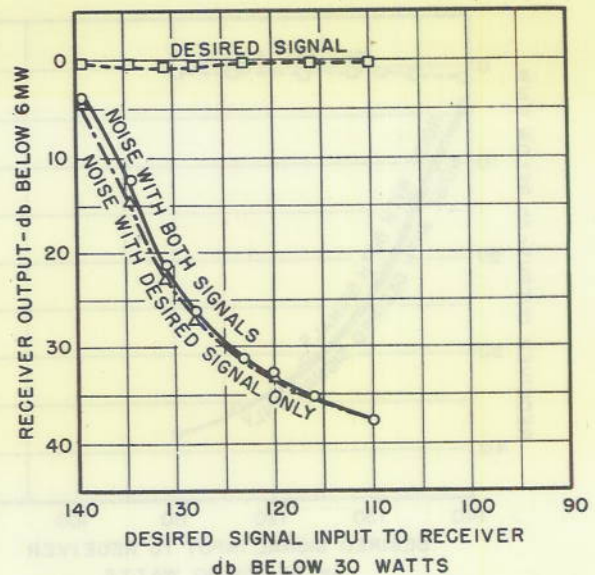


C - Frequency separation: 1.2 Mc

Fig. 23 - Depreciation of f-m signals by an undesired carrier of 36 db below 30 watts for frequencies below the desired signal



A - Frequency separation: 1.6 Mc



B - Frequency separation: 2.4 Mc

Notes; Desired signal frequency: 329 Mc; receiver output maintained at 6 mW in absence of undesired signal by adjustment of audio gain control; receiver AVC "OFF."

The zero db ordinate represents the receiver output in the absence of the undesired signal.

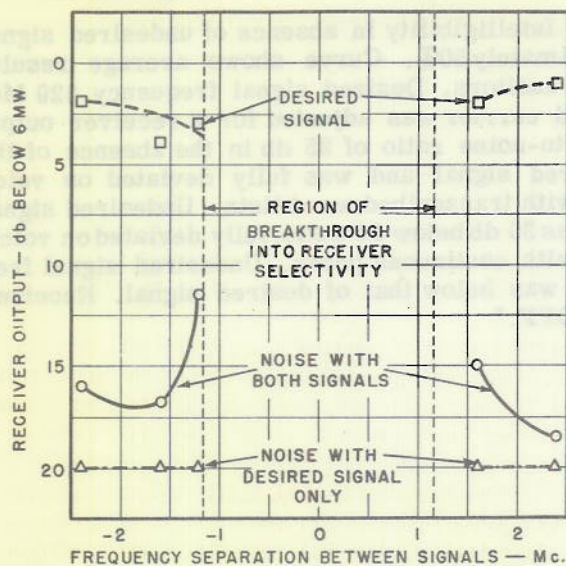
Uppermost curves show receiver output from desired signal fully deviated with 1000-cycle tone, in presence of unmodulated undesired carrier.

Middle curves show receiver noise output due to simultaneous presence of desired and undesired carriers, unmodulated.

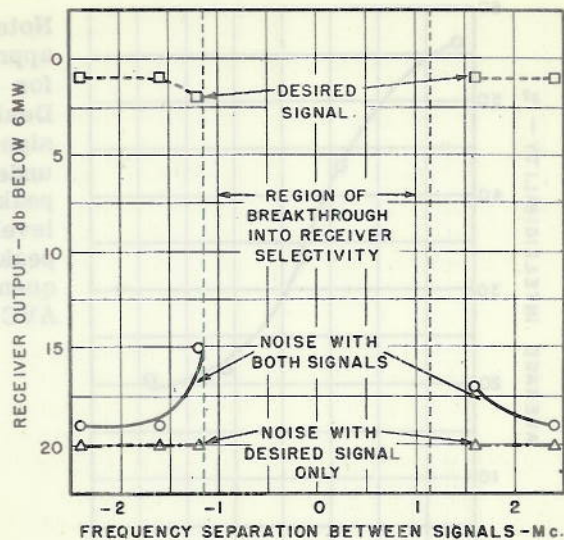
Lower curves show the receiver noise output with only the desired carrier applied.

Fig. 24 - Depreciation of f-m signals by an undesired carrier of 36 db below 30 watts for frequencies above the desired signal

No evidence of cross-modulation was observed during the course of tests with the f-m system. The only effects of significance shown in the curves are the reduction of desired signal output and increase in receiver noise output with resulting depreciation of receiver output signal-to-noise ratio. These effects increase in magnitude as the desired signal level decreases. As illustrative of conditions prevailing during adjacent-channel operation, the following data extracted from the curves is cited. As shown in Figure 21C, a desired signal yielding a receiver output signal-to-noise ratio of 20 db depreciates to a 9-db ratio in the presence of an undesired signal 30 db below 30 watts at a frequency 1.2 megacycles lower than that of the desired signal.



A - Undesired signal level:
30 db below 30 watts



B - Undesired signal level:
36 db below 30 watts

Notes: Desired signal frequency: 329 Mc; receiver AVC "OFF;" receiver output maintained at 6 mW in absence of undesired signal by adjustment of audio gain control; desired signal level: 133 db below 30 watts.

The zero db ordinate represents the receiver output in the absence of the undesired signal.

Uppermost curves show receiver output from desired signal fully deviated with 1000-cycle tone, in presence of unmodulated undesired signal.

Middle curves show receiver noise output due to simultaneous presence of desired and undesired carriers, unmodulated.

Lower curves show the receiver noise output with only the desired carrier applied.

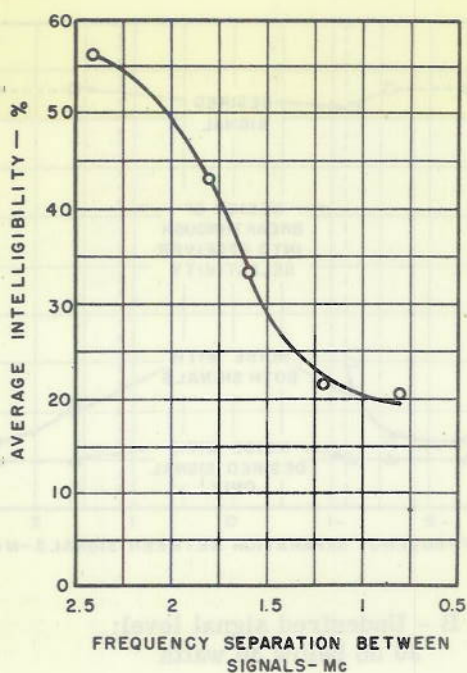
Fig. 25 - Depreciation of f-m signals as a function of frequency separation between signals

To indicate more clearly the effect of frequency separation on adjacent-channel operation, the results shown in Figure 25 are presented. These data were extracted from results appearing in Figures 21 to 24, inclusive, and give similar information in a different form. The increase in magnitude of the effects of adjacent-channel operation as the undesired signal frequency approaches the receiver resonant frequency is illustrated. The asymmetrical nature of the results is apparent as was the case in similar data on the a-m system. The reason for the asymmetry is the same in both communication systems.

Intelligibility studies were also carried out during adjacent-channel operation. The average of results obtained by 10 auditors is shown in Figure 26. A loss in intelligibility results as the separation between desired and undesired signal frequencies becomes less.

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Notes: Intelligibility in absence of undesired signal approximately 50%. Curve shows average results for 10 auditors. Desired signal frequency 329 Mc. Desired carrier was adjusted for a receiver output signal-to-noise ratio of 25 db in the absence of the undesired signal and was fully deviated on voice peaks with transcribed word lists. Undesired signal level was 30 db below 30 watts, fully deviated on voice peaks with continuous prose. Undesired signal frequency was below that of desired signal. Receiver AVC "OFF."

Fig. 26 - Intelligibility data for the f-m system during adjacent-channel operation as a function of frequency separation between signals

Other tests (the results of which are not included in Figure 26), indicated no influence on the desired signal intelligibility at frequency spacings greater than 2.4 megacycles. Comparison of the data in Figure 26 with those shown in Figure 10 shows that the intelligibility rating in the former illustration at a 2.4-megacycle spacing is reasonably consistent with that found during single-signal operation at a similar signal-to-noise ratio. Thus, it is further shown that for the desired and undesired signal ratios used in Figure 26, if the frequency spacing between the desired and undesired signals is at least equal to 2.4 megacycles, no impairment in desired signal intelligibility occurs.

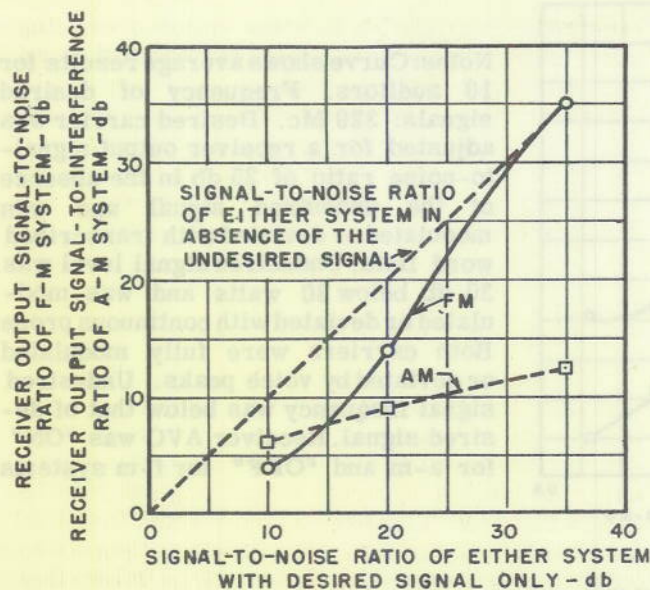
COMPARISON OF THE COMMUNICATION SYSTEMS DURING ADJACENT-CHANNEL OPERATION

A comparison of the two systems using tone modulation measurements as a basis is shown in Figure 27. This shows the effect of an undesired signal upon the desired signal output as a function of the receiver output signal-to-noise ratio produced by the desired signal in the absence of the undesired signal. These data are extracted from other curves already presented on the subject of adjacent-channel operation. In the case of the a-m system, the impairment is largely due to cross-modulation effects. In the f-m system, however, the impairment is caused by depression of the desired signal output of the receiver together with increase in receiver noise output. If it is assumed that the deleterious effects upon a receiver output signal due to extraneous noise content and that due to extraneous interference content resulting from cross-modulation are of equal significance, the following conclusion may be drawn from the data in Figure 27. For desired signal levels producing a receiver output signal-to-noise ratio of less than 15 db in the absence of an undesired signal, the a-m system is preferable, but for higher desired signal levels, the f-m system is the more satisfactory.

Comparative intelligibility data for a 25-db interference-free receiver-output signal-to-noise ratio, shown in Figure 28, further support this conclusion. It is also apparent

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Notes: Desired signal frequency: 329 Mc. Undesired signal level was maintained at 30 db below 30 watts and its frequency was 2.4 Mc below that of the desired signal. Receiver AVC was "ON" for a-m and "OFF" for f-m. Interference for a-m system was cross-modulation while interference for f-m system was noise alone.

Fig. 27 - Comparison of adjacent-channel operation performance of the two communication systems

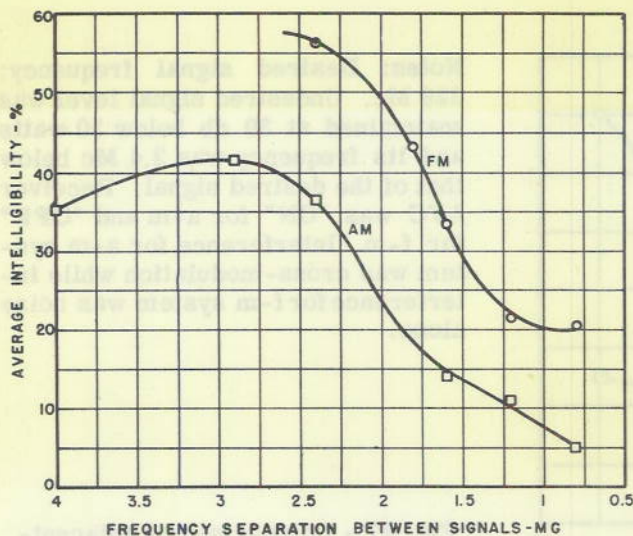
that in the region of frequency spacings between the desired and undesired signals wherein the intelligibility of either system is impaired, that a spacing of about one and one-half times that necessary in the f-m system is required in the a-m system for equal loss in intelligibility as judged from word-list tests. Thus, wider frequency channel spacings are necessary in the a-m system than in the f-m system for similar intelligibility ratings, other factors being equal, under adjacent-channel operational conditions experienced on Naval craft.

With reference to operation under conditions where break-through is experienced, all of the data heretofore discussed are not fully consistent as regards the frequency separation at which the effects become significant. The threshold of break-through region in various data has been indicated as occurring at frequency separations ranging from 0.6 to 2.4 megacycles. It appears that 1.2 megacycles is a reasonable value for both the f-m and a-m systems.

SUMMARY

The only deleterious effect of major significance experienced in the a-m system during adjacent-channel operation is cross-modulation. In the f-m system the deleterious effects consist of depression of desired signal receiver output and increase in receiver output noise, with resulting depreciation of desired signal receiver output signal-to-noise ratio.

If it is assumed that the deleterious effect upon a receiver output signal due to interference arising from cross-modulation and that due to interference in the form of noise are of equal consequence, the following conclusion may be drawn from the data taken with a 2.4-megacycle frequency spacing and with an undesired signal level 30 db below 30 watts. For desired signals producing a receiver output signal-to-noise ratio of 15 db in the absence of an undesired signal, similar impairment of the receiver output results in both systems. For appreciably lower values of desired signal level, the f-m system provides the better performance; and for appreciably higher desired signal levels, the a-m system is the more satisfactory.



Notes: Curve shows average results for 10 auditors. Frequency of desired signals: 329 Mc. Desired carrier was adjusted for a receiver output signal-to-noise ratio of 25 db in the absence of the undesired signal and was modulated or deviated with transcribed word lists. Undesired signal level was 30 db below 30 watts and was modulated or deviated with continuous prose. Both carriers were fully modulated or deviated by voice peaks. Undesired signal frequency was below that of desired signal. Receiver AVC was "ON" for a-m and "OFF" for f-m systems

Fig. 28 - Comparative intelligibility of the two communication systems during adjacent-channel operation

With two similar types of communication systems of the nature herein discussed, a desired signal interference-free receiver output signal-to-noise ratio of 25 db, and with an undesired signal input level 30 db below 30 watts, a frequency spacing between two adjacent signals must be used which is approximately 50 percent greater in the a-m system than is necessary in the f-m system for equality in the word-list intelligibility of received signals.

Direct break-through of an undesired signal appears to become appreciable in either system at frequency spacings less than 1.2 megacycles.

OPERATION DURING INTERFERENCE

INTRODUCTION

As a final phase of the comparison of the two communication systems, tests were made as to the susceptibility of each system to radio-frequency noise. Both impulse and random types of noise were considered. In the case of impulse noise, the work carried out was with regard to the effects of interference created by several types of standard Navy radar equipments upon the reception of signals transmitted through space. To determine the influence of random noise, however, the output of a specially-developed spark-oscillator was introduced into the circuit arrangement shown in Figure 1, and in this case replaced one of the transmitters. The influence of noise, where present in a communication system, is in the main governed by the effects of noise on the receiver.

RADAR INTERFERENCE

Procedure

Various tests were made at a channel frequency of 328.2 megacycles to determine the influence of interference upon reception of low-level received signals by several standard

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Navy radar equipments. The following tabulation lists the pertinent characteristics of the radar equipments used:

Navy Model:	SC-5	SG-3	SR-2	Mark 12
Operating Frequency, (Mc):	200	3000	575	900
Peak Power, (Kw):	200	400	300	100
Pulse Frequency, (Cycles):	60	760	600/180	480
Pulse Duration (μ s):	2-1/2 & 5	1/3 & 1-1/4	1 & 4	1-1/2
Type of Modulation:	squegging oscillator	spark-gap	spark-gap	spark-gap

The installation of the radars employed in this work was considered to be reasonably typical of standard shipboard practice, although the work was carried out with shore-based radars.

The receiving antenna used for the reception of desired signals was a Type 66147 dipole which was mounted in such a location that all the radar antennas were within a radius of 40 feet of the dipole. The receiving antenna was connected through 68 feet of Type RG-8/U cable to a coaxial switch which permitted connection to either the a-m or the f-m receiver as required. By means of suitable switching arrangements the output of either receiver could be connected to an output circuit consisting of an electronic voltmeter, an oscilloscope, a 600-ohm resistive load, and a pair of high-impedance headphones. These indicators assured detection of any significant noise response. Power for receivers, instruments, and radars was drawn directly from common distribution lines without any isolating devices such as transformers or filters.

Desired a-m and f-m signals were supplied by Model TDZ and Model X-TDZ-2 transmitters, respectively. A single Type 66147 dipole antenna was used for transmission, with appropriate antenna switching from one transmitter to the other being accomplished with a coaxial switch. The transmitting antenna was located approximately 150 yards from the receiving antenna. In order to produce a signal at the receiver of a satisfactorily low level, an attenuator was used in the cable to the transmitting antenna. After attenuation, the power input to the transmitting antenna was approximately 1.5 milliwatts in all cases, this being sufficient to produce a receiver output signal of moderate level.

The receivers were selected and aligned to attain essentially equal selectivity and sensitivity characteristics and otherwise were standardized in all respects. Full modulation or deviation with 1000-cycle tone was applied to each transmitter. The transmitter power used gave a receiver output signal-to-noise ratio of 23 db for the a-m system and 26 db for the f-m system. Each receiver was adjusted to give an audio output of 6 milliwatts into the 600-ohm load. With the cable disconnected from the antenna input receptacle of either receiver and the receptacle left open-circuited, no radar noise was detected under any operating condition, with one exception. When a radar antenna was beamed to within 5 degrees of a direct line to the a-m receiver cabinet, under the Noise Limiter "OFF" condition, interference was discernible. With the limiter "ON," however, no interference was detected.

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Upon reconnecting the antenna cables to the receivers, the four radar equipments were operated successively at full power. Tests were made utilizing the various repetition rates and pulse durations possible in each. In searching for a receiver antenna position around any radar equipment that would cause a noise response maximum, the receiver dipole was oriented at various heights and polarization angles with respect to the radar arrays, while the horizontal spacing between the receiving and radar antennas was varied from 10 feet to 1/4 inch. These were initial explorations which were conducted with the a-m receiver with noise limiter "OFF," since this receiver, without noise limiting, was responsive to noise. After a receiving antenna position of maximum noise was located, interference investigations were conducted using the particular radar equipment under consideration.

Results

Proceeding under the conditions described, the following observations were noted.

1. When using either the f-m receiver, or the a-m receiver with noise limiter "ON," no external noise from any of the four radar units could be detected. This condition held even in the absence of a desired signal carrier from the transmitter. Also, even though the receiver audio frequency output levels were readjusted to produce 6 milliwatts of receiver output noise, no radar noise component could be detected in the headphones or recognized on the oscilloscope.

2. The Model SR-2 and the Mark 12 radars produced some slight audible and oscillographic noise indications on the a-m receiver with noise limiter "OFF," unless the desired input signal level was increased to a value of 25 microvolts. At any higher level all traces of noise indications disappeared.

3. No noise response whatever could be secured from the Models SC-5 or SG-3 radars in either receiver under any operating condition.

4. At one stage of the investigation a total of 10 radar equipments of various types were in operation within 100 feet of the receiving dipole antenna, but no interference appeared in the output of either receiver so long as the a-m receiver noise limiter was "ON."

Thus it is evident that either system is capable of satisfactory operation under conditions where the receiver is located close to a radar installation employing commonly used models of Navy radar equipments.

SPARK-NOISE INTERFERENCE

Introduction

Various experiments with intense received random noise were performed to yield information as to the respective performance of the two systems. A corona-isolated spark oscillator was developed and used for this purpose, this oscillator providing a noise source having an approximate random noise distribution over the radio-frequency spectrum around 328.2 megacycles, the receiver resonant frequency during these tests

Spark-Noise Oscillator

The noise source consisted of a quarter-wave tuned rod operating against a ground plane, together with associated damping resistances and a quarter-wave pick-up probe. The oscillating element was a 1/8-inch diameter brass rod, 8-1/2 inches long, mounted vertically with its lower end spaced about 0.01 inch from a horizontal sheet of duralumin. The top of this rod was fitted with a slightly convex brass disc about 5/8-inch in diameter.

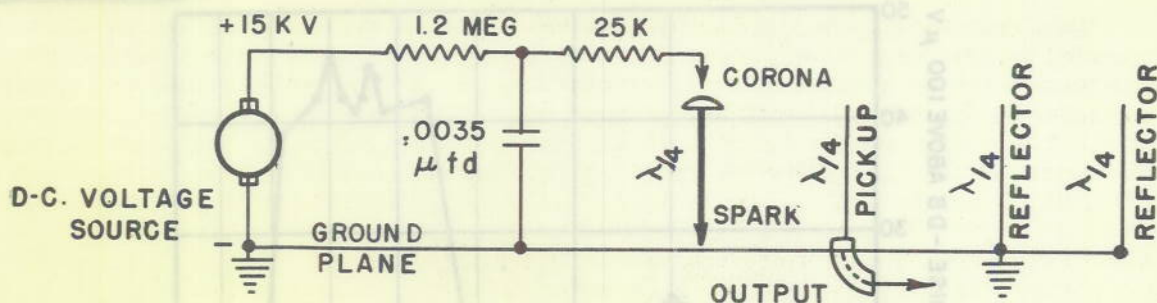


Fig. 29 - Schematic diagram of spark-noise generator

A 1-inch length of 16 gauge copper wire was mounted so that its flat circular end was parallel to and 1/2-inch removed from center of the disc. This copper wire was connected to a 25,000-ohm damping resistor which, in turn, was attached to a 15,000 volt direct-current source of potential through a resistance-capacity filter. A diagram of the circuit is shown in Figure 29. An 8-1/2-inch vertical pick-up rod, soldered to a Type-N chassis connector was mounted on the duralumin sheet 2 inches from the oscillating element. This rod was connected through the coaxial fitting to a length of 50-ohm lossy cable and thence to the equipment utilizing the noise source. The other vertical rods were mounted as reflectors on the duralumin ground plane in positions which increased the energy pick-up at 328.2 megacycles.

In operation, a steady, purple, hissing glow discharge was obtained between the wire and disc, while a small, bright spark was observed between the oscillating element and its ground plane. Both discharges were stable as long as the electrodes were kept clean. The spark-oscillator generated a noise which was indistinguishable by aural or oscillographic means from ordinary receiver output noise.

It is well known that various types of noise meters indicate different intensities for the same noise source. A Navy Type OCV Noise Meter was chosen for determining the level of noise in these measurements as its band-pass, time-constants, and other characteristics have been standardized. Among these are:

Selectivity: 210 kilocycles at 6 db down

Sensitivity: 5 microvolts

A-F Response: ± 3 db from its 1000 cycle response between 200 and 2000 cycles

Time Constants in Meter Circuit: 5 milliseconds on charge, and 600 milliseconds on discharge, for "Quasi-Peak" measurements.

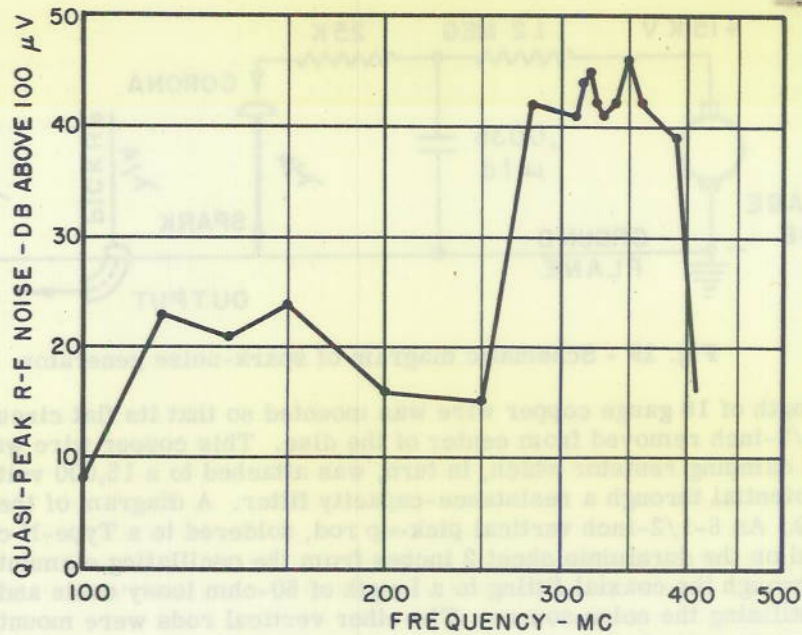
The intensity of radio-frequency noise was measured by coupling the Type OCV Noise Meter through its input transformer and a calibrated length of 50-ohm lossy cable. The "meter selector" switch was set at "Quasi-Peak" for all measurements. The r-f noise spectrum of the spark oscillator observed with the noise meter is plotted in Figure 30A. A maximum noise level of 20,000 microvolts occurred around 350 megacycles. No attempt was made to determine the true peaks of the noise because of the difficulty of obtaining significant data.

The audio spectrum of the noise source was measured at the noise meter output by means of a General Radio Type 736-A Wave Analyzer. With the noise meter tuned to 328.2 megacycles, the audio distribution appeared as shown in Figure 30B. The curve corresponds closely to the audio frequency characteristic of the Type OCV Noise Meter, which indicates that the original noise amplitude was essentially uniform over the audio spectrum used by the transmitting and receiving equipments under consideration.

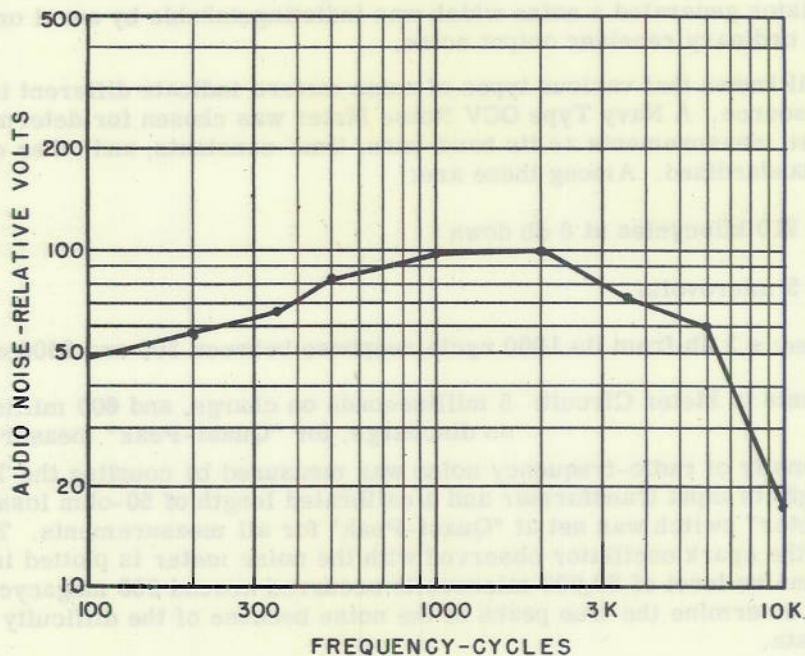
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A - Radio spectrum of spark-noise generator



B - Audio spectrum of spark-noise generator

Fig. 30 - Characteristics of the spark-noise generator

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Method of Investigation

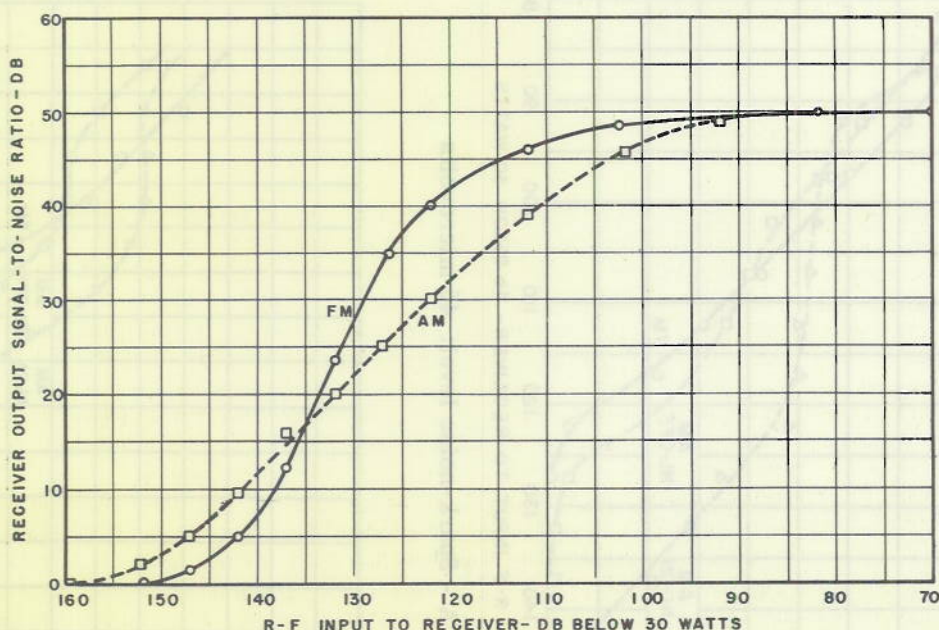
The circuit arrangement shown in Figure 1 was also used in these tests. The general practices followed in studying two-signal operation were employed in this instance except that the undesired signal source consisted of the spark-noise oscillator instead of an a-m or f-m transmitter.

The a-m receiver incorporates a series-diode type of noise limiter. In the f-m receiver this diode is used as part of the circuitry for the ratio detector, so the f-m receiver has no audio noise limiter. Data were taken with the limiter in the a-m receiver both "ON" and "OFF," and with AVC both "ON" and "OFF" in the f-m and a-m receivers. Transmitter modulation, where used, was with 1000-cycle tone, and full modulation or full deviation was always employed during the modulated condition.

Investigations were made with moderate, strong, and intense levels of spark noise. These levels were approximately 45, 250, and 3,000 microvolts "Quasi-Peak" at the receiver input. The desired signal level from the transmitter was varied in steps from approximately 80 to 150 db below 30 watts. At each level, the receiver output signal-to-noise ratio without noise interference and the output signal-to-interference ratio were measured.

Results

The output signal-to-noise ratio characteristics of the a-m and f-m receivers in the absence of interference are presented in Figure 31. These curves are similar to the range trial curves previously presented, with cross-over occurring at a 17-db signal-to-noise ratio. Comparison of the two communication systems with spark-noise interference levels of 45, 250, and 3,000 microvolts at the receiver input with AVC "ON" are shown in Figure 32. Similar curves for AVC "OFF" are shown in Figure 33.

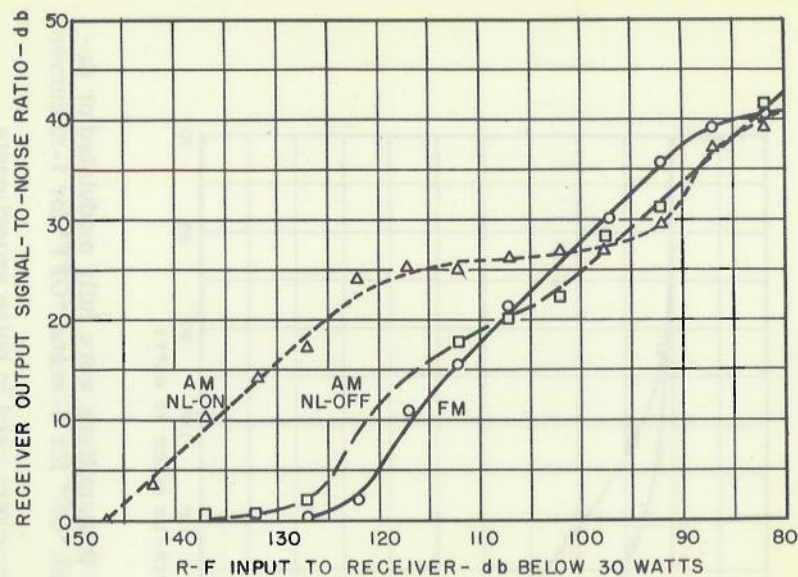


Notes: Operating frequency: 328.2 Mc. The transmitters were fully modulated or deviated with 1000-cycle tone. Receiver AVC was "ON" for a-m and "OFF" for f-m curves.

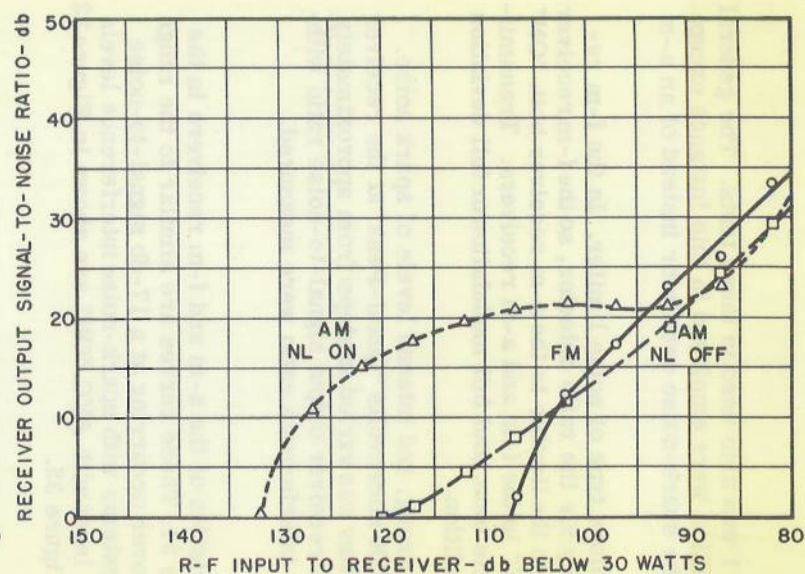
Fig. 31 - Range characteristics of receivers used in noise experiments

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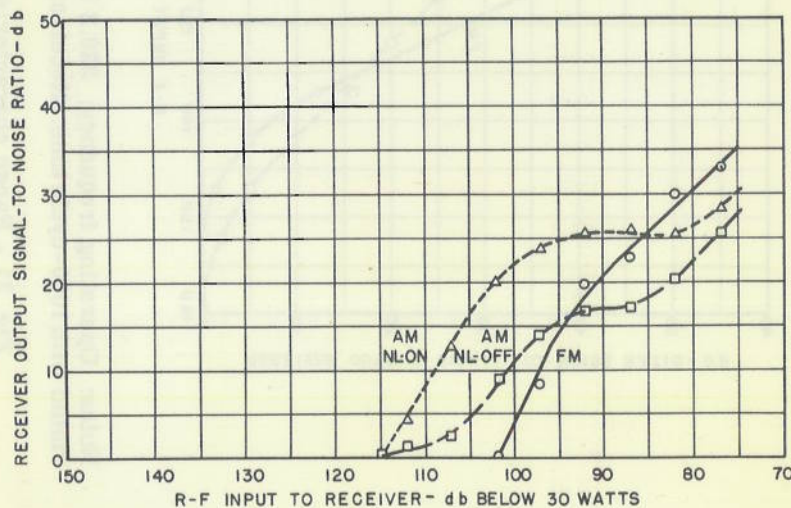
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A - Spark-noise level: 45 microvolts



B - Spark-noise level: 250 microvolts



C - Spark-noise level: 3000 Mc

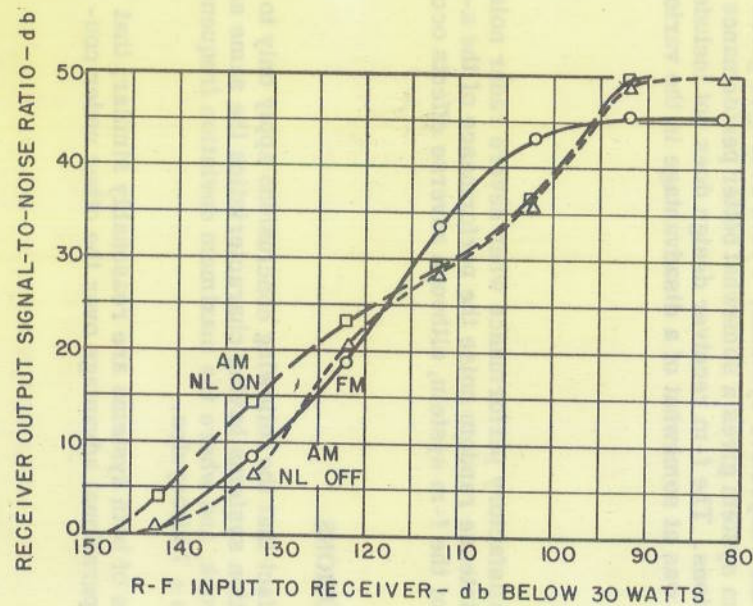
Fig. 32 - Comparison of noise characteristics of the two communication systems with AVC "ON" for several levels of spark-noise

Notes: Operating frequency: 328.2 Mc.
Transmitters were fully modulated or deviated by 1000-cycle tone

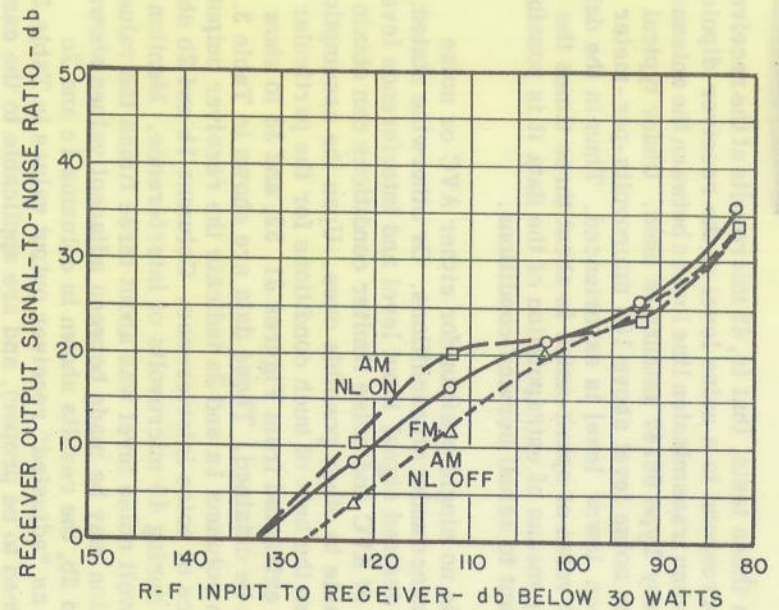
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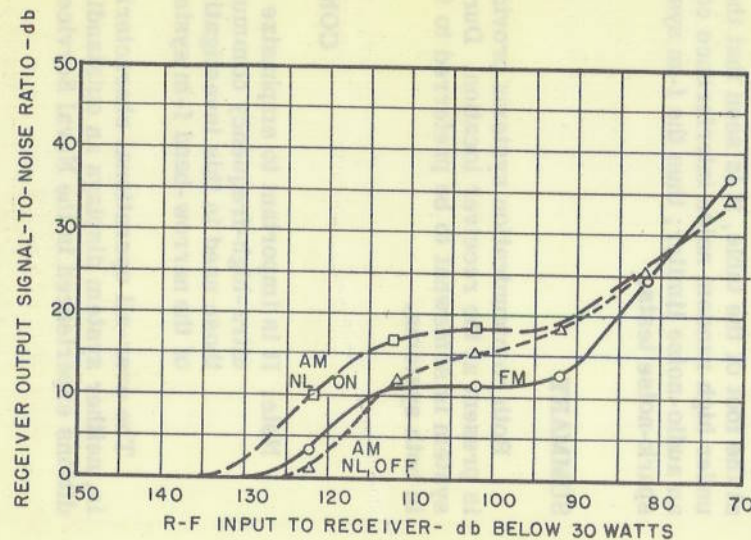
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A - Spark-noise level: 45 microvolts



B - Spark-noise level: 250 microvolts



C - Spark-noise level: 3000 microvolts

Fig. 33 - Comparison of noise characteristics of the two communication systems with AVC "OFF" for several levels of spark-noise

Notes: Operating frequency: 328.2 Mc.
Transmitters were fully modulated or
deviated by 1000-cycle tone

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The lowest level of spark-noise used in these tests, that is, 45 microvolts at the receiver input terminal, would in actual practice correspond to a noise level at the receiver dipole antenna of about 315 microvolts-per-meter when transmission line losses between the antenna and receiver are disregarded and when a Navy Type 66147 antenna is used. Under typical operating conditions on Navy craft, a random noise level above 100 microvolts-per-meter is seldom exceeded and in most cases a much lower level is experienced. Thus in the data shown in Figures 32 and 33, even the lowest value of spark-noise is about three times the maximum level encountered in practice. By means of extrapolation of the data it is possible, however, to make the results more significant to actual service conditions.

According to Figures 32 and 33, there is no single position for either AVC or noise limiter controls to provide optimum performance under all conditions. Or otherwise stated: for either system, during any given receiver desired signal input level and interference level combination, the operator by proper choice of AVC and noise limiter conditions can obtain reception characteristics which are preferable to other possible ones. Upon the assumption that in actual service the operator would choose the best of such conditions for the particular situation prevailing, certain data have been extracted from Figures 31, 32, and 33 to show the nature of performance which would then be obtained. These data are shown in Table 3. At various receiver input levels, the data in columns 1a and 2a indicate the receiver output for both systems respectively, in the absence of noise interference. Columns 1b and 2b show the receiver output from the desired signal during 45 microvolts of interference. Mention has been made of the fact that the 45-microvolt noise level was about three times the value anticipated in practice, thus if an interpolation may be made between adjacent values shown in columns 1a and 1b, and in columns 2a and 2b, the results shown in columns 1c and 2c are obtainable. These data are referred to as "adjusted" receiver output values in Table 3, were obtained by linear interpolation (assumed to be proper), and are applicable to the case of a noise level of 15 microvolts. The remaining columns show "adjusted" loss in receiver output due to a 15-microvolt noise level for the respective systems. From averages given at the foot of the table, it is seen that the a-m system gives a somewhat better performance under high random noise interference conditions. The f-m receiver design does not include an audio-noise limiter; thus the f-m system was at somewhat of a disadvantage in the various spark-noise tests.

SUMMARY

Both communication systems provide satisfactory performance when severe radar noise is present at the receiver location. During intense random noise the performance of the a-m system is somewhat to be preferred to that of the f-m system, although adverse effects occur in both systems.

CONCLUSIONS

Note: It is important to emphasize the fact that the following conclusions apply only to ultra-high-frequency communication systems having characteristics the same as those used in this investigative work, and where the maximum deviation frequency of the narrow-band f-m system is ± 7 kilocycles.

The over-all operational characteristics of both systems are reasonably similar; that is, neither system displays an outstanding operational advantage over the other under conditions experienced in the Naval Service.

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TABLE 3
SUMMARY OF SPARK-NOISE DATA
(Spark-Noise Level = $45 \mu v$)

	a-m System				f-m System			
	(1a)	(1b)	(1c)	(1d)	(2a)	(2b)	(2c)	(2d)
Received Signal Level (db below 30 watts)	Receiver Output S/N Ratio without Interference (db)	Receiver Output S/N Ratio with Interference (db)	Adjusted Receiver Output S/N Ratio with Interference (db)	Adjusted Loss in Receiver Output S/N Ratio with Interference (db)	Receiver Output S/N Ratio without Interference (db)	Receiver Output S/N Ratio with Interference (db)	Adjusted Receiver Output S/N Ratio with Interference (db)	Adjusted Loss in Receiver Output S/N Ratio with Interference (db)
147	5	0	-	-	1	-	-	-
142	10	4	8	2	5	0	-	-
137	15	9	13	2	11	4	8.7	2.3
132	20	14	18	2	23	8	18	5.0
127	25	18	22.7	2.3	35	13	27.7	7.3
122	30	22	27.3	2.7	40	18	32.7	7.3
117	35	26	32	3.0	43	26	37.3	5.7
111	40	30	36.7	3.3	46	36	42.7	3.3
104	45	35	42	3.0	48	41	45.7	2.3
85	50	50	0	0	50	45	48.3	1.7
			Average: 2.5				Average: 4.1	

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Range: The a-m system provides a somewhat greater range of communication; however, the f-m system yields a greater receiver output signal-to-noise ratio at shorter ranges.

Co-Channel Operation: The a-m system performs more satisfactorily on the basis that capture and auditory masking effects are less.

Adjacent-Channel Operation: The f-m system performance is preferable on the basis that closer channel spacing is possible for the same degradation of word-list intelligibility.

Interference: Both systems function without impairment where intense impulse interference such as radar noise is present at the point of reception. When high level spark noise is present at the point of reception, however, the performance of the a-m system is somewhat to be preferred.

For more expanded statements as to the respective performance of the two systems under each of the four above categories, refer to the detailed summaries for each on pages 19, 25, 41, and 50.

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