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# COMPARISON OF AM AND NARROW-BAND FM UHF COMMUNICATION SYSTEMS FINAL SUMMARY REPORT AND APPENDIX A

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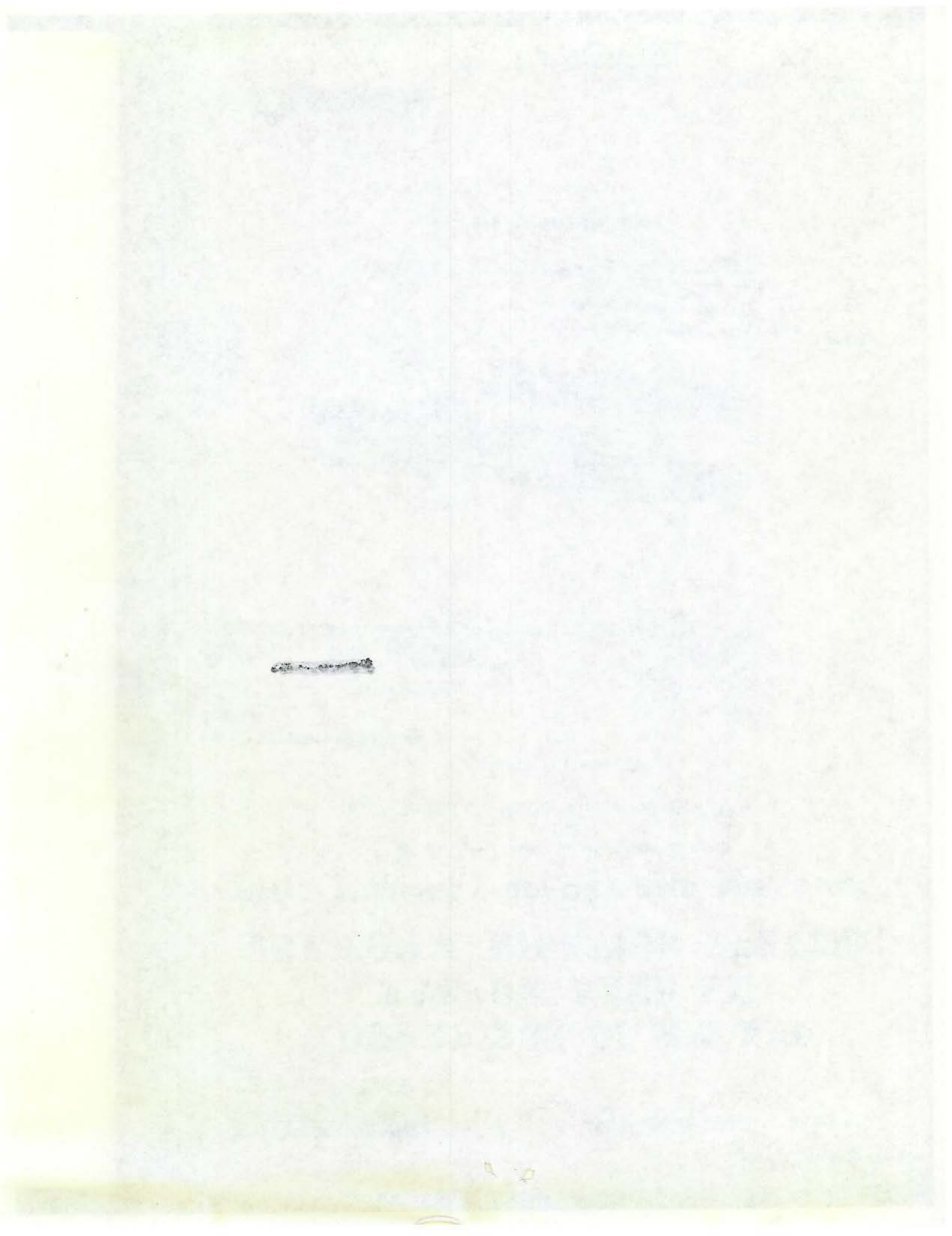
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CONTENTS

Abstract iii

Problem Status iv

Authorization iv

INTRODUCTION 1

    General Considerations 1

    Operational Conditions 2

    Choice of FM Detector 3

    Transmitting and Receiving Equipments 4

    Standardization 7

    Records and Maintenance 8

TRIALS 8

    Laboratory 8

    Field 9

    Conditions Established 9

    Range 11

    Noise 11

    Common-Channel Operation 12

    Adjacent-Channel Operation 12

TRIAL RESULTS 13

    Range 13

    Radar Interference 15

    Impulse-Noise 16

    Common-Channel Operation 16

    Adjacent-Channel Operation 18

THEORETICAL PERFORMANCE 21

    FM Output Signal-to-Noise Ratio with No Limiting 21

    FM Output Signal-to-Noise Ratio with Ideal Limiting 22

    AM Output Signal-to-Noise Ratio 23

    Theoretical "Range" Curves 23

    Experimental "Range" Curves 24

    Computed Effect of Detuning 25

    Effect of Improved Limiting on Performance with Impulse Noise 27

    Influence of Limiting on Common- and Adjacent-Channel Performance 28

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DISCUSSION OF RESULTS	29
Range	29
Noise Interference	31
Common-Channel Operation	32
Adjacent-Channel Operation	33
OTHER FACTORS CONSIDERED	34
Multi-Path Propagation	34
Pre-Emphasis and De-Emphasis	35
Theoretical Improvement Afforded by Emphasis	36
GENERAL DESIGN CONSIDERATIONS	37
Transmitters	37
Receivers	38
SUMMARY OF COMPARATIVE AM/FM PERFORMANCE	39
CONCLUSIONS	39
RECOMMENDATIONS	41
ACKNOWLEDGMENTS	41
APPENDIX A - Background Information	42

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Previous Reports in This Series

- (1) NRL Reports R-3231 through R-3235 inclusive, entitled "Comparison of Amplitude-Modulated and Narrow-Band Frequency - Modulated Ultra-High-Frequency Communication Systems," subtitled as follows:

NRL Report R-3231, "Appendix B, Theoretical Considerations," 17 March 1950

NRL Report R-3232, "Appendix C, Design and Performance Characteristics of Equipment Employed," 11 March 1948

NRL Report R-3233, "Appendix D, Laboratory Studies and Investigations," 18 February 1949

NRL Report R-3234, "Appendix E, Shipboard Studies and Investigations," 8 March 1948

NRL Report R-3235, "Appendix F, Airborne Studies and Investigations," 3 June 1948

- (2) NRL Letter Report R-1220-170/47 (1210-1221) of 15 October 1947 to Chief BuShips
- (3) NRL Letter Report R-3920-151/48 of 22 July 1948

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## ABSTRACT

The performance of two equivalent uhf voice communications systems, one amplitude-modulated and the other narrow-band frequency-modulated, is presented in comparative form. The carrier frequency for these studies was 328.2 Mc and the deviation for the FM case was  $\pm 7$  kc. A ratio-type FM detector was used in the FM receivers. One- and two-signal conditions were set up and investigated in the laboratory and field. Output signal-to-noise ratio was used as the quantitative measure of system performance, along with qualitative evaluations based on listening tests.

A comprehensive theoretical study was conducted to establish criteria of ideal performance and to derive equations for computing theoretical limits. The characteristics of the transmitting and receiving equipments used (Models TDZ and RDZ) were carefully determined, and the various units were "standardized" in AM/FM pairs. The laboratory system trials utilized calibrated lossy cables and uhf attenuators for simulated propagation paths. The shipboard trials employed installations on an AGC and two smaller vessels operating at sea. The aircraft trials utilized an air-to-ground circuit at the Laboratory's Chesapeake Bay Annex (ARC-13 transmitter, RDZ receiver). Laboratory studies were made to determine the reduction in performance resulting from use of a ratio-type detector in place of one with more nearly ideal limiting. Performance measurements and observations were made to determine single-signal range of communications. The effects of interfering signals on the same channel and on adjacent channels were studied, as well as the changes in performance resulting from spark-noise and radar interference. The influence of audio-frequency emphasis was investigated in laboratory measurements and also mathematically. Multi-path propagation was considered. The effect of type of modulation on equipment design factors, such as size and weight, was examined.

The general conclusion was reached that for the highly mobile terminal conditions typical of much of the Naval service, AM is preferable to FM. In brief, it was found that the AM signal occupied less of the radio spectrum, gave better weak-signal performance (fringe-area reception), greater freedom from co-channel and adjacent-channel capture effects, was much more tolerant of circuit misalignment and detuning, and the equipment was generally simpler in design and easier to adjust and maintain. The FM system provided about 10 db higher output signal-to-noise ratio on medium and strong input signals, was advantageous for "high-fidelity" or wide-band low-distortion reproduction, required less transmitter power but also more complex transmitter and receiver circuitry, and permitted closer adjacent-channel frequency spacing (by a ratio of about 2 to 3) under conditions of strong-signal interference which produced cross-modulation and signal-to-noise ratio-depression effects. In general, FM should be considered for use in high-frequency systems with both terminals geographically fixed.

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The theoretical treatment evolved in the course of this problem was capable of ready extension to other conditions of carrier frequency, modulation frequency, and deviation. Future questions of relative AM/FM performance could be largely answered by rapid and fairly simple computations of ideal performance, with a minimum of costly and elaborate laboratory and field tests required for substantiation.

PROBLEM STATUS

This report completes work on this problem; unless otherwise notified by the Bureau, the Laboratory will close this problem one month from the mailing date of this report.

AUTHORIZATION

NRL Problem R01-12  
RDB Project NR 501-120

Manuscript submitted April 23, 1952

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**COMPARISON OF AM AND NARROW-BAND FM  
UHF COMMUNICATION SYSTEMS****FINAL SUMMARY REPORT AND APPENDIX A****INTRODUCTION****General Considerations**

The investigation covered in this report was undertaken by the Naval Research Laboratory at the request of the Bureau of Ships, Navy Department.<sup>1</sup> It is the latest of similar studies made by the Navy in past years for guidance in choice of modulation type. Every effort was made during its course to insure that it was as thorough and careful a comparison of the two basic methods of modulating a radio wave as could be devised.

An ideal fundamental comparison of relative AM and FM performance might be made with equal spectrum occupancy and equal radiated power at maximum modulation as basic conditions. The investigation herein reported, however, was conducted with some departure from this ideal. Practical considerations dictated use of a frequency-deviation which resulted in greater spectrum occupancy by the FM signal than by the AM signal, and it was found more feasible in both the experimental and theoretical phases of the problem to make the unmodulated rather than the modulated power output of the two transmitters equal.

Any valid operational comparison must be based on identical equipment for both modulation systems, or on equipment with known, accountable differences. The comparison trials described in this report were made with transmitters and receivers which were identical except for essential differences in the modulator and demodulator elements, and with identical antenna installations. In addition to laboratory and field operational trials,<sup>2</sup> a mathematical study<sup>3</sup> of comparative AM/FM performance was undertaken with the intent of determining the applicable theoretical limits, particularly in the weak-signal region into which then available theoretical treatments did not appear to extend.

Examination of all available records of other AM/FM comparison trials and investigations has indicated one common shortcoming: In general, the published data on equipment characteristics and operating conditions have been too meager to permit any sound judgement by the reader as to the validity of the tests and the conclusions derived therefrom. The following information concerning operational conditions, equipment characteristics, and data taken is therefore included as a guide to independent judgement and to anticipate some of the inevitable questions.

<sup>1</sup> BuShips ltr. 3653(925B) of 18 November 1946

<sup>2</sup> NRL Reports R-3233, R-3234, R-3235

<sup>3</sup> NRL Report R-3231

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## Operational Conditions

In a radio communication system, the receiver bandwidth prior to the final detector is usually determined by the spectrum occupancy of the radiated signal plus the combined frequency stability of transmitter and receiver. In the case of the equipment chosen for this investigation, this bandwidth was 125 kc at -6 db, a figure determined mainly by the frequency-stability consideration. The increased spectrum occupancy of an FM signal with a modulation index ( $m_f$ ) of more than 1 could therefore be tolerated, provided that it did not exceed a value of about  $\pm 10$  kc. A figure for  $m_f$  of about 2.3 was adopted, based on a nominal top modulation frequency of 3000 cps. This resulted in a maximum frequency-deviation value of  $\pm 7$  kc, as compared to a maximum AM spectrum of  $\pm 3$  kc. Such a relatively small difference between AM and FM spectra (considering the important side-bands only) in an over-all bandwidth of 125 kc made it practicable to keep the receiver bandwidth the same for both types of modulation. A value of  $m_f = 1$  would have resulted in a maximum deviation of  $\pm 3$  kc, representing only  $\pm 0.0009$  percent frequency variation at the carrier frequency used in the tests. Such small variations are difficult to monitor; the errors in measured results would consequently have been greater.

The reference or desired-signal frequency used throughout the trials was generally 328.2 Mc, although in a few cases a slightly different frequency was employed. This frequency was chosen mainly on the basis of a minimum number and amplitude of spurious responses for the transmitter-receiver combination employed.<sup>4</sup> The over-all audio response range of the equipment was approximately 300 to 3000 cps, corresponding to a maximum intelligibility or articulation factor for ideal conditions with male speech of about 90 percent (1 word in 10 misunderstood). Figure 1 shows the over-all audio frequency characteristic of the transmitter-receiver combinations, together with a curve of over-all harmonic distortion.<sup>5</sup> The receiving equipment was used in "narrow-audio" condition; the receivers, as determined by signal-generator tests, had a measured harmonic distortion of well under 2 percent at 1000 cps for 30 percent AM operation and less than 0.5 percent with FM up to  $\pm 20$ -kc deviation.

It was decided, for ease of setting-up and measurement of operating conditions, that all single-tone modulation tests would be made at 100 percent modulation with AM and maximum or peak deviation ( $\pm 7$  kc) with FM. The actual adjustment of modulation voltage in the FM transmitters was accomplished by using the carrier drop-out at  $m_f = 2.4$ , as observed with spectrum-scanning equipment at a modulating frequency of 2910 cps. Voice modulation was maintained at 30 percent average in the AM system and at about  $\pm 2.1$ -kc average with FM. No pre-emphasis or de-emphasis was utilized in the trials since, with the i-f and a-f bandwidths employed, both modulation systems were assumed to be about equally capable of improvement by this means. Subsequent theoretical and laboratory investigations<sup>6</sup> were made to determine the effects of emphasis.

<sup>4</sup> Additional information may be found in NRL Report R-2967, "Interference Analysis of 100 Primary Communication Channels, 225-400 Mc (TDZ-RDZ Equipments)."

<sup>5</sup> Figure 1 combines the information in the graphs in NRL Report R-3232, p. 38-39

<sup>6</sup> NRL Report R-3422, "Investigation and Analysis of 'Capture Effect' in FM and AM Communication Systems," p. 29; NRL Letter Report R-3910-64/49, "Investigation of Preemphasis-Deemphasis for U-H-F AM Voice Communication"; NRL Report R-3231, p. 47-51

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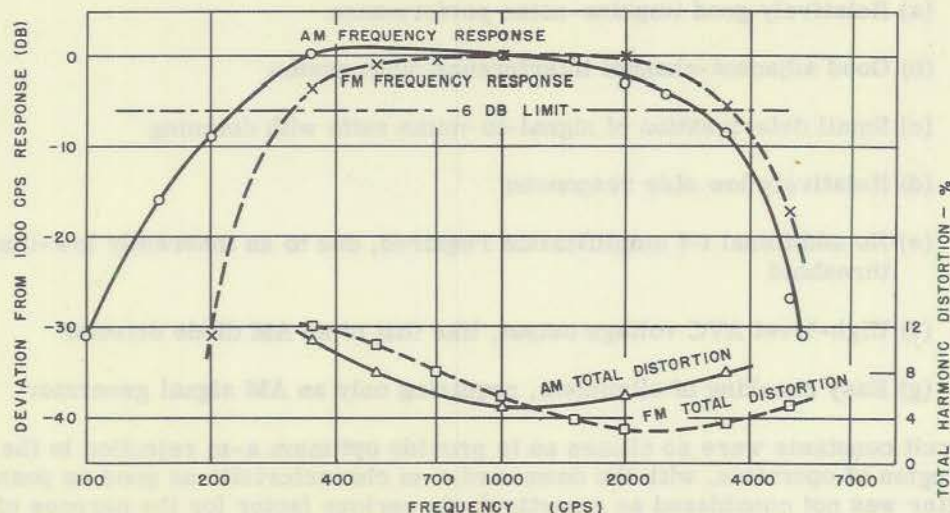


Figure 1 - Audio-frequency response over-all and total audio harmonic-distortion of AM and FM transmitter-receiver combinations

All output signal-to-noise ratio figures in the graphs and discussions that follow are rms values measured with 100 percent modulation for AM and  $\pm 7$  kc deviation for FM, both with 1000-cps tone modulation, unless otherwise stated. Thus, if a figure of +30 db output S/N ratio is given, it would be about 10 db less, or +20 db, for 30 percent AM or  $\pm 2.1$ -kc deviation with FM.

#### Choice of FM Detector

Much thought was given to choice of the FM limiter and detector combination for the receiving equipment.<sup>7</sup> It was considered essential that, in addition to suitable operating characteristics, this portion of the FM system should not require any considerable design differences in the circuits preceding it, so that gain, selectivity, and all other characteristics up to the final demodulator stage itself would be identical in both the AM and FM receivers. Grid-bias, plate-saturation type limiters were considered and rejected as unsatisfactory from the standpoint of relatively poor impulse-noise limiting, inferior adjacent-channel performance, and relatively high limiting threshold; this latter would have required an additional stage of i-f amplification, which was inadmissible. After examination of the various other possible arrangements, such as the locked-oscillator types, etc., the so-called ratio-detector was chosen as the best compromise, with the intent that a subsequent theoretical analysis would be undertaken before closing of the AM/FM comparison problem to determine how far the ratio-detector as used caused departure from the theoretical optimum performance of an ideal FM system.

The ratio-detector is essentially a phase-discriminator with current-balance rectifiers, arranged to provide simultaneous detection and half-wave shunt-diode limiting in the discriminator-secondary circuit. In this application, it provided the following advantages:

<sup>7</sup> NRL Report R-3232, p. 4-5 (See footnote p. 5); limiters were also treated in NRL Report R-3375, "Amplitude Limiters"

- (a) Relatively good impulse-noise performance
- (b) Good adjacent-channel interference suppression
- (c) Small deterioration of signal-to-noise ratio with detuning
- (d) Relatively low side responses
- (e) No additional i-f amplification required, due to an inherently low-limiting threshold
- (f) High-level AVC voltage output, like that of an AM diode detector
- (g) Easy checking of alignment, requiring only an AM signal generator

The circuit constants were so chosen as to provide optimum a-m rejection in the weak-signal region of operation, with the downward a-m characteristic as good as possible.<sup>8</sup> This latter was not considered as a particularly serious factor for the purpose of most of the tests, since main reliance was to be placed on the results of laboratory trials, where fading or multi-path propagation would not be encountered. It could, however, be a factor in the field tests, provided that the average signal energy reaching the FM detector fluctuated to a considerable extent at a rate faster than about one-fifth of a second, a figure determined mainly by the detector time-constant. Distortion measurements taken over-all showed that the detector linearity was good, the over-all harmonic distortion of the receiver being less than 0.5 percent up to  $\pm 20$  kc deviation with proper centering of the carrier on the discriminator characteristic.

#### Transmitting and Receiving Equipments

The transmitting equipments utilized are shown in block-diagram form in Figure 2. Elements A, B, C, D, and E were identical in both the AM and the FM equipments; elements G and H were substituted in the FM transmitter for element F of the AM transmitter. The AM modulator controlled the plate current of the final r-f amplifier and was required to be capable of supplying as much a-f power as needed for 100 percent modulation of the carrier. The integrating network and phase modulator which provided FM, however, operated at a low power level and demanded much less primary power input than the AM modulator.

The receiving equipments are shown in block-diagram form in Figure 3. Elements A, B, C, D, E, and F were identical in both the AM and the FM equipments; element I was substituted in the FM receiver for elements G and H of the AM receiver. The duo-diode utilized for G and H was reconnected to provide the series-aiding diodes of a ratio-detector, and a suitable phase-discriminator transformer was substituted for the final i-f transformer normally used in the AM equipment. The space provided on terminal boards by removal of the AM detector and limiter components was utilized for the FM detector components. The result was a neat conversion, with essentially the same selectivity, reserve gain, freedom from regeneration, fidelity, etc., as the original AM form of the receiver.

<sup>8</sup> NRL Report R-3190, "Investigation and Study of the AM Reduction and Downward AM Characteristics of Three Forms of Ratio-Type FM Detector," NRL Report R-3194, "Development and Performance of a Ratio-Type FM Detector as Applied to the Model RDO Receiving Equipment"; NRL Report R-3231, p. 42-47

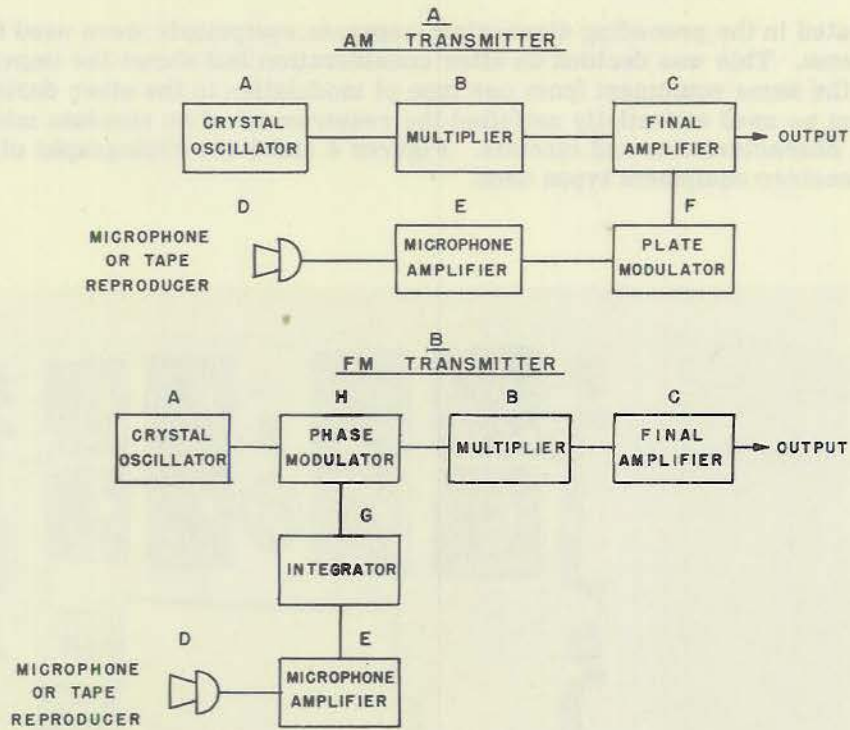


Figure 2 - Simplified block diagrams of (a) AM transmitter and (b) FM transmitter

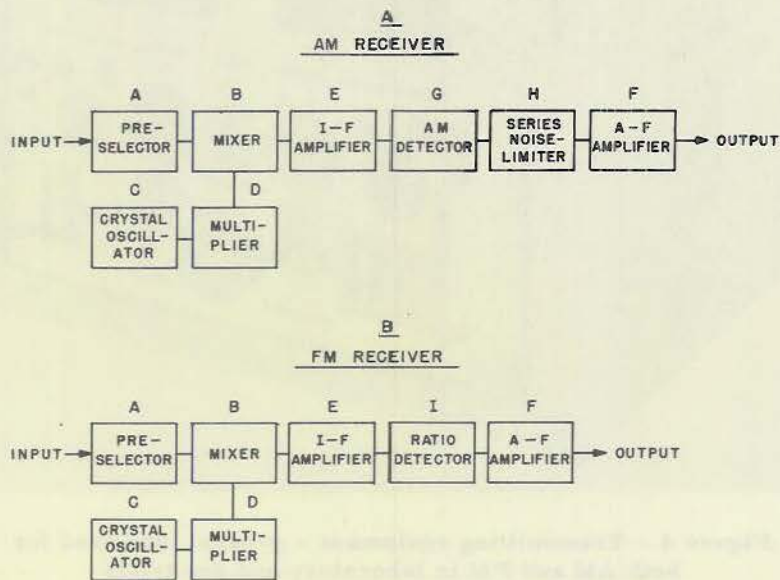


Figure 3 - Simplified block diagrams of (a) AM receiver and (b) FM receiver

As indicated in the preceding discussion, separate equipments were used for the AM and FM systems. This was decided on after consideration had shown the impracticality of switching the same equipment from one type of modulation to the other during the tests. The equipment as used essentially satisfied the requirement of an absolute minimum of difference in characteristics and circuits. Figures 4 and 5 are photographs of the transmitter and receiver equipment types used.

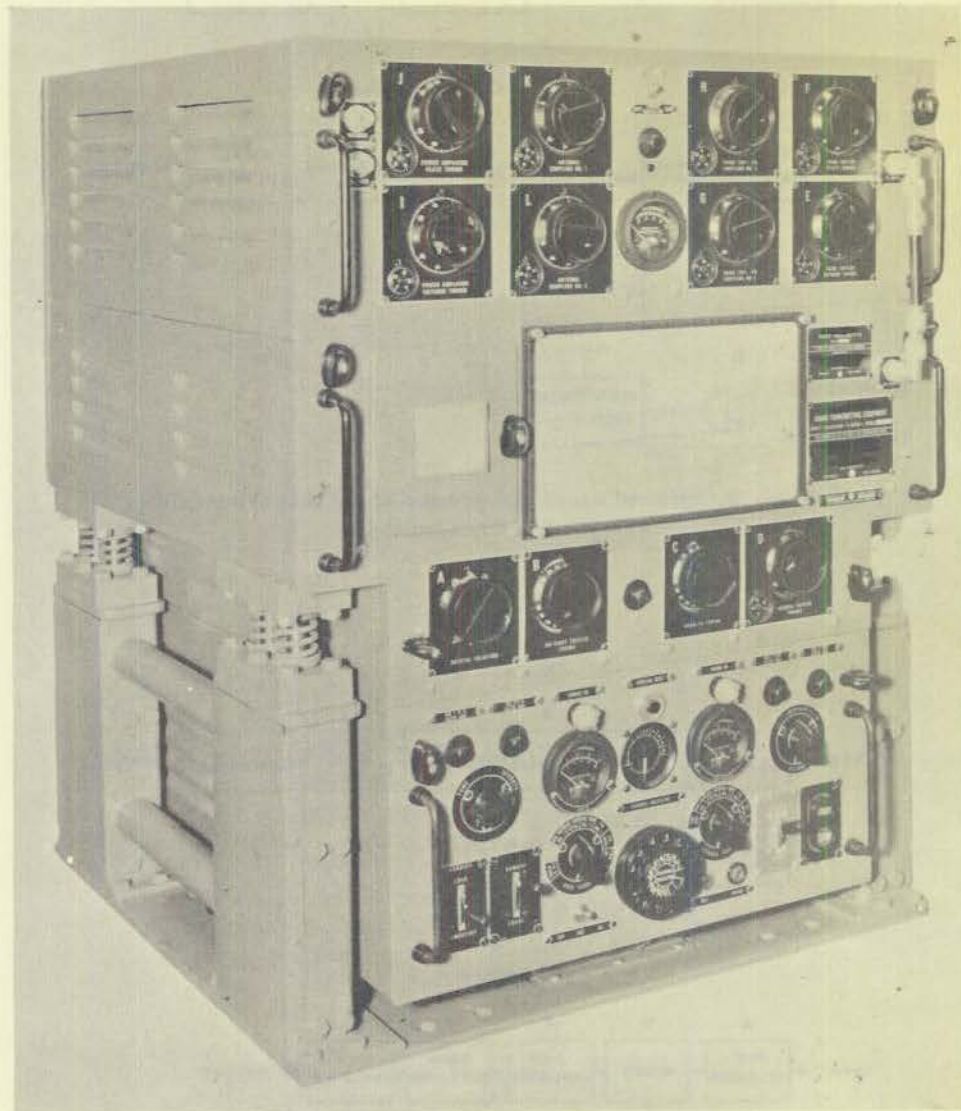


Figure 4 - Transmitting equipment - general type used for both AM and FM in laboratory and sea trials



Figure 5 - Receiving equipment - general type used for both AM and FM throughout all tests

#### Standardization

The performance characteristics of the AM transmitters and receivers had been thoroughly investigated prior to this problem.<sup>9</sup> Similar thorough studies were made of the FM transmitting and receiving equipment before starting the system trials.<sup>10</sup> The measurements included determination of the noise-factor (NF) of each receiver from the antenna circuit to the plate of the final i-f amplifier. The receivers were then "standardized" in pairs, a pair consisting of one AM and one FM equipment, each with NF within 1 db of the other.<sup>11</sup> It was subsequently found, as expected, that differences in standard sensitivity figures checked quite well with the differences observed in NF between receivers, and further checking of pairs for NF was done in terms of standard sensitivity. Standardized pairs were used throughout both the laboratory and field tests; these pairs were substantially identical in all characteristics, facilitating the segregation of differences

<sup>9</sup> NRL Report R-2667, "Test of Model CXHY (RDZ) Radio Receiving Equipment";  
NRL Report R-2929, "Test of Model RDZ-1 Radio Receiving Equipment";  
NRL Report R-2967; NRL Report R-3232, p. 1-4, 32-41

<sup>10</sup> NRL Report R-3232, p. 4-28, 32-41

NRL Report R-3232, p. 29

in system performance due to modulation-type by cancelling out, in effect, the equipment factor. It was found unnecessary to "standardize" the transmitters, since the unmodulated power output and degree of modulation, which were the factors of main importance, were easily adjusted and measured in each individual setup.

Since close alignment of the desired signal to the center frequency of the FM detector was considered essential for optimum and consistent results, a particular effort was made to select standardized or paired control crystals for each FM transmitter and companion receiver. The crystals were selected so that the FM system was within  $\pm 5$  kc of centering in its receiver pass-band at the signal frequency chosen, giving an over-all accuracy of about  $\pm 0.0015$  percent provided that the discriminator circuits were very accurately aligned. Similar standardized control-crystal pairs accurate within  $\pm 20$  kc were used for the AM equipments. Crystals were also selected for detuning, cross-modulation, and other off-channel tests.

### Records and Maintenance

Careful records of technical data and meticulous maintenance of equipment in top operating condition are essential in an investigation involving as many observers and tests as did the subject study. All pertinent and useful data were recorded in written form; additionally, magnetic-tape records were made of all significant audio output to permit subsequent comparison and evaluation by jury. The audio records were considered of particular importance in the analysis of such items as difference in character of noise output from the two systems, presence or absence of transient effects such as "swish," the auditory masking caused by heterodyne beats, and other conditions not apparent from meter readings alone. Paper-backed magnetic tape was used and recorded in modified Brush magnetic-recording equipment. This tape could be readily edited, permitting easy juxtaposition of significant sections for immediate comparison or the shortening of long runs of data to only the essential material for analysis. The frequency-response, dynamic range, and other important characteristics of the recording system were satisfactory for the purpose intended.

All transmitting equipment was thoroughly checked before each run, including such modulating equipment as was involved in the particular test. Transmitter power output and modulation level were carefully maintained during the runs. Likewise each receiver was checked for alignment, sensitivity, and bandwidth before each test, using calibrated standard signal generators, with particular attention to centering and symmetry of the FM detectors.

### TRIALS

#### Laboratory

The laboratory trials<sup>12</sup> utilized the receiving and transmitting equipments described above, with simulated propagation paths consisting of "lossy" cables and special attenuators of 50-ohm characteristic impedance. Figure 6 shows the setup in block-diagram form and Figure 7 is a photograph showing the physical arrangement of equipment. One or more signals could be simultaneously provided in the system; such signals could be any desired combination of modulated carriers, unmodulated carriers, and impulse-type noise.

<sup>12</sup> NRL Report R-3233

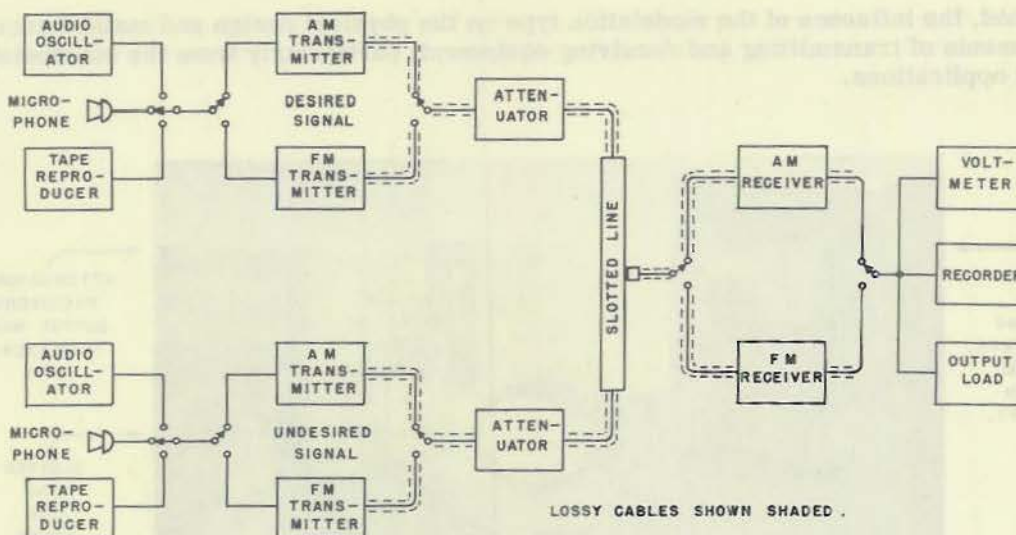


Figure 6 - Simplified block diagram of laboratory trials setup (transmitter wattmeters, spectrum analyzers, etc., not shown)

Intelligibility tests were made using standard word lists and also connected prose, and the relationship of intelligibility with both types of test material to the output signal-to-noise ratio with the approximately 300 to 3000 cps audio band utilized was established.<sup>13</sup>

Field

Sea trials<sup>14</sup> were conducted in cooperation with the Operational Development Force off the coast of Virginia. Three ships were utilized to permit controlled measurements under both single-signal and two-signal conditions. The radiation patterns<sup>15</sup> of all antennas used were carefully determined; these patterns were utilized in planning the ship's courses and allowable deviations therefrom, etc. Similar tests<sup>16</sup> were made of air-to-ground transmission, with the ground station located at one of the field activities of the Naval Research Laboratory, in cooperation with aircraft attached to the Naval Air Station, Patuxent, Maryland. Radar noise-interference tests<sup>17</sup> were made using facilities provided by the Naval Electronics School at the Naval Research Laboratory.

Conditions Established

There were two factors considered of major importance in this problem. The first was the relative operational performance obtained with the two types of modulation, and

<sup>13</sup> NRL Report R-3233, p. 16-19

<sup>14</sup> NRL Report R-3234

<sup>15</sup> NRL Report R-3234, p. 5-14

<sup>16</sup> NRL Report R-3235

<sup>17</sup> NRL Report R-3233, p. 42-44

the second, the influence of the modulation type on the physical design and maintenance requirements of transmitting and receiving equipment, particularly from the standpoint of naval applications.

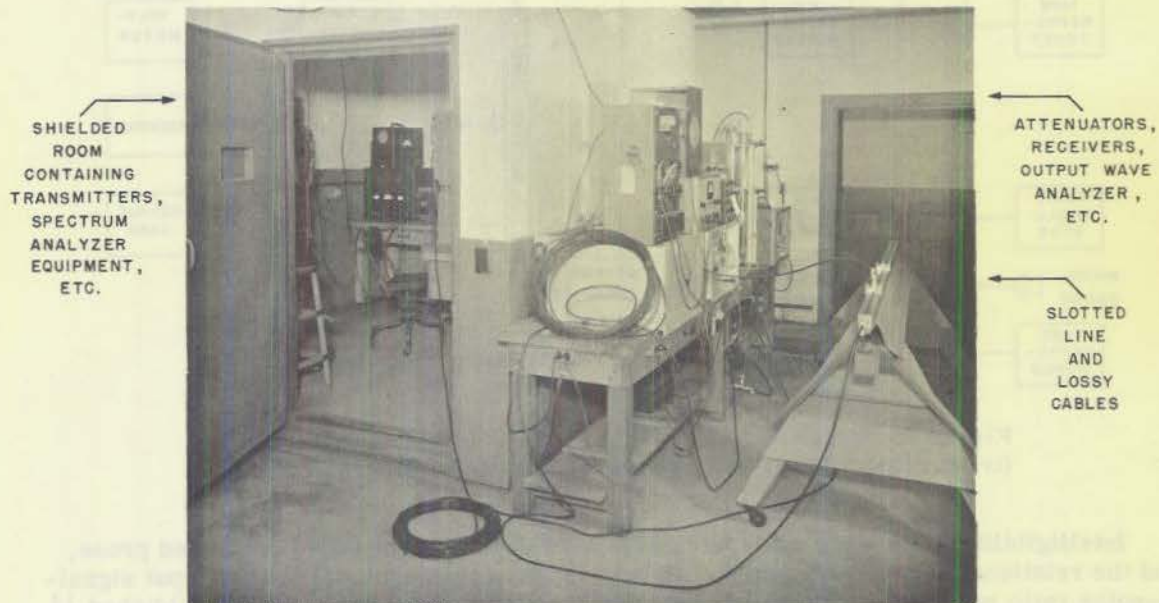


Figure 7 - Laboratory trials setup

Since the AM and FM systems under consideration were identical with respect to the gain and bandwidth of the audio, intermediate-frequency and radio-frequency portions of the receivers, it was feasible to make comparisons on the basis of the output signal-to-noise ratios (S/N) obtained for given values of carrier level at the input to the receiver equipment. The performance comparisons which follow are based on this premise. Many factors combine to make it difficult to designate any given single output S/N ratio as an absolute minimum standard of communication. A series of investigations was made, however, to establish an approximate "absolute low-limit" of output S/N below which intelligible voice communication should not be considered as normally possible without "repeats." This "absolute low-limit" rms S/N figure was found to be about +5 db (for peak or 100 percent modulation) for the audio band employed (approximately 300 to 3000 cps), as determined by laboratory intelligibility and field communication tests using connected prose.<sup>18</sup> The operational figure for minimum acceptable S/N ratio for "safe communication" employed by several military laboratories is between +16 and +20 db (for peak modulation). It is understood that figures of +30 db or over are generally preferred for good land-line telephone systems. It should be emphasized that the +5 db S/N value is an absolute low-limit for the 300 to 3000 cps audio band, which can be tolerated as a transient condition but not used as a design figure for safe-communication range.

In most tests the receiver output voltages, both signal and noise, were measured with vacuum-tube voltmeters which gave rms indication. In some cases the signal was separated from the noise by very sharp filters and corrected to give rms values.

<sup>18</sup> NRL Report R-3233, p. 16-19; NRL Report R-3234, p. 20

In evaluating any communication system, two major operational conditions require examination:

- (a) Single-signal operation, i.e., one signal carrier only present in the system, and
- (b) Multiple-signal operation, i.e., two or more signal carriers simultaneously present in the system.

In the comparisons reported herein, both single-signal and multiple-signal operations were investigated. Although many single-signal characteristics of the equipments used were separately studied and compared, the single-signal operational factor considered of greatest importance in this report is that of relative "range," which is indicative of relative radius of communication. In the multiple-signal case, three different conditions of operation were studied:

- (a) A desired signal in the presence of an undesired signal, where the undesired signal was in the form of spark or impulse noise (noise interference)
- (b) A desired signal in the presence of an undesired signal, where both had the same characteristics and the undesired signal was on the same carrier frequency as the desired signal (common-channel operation)
- (c) A desired signal in the presence of an undesired signal, where both had the same characteristics except that the undesired signal carrier was separated from the desired signal carrier by a frequency interval of one channel or more (adjacent-channel operation)

As indicated, multiple signal operation studies were confined to two-signal conditions; time, unfortunately, did not permit three-signal investigations.

#### Range

In the laboratory trials, the range data were obtained in terms of  $S+N/N$  output ratio versus db attenuation in the transmission path. In the field trials, the output  $S+N/N$  ratios were measured in the same manner as in the laboratory trials but the attenuation was determined in terms of distance. Data were taken in both cases which allowed conversion of the transmission-path attenuation and the distance into microvolts input to the receivers.

#### Noise

Two separate forms of noise interference were investigated, namely, radar interference and spark-noise interference. Radar effects were studied under the worst possible conditions of antenna spacings and equipment separation. No precautions were taken to filter the power lines of the equipments involved. The receivers used were energized from the same unfiltered power source as the radar equipments. Various pulse lengths, repetition rates and radar carrier-frequencies were selected with the intent of producing maximum interference with a desired signal. In the case of the spark-noise tests, a value of 45 microvolts spark noise (quasi-peak) was selected as representative of the general noise level which previous measurements had indicated would prevail under average naval shipboard conditions. It is considered doubtful, however, that a noise level as high as 45 microvolts would be encountered in the regions where UHF receiving antennas are normally located. Operation with other levels of spark-noise interference (250 and 3000 microvolts)

was also investigated, with substantially the same results as obtained with 45 microvolts. The spark-noise generator employed was essentially a spark transmitter tuned to provide maximum energy in the range of 280 to 380 Mc; its output spectrum resembled that produced by motor commutator noise.<sup>19</sup>

#### Common-Channel Operation

Two separate effects are encountered in common-channel operation. One of these is the so-called "capture effect," which manifests itself as a suppression or depression of the desired-signal output in the presence of an interfering signal on the same channel.<sup>20</sup> This effect normally occurs in both AM and FM systems, although to a different degree. If the two carriers are of identical frequency so that there is no resultant beat, or if the carriers are sufficiently displaced in frequency so that no audible beat is produced, the capture or signal-depression effect will be more apparent, generally accompanied by variation in output noise level. If the carrier separations are such that the heterodyne products fall in the audible range, heterodyne tone masking of the desired signal will occur, making it difficult to segregate the capture phenomena. In these trials, as previously mentioned, a consistent effort was made to secure identical carrier frequencies for both the desired and interfering signals. Due to unavoidable variations between the control crystals, audible heterodyne-tone effects were encountered in most cases. Therefore, common-channel operations were evaluated on two bases. In the laboratory trials, capture effects were segregated by the use of extremely sharp filters. The combined effects, in both the laboratory and field trials, were evaluated using speech intelligibility or articulation techniques. For the purpose of the capture effect comparisons, a depression of the desired signal output to 30 db below its interference-free level was chosen as the standard of comparison. This value of 30 db represents the maximum depression of desired signal output level beyond which it was considered no longer practicable, under normal operating conditions, to obtain intelligence from the desired signal in the presence of the interfering signal.

#### Adjacent-Channel Operation

In the adjacent-channel interference studies, the cross-modulation measurements were made employing the standard Navy techniques.<sup>21</sup> Some of the 30-db-below-30-watts interference measurements with AM were discontinued at separations of 2.4 Mc, since closer frequency spacings appeared to result in direct break-through. Information obtained subsequent to these measurements, however, indicated that direct break-through actually occurred at frequency spacings of about 1.2 Mc for both the AM and FM systems. The standard interfering signal level of 30 db below 30 watts (1.23 volts rms) was adopted as representing the maximum likely interference to be encountered in UHF shipboard installations with present transmitters. The output S/N ratio depression effects are considered to be largely caused by carrier interference phenomena in the limiters and final detector, with possibly some mixer saturation effects. The onset of these effects was indicated by desired signal output decrease or noise output level increase, or, more usually, by the occurrence of both changes simultaneously in the presence of the interfering signal.

<sup>19</sup> NRL Report R-3233, p. 42-44; NRL Report R-3234, p. 32; NRL Report R-3233, p. 42-

<sup>20</sup> Additional information may be found in NRL Report R-3422, NRL Report R-3460

<sup>21</sup> NRL Report R-3233, p. 25-31

TRIAL RESULTS

Range

The average of five laboratory range runs<sup>22</sup> is plotted in Figure 8. Increasing attenuation in the propagation path, shown as the abscissa, is equivalent to a decreasing level of signal input to the receivers, such as would result from "opening the range" in field tests. Figure 9 is part of the record of one of the field tests in the medium and weak signal region, made with two ships drawing apart in an open-sea area about 200 miles from land.<sup>23</sup> It shows the fluctuations in signal level which make field data more difficult to interpret than controlled laboratory test data. Figure 10 is a similar graph for air-to-ground transmission.<sup>24</sup> These last tests were characterized by very rapid fluctuations of signal input level, which tended to obscure differences in performance by introducing meter lag effects and increasing the difficulty of averaging input and output meter readings. In general, however, the data for all tests indicated a "crossover" of the AM and FM range curves at output S/N ratios between +14 and +20 db.

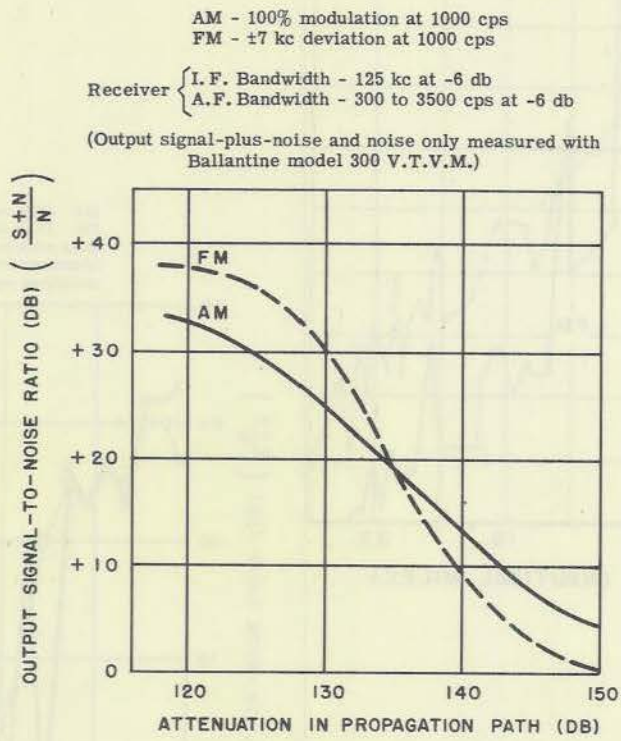


Figure 8 - Laboratory trials "Range" runs - medium and weak signal region; average of five tests (AVC OFF)

<sup>22</sup> Graphs of individual laboratory range runs with explanatory text material are included in NRL Report R-3233, p. 10-12

<sup>23</sup> NRL Report R-3234, p. 24

<sup>24</sup> NRL Report R-3235, p. 13

Medium and weak signal region  
 AM - 100% modulation  
 FM -  $\pm 7$  kc deviation  
 (Output signal-plus-noise and noise only measured with Ballantine model 300 V.T.V.M.) Same receiver conditions as in laboratory trials and same output measuring equipment

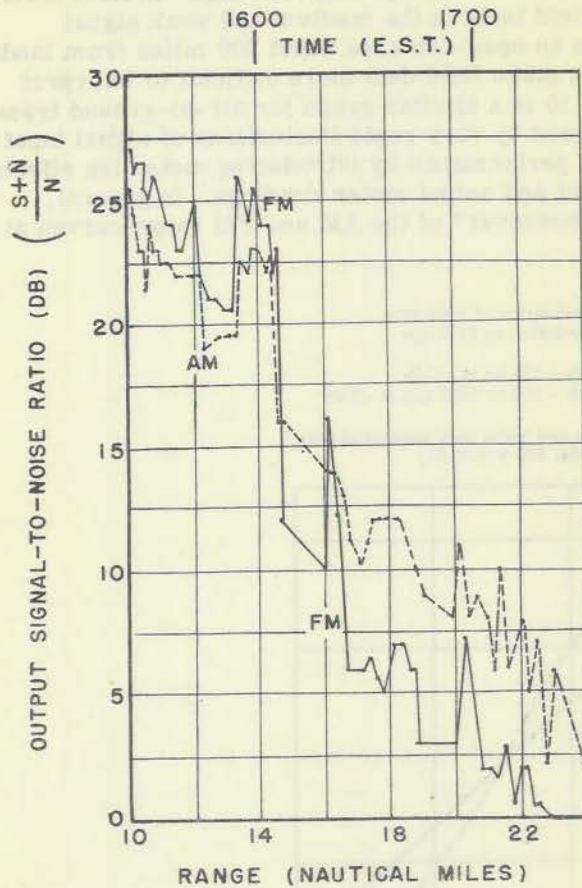
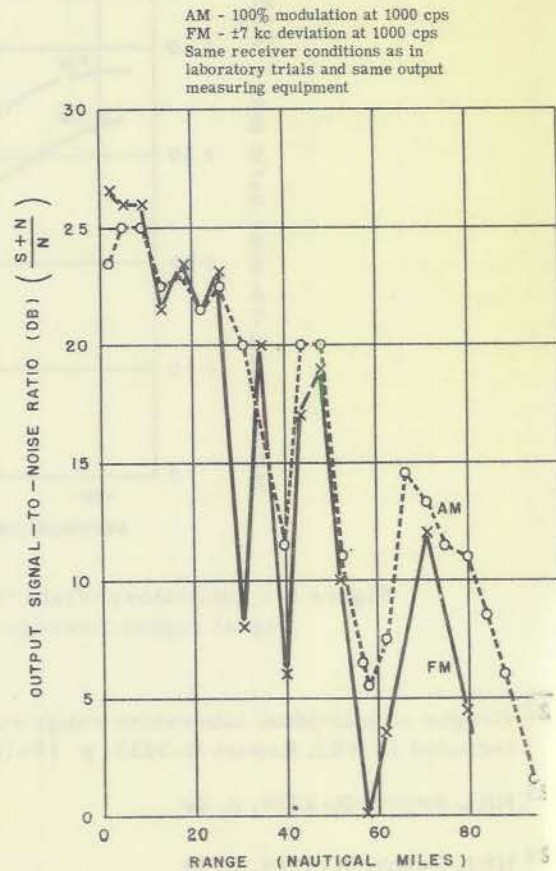


Figure 9 - Ship trials range run - daylight

Figure 10 - Air-to-ground range run



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Figure 11 shows the transmitter power increase (or decrease) required to provide the same output signal-to-noise ratio with FM as obtained with AM for the same range or distance from the transmitter.<sup>25</sup> This comparison is based on the laboratory trials, which were essentially confirmed (within about 5 db) by the associated field trials. The transmitter unmodulated carrier output power requirement is the same for both systems at an output S/N ratio of about +19 db with the imperfect limiting of the ratio-detector. For S/N ratios of less than +19 db, the FM transmitter requires more unmodulated carrier power, while the converse is true for S/N ratios greater than +19 db. The dotted curve shows the theoretical comparison based on an ideal FM receiver with perfect limiter. Under these conditions, the same AM and FM transmitter unmodulated power is required for +11 db output S/N ratio, with the FM transmitter requiring about 0.7 db more power than the AM transmitter for each db decrease of S/N ratio below +11 db and about 0.7 db less power for each db of S/N ratio increase above +11 db.

(No interference present in either system)  
Receivers at same "distance" from transmitters

AM - 100% modulation at 1000 cps  
FM - ±7 kc deviation at 1000 cps

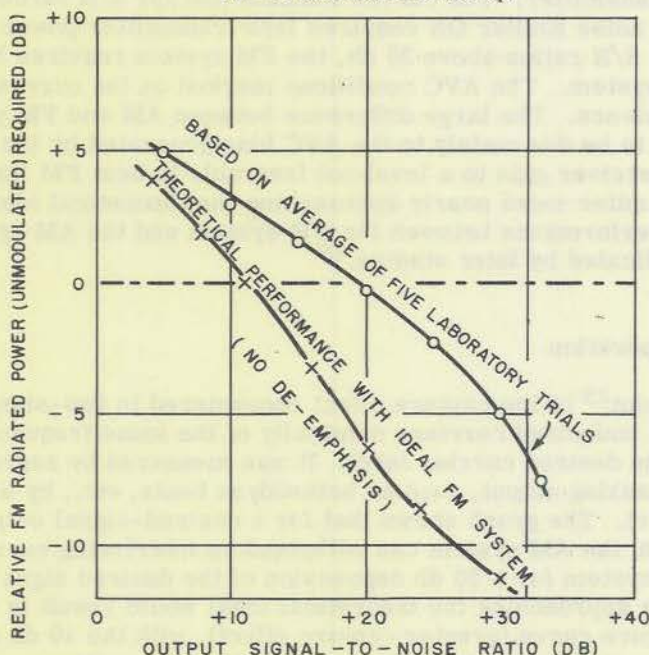


Figure 11 - Relative FM transmitter power required to produce the same output S/N ratio as obtained with AM

dar Interference

In the two-signal investigations in which the interfering signal was a pulse-modulated channel carrier, Navy radar transmitters were used to produce the undesired signal.

This figure was derived from Figure 8.

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With radar carrier-frequencies ranging from 200 Mc to 3000 Mc (all outside the receiver signal band), peak power outputs of 100 KW to 400 KW, pulse durations of 0.3 to 5 micro-seconds, and pulse repetition rates of 60 pps to 600 pps, no observable interference output was noted from the FM receiver under any conditions. Some interference was observed in the AM receiver output, but this was completely eliminated when the noise-limiter was turned ON. Spacings between the radar and receiver antennas were adjusted to produce maximum possible interference. Actual antenna separations ranged from one-quarter inch to ten feet. Various levels of desired signal were used, with the receiver on a channel frequency of 328.2 Mc.<sup>26</sup>

#### Impulse-Noise

In the two-signal studies in which the interfering signal was impulse-type noise, the spark generator previously mentioned was used to provide a broad spectrum of interference which centered close to the desired-signal frequency. The results of these studies<sup>27</sup> are shown in Figure 12, in the form of the FM transmitter power increase (or decrease) required to provide the same S/N output ratio with FM as obtained with AM for the same distance from the transmitter. The curves indicate that for S/N ratios of +25 db or less, the AM system with noise limiter ON requires less transmitter power than the FM system and, conversely, for S/N ratios above 25 db, the FM system requires less transmitter power than the AM system. The AVC conditions marked on the curves apply to both the AM and the FM receivers. The large difference between AM and FM performance with AVC ON is believed to be due mainly to the AVC bias generated by the noise impulses, which reduced the receiver gain to a level not favorable to best FM limiter action. Incorporation of an FM limiter more nearly approaching the theoretical ideal should result in more nearly equal performance between the FM system and the AM system with NOISE LIMITER ON, as indicated by later studies.<sup>28</sup>

#### Common-Channel Operation

Figure 13 is a plot<sup>29</sup> of the capture effect encountered in two-signal operation, with both the desired and undesired carriers nominally of the same frequency and the undesired carrier exceeding the desired carrier level. It was measured by segregating the desired signal from other masking output, such as heterodyne beats, etc., by use of a very sharp filter (wave-analyzer). The graph shows that for a desired-signal output S/N ratio on the order of +15 to 20 db, the AM system can withstand an interfering carrier level about 10 db higher than the FM system for a 30 db depression of the desired signal. Incorporation of limiting more nearly approaching the theoretical ideal would result in slight increase in slope of the FM capture curve (greater capture effect), with the 30 db standard signal depression occurring at lower undesired-to-desired carrier ratios.

<sup>26</sup> NRL Report R-3233, p. 42-44

<sup>27</sup> Derived from graphs in NRL Report R-3233, p. 48-49

<sup>28</sup> NRL Report R-3233, p. 44-52; NRL Report R-3231, p. 44-47

<sup>29</sup> Derived from graphs in NRL Report R-3233, p. 24

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(45 microvolts [quasi-peak] impulse-type noise-interference present in both systems), Receivers at same "distance" from transmitters

AM - 100% modulation at 1000 cps  
 FM - +7 kc deviation at 1000 cps

Note: AVC conditions apply to both the AM and the FM receivers

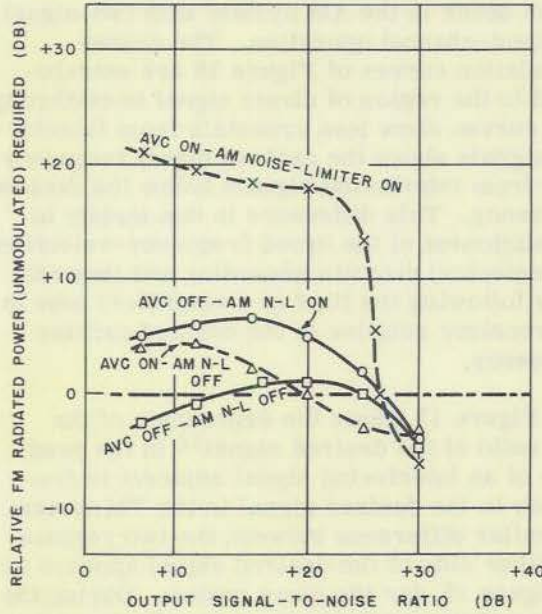


Figure 12 - Relative FM transmitter power required to produce the same output S/N ratio as obtained with AM

AVC ON - FM capture unaffected by AVC; AM capture somewhat affected by AVC, dependent on input levels. Desired signal output determined with wave analyzer.

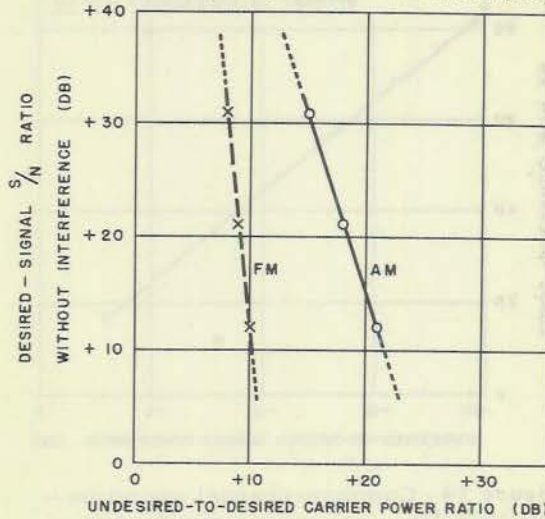


Figure 13 - Common-channel operation-capture effect for 30 db depression of desired signal

Figure 14 shows an intelligibility comparison<sup>30</sup> with the undesired carrier below the desired carrier level. No output components were filtered out in this test. The graph shows the number of words correctly understood when listening to the FM system for each one hundred words understood with the AM system; it is comparative and does not show the absolute intelligibility of either system. The average AM intelligibility was, however, on the order of 50 percent between -10 and -20 db undesired-to-desired carrier ratio. The AM and FM systems employed in the laboratory tests had an over-all measured audio distortion of about 5 percent at 1000 cps, as previously indicated. Figures 13 and 14 together cover input ratios ranging from an undesired signal well below the desired signal level, under which condition masking by heterodyne tone, etc., is the main effect, to undesired signals well above the desired signal level, where capture effect is of more importance. Incorporation of more nearly perfect limiting could be expected to cause a greater upward tilt of the curve in Figure 14, when the comparison is based on the same interference-free output S/N ratio of +27 db (speech-to-noise ratio of +17 db, 30 percent modulation).

Derived from graphs of NRL Report R-3233, p. 22

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Desired signal modulated with standard word lists; undesired signal modulated with same voice reading connected prose. Results shown are average score of ten auditors. Output in all cases included heterodyne, "swish," noise, etc.

AM heterodyne average frequency = 2500 cps  
 FM heterodyne average frequency = 3000 cps  
 Absolute intelligibility of AM system between -10 db and -20 db undesired-to-desired carrier power ratio is 50% average (1 word in 2 misunderstood).

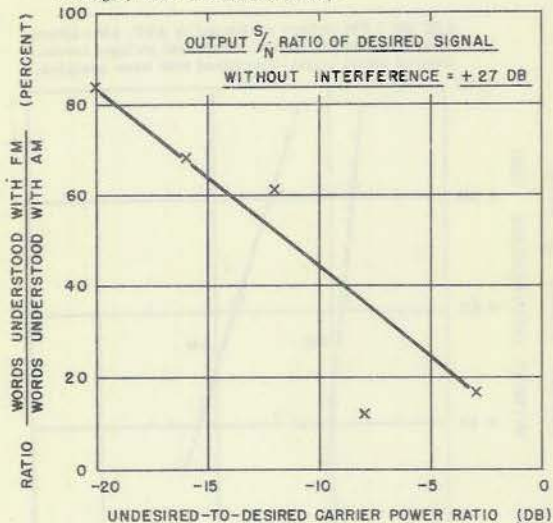


Figure 14 - Common-channel operation—intelligibility comparison words understood on FM system for each 100 words understood on AM system

### Adjacent-Channel Operation

Figures 15 and 16 show the cross-modulation and S/N ratio depression effects<sup>31</sup> which occur in the AM system with two-signal adjacent-channel operation. The cross-modulation curves of Figure 15 are extrapolated to the region of direct signal breakthrough. The curves show less crosstalk from interfering signals above the desired signal frequency than from interfering signals below the desired frequency. This difference is due mainly to the alignment of the broad frequency-selective (preselector) circuits preceding and immediately following the first (r-f amplifier) tube in the receiver relative to the desired carrier frequency.

Figure 17 shows the depression of the S/N ratio of the desired signal<sup>32</sup> in the presence of an interfering signal adjacent in frequency to the desired signal in the FM system. A similar difference between the two regions on either side of the desired signal appears as in Figure 15, for the same reason. During the course of these trials, no crosstalk due to cross-modulation effects were discernible in the FM system.

Figure 18 summarizes the effects of adjacent channel interference in both the AM and FM systems,<sup>33</sup> with the interfering signal 2.4 Mc below the desired signal frequency at a level of 30 db below 30 watts. From these curves it is apparent that:

- At input signal levels corresponding to an output S/N ratio of the desired signal (without interference) of +20 db or less, the interfering signal causes substantially constant depression of the S/N ratio. This depression is about 1 db with AM and about 6.5 db with FM.
- Above this +20 db point, the AM S/N ratio depression remains constant at about 1 db, while the FM S/N ratio depression decreases.
- The major interference effect in the case of the AM system is the crosstalk resulting from cross-modulation, while in the FM system it is the depression of the S/N ratio of the desired signal.
- If it is assumed that the deteriorating effects of crosstalk interference and fluctuation-noise interference are of equal significance, it can be concluded that at input signal levels corresponding to an output S/N ratio below about 14 db (without interference) the resulting ratio of desired-signal to interference is higher with AM than FM. Above this 14 db point, the converse is true.

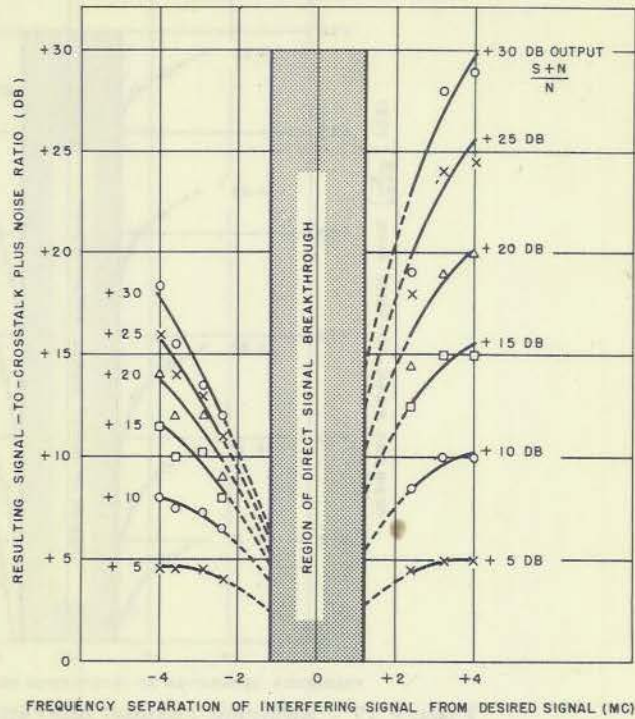
<sup>31</sup> Curves shown in these figures were derived from individual graphs in NRL Report R-3233, p. 27-33

<sup>32</sup> Curves shown in this figure were derived from individual graphs in NRL Report R-3233, p. 35-39

<sup>33</sup> This figure was derived from Figures 15, 16, 17

Interfering-carrier level at receiver held constant at 30 db below 30 watts (approx. 1.2 volts) and modulated 100% at 1000 cps. Output S/N ratio figures identifying curves are desired-signal values obtained for 100% modulation without interference.

Figure 15 - Adjacent channel operation—AM system cross-talk due to cross-modulation



Interfering carrier level at receiver held constant at 30 db below 30 watts (approx. 1.2 volts) - unmodulated. Output S/N ratio figures identifying curves are desired-signal values obtained for 100% modulation without interference.

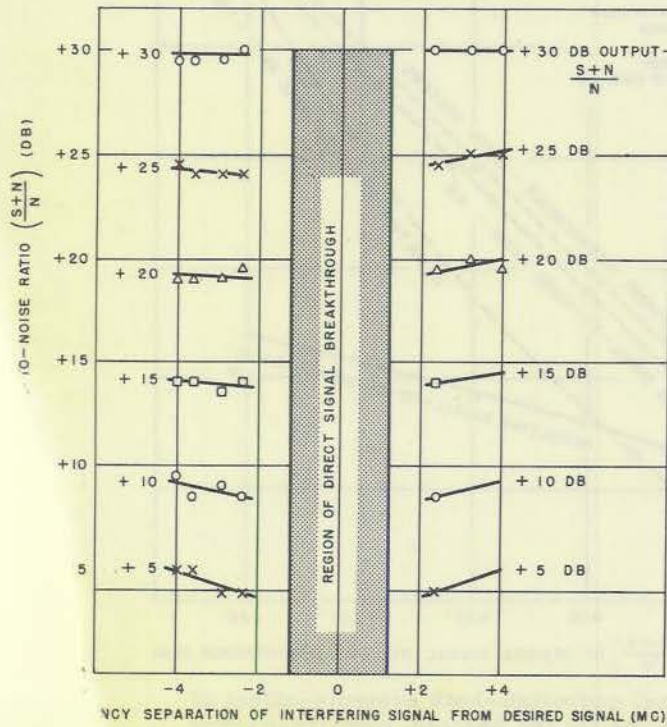


Figure 16 - Adjacent channel operation—AM system depression of signal-to-noise ratio by interfering carrier

Interfering carrier level at receiver held constant at 30 db below 30 watts (approx. 1.2 volts) - unmodulated  
 Note: modulation at 1000 cps with  $\pm 7$  kc deviation gave same results)  
 Output S/N ratio figures identifying curves are desired-signal values as obtained for  $\pm 7$  kc deviation without interference

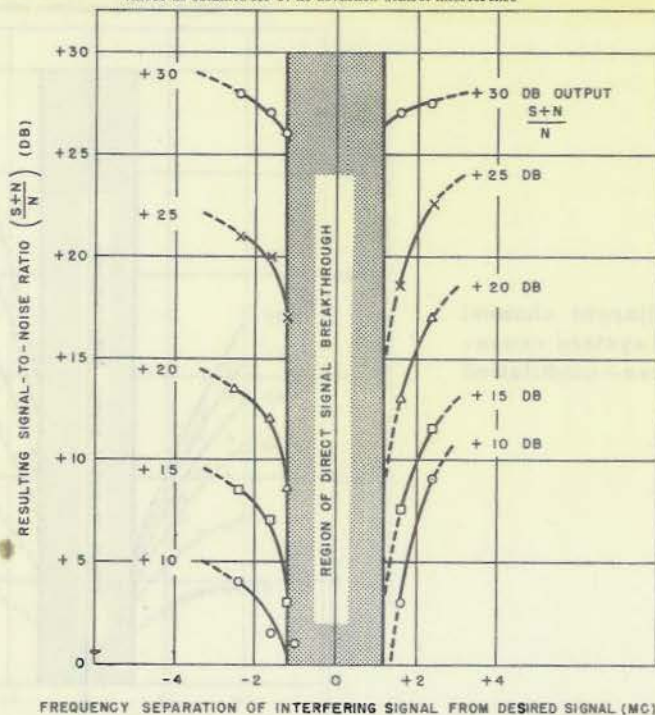


Figure 17 - Adjacent channel operation-FM system depression of signal-to-noise ratio by interfering carrier

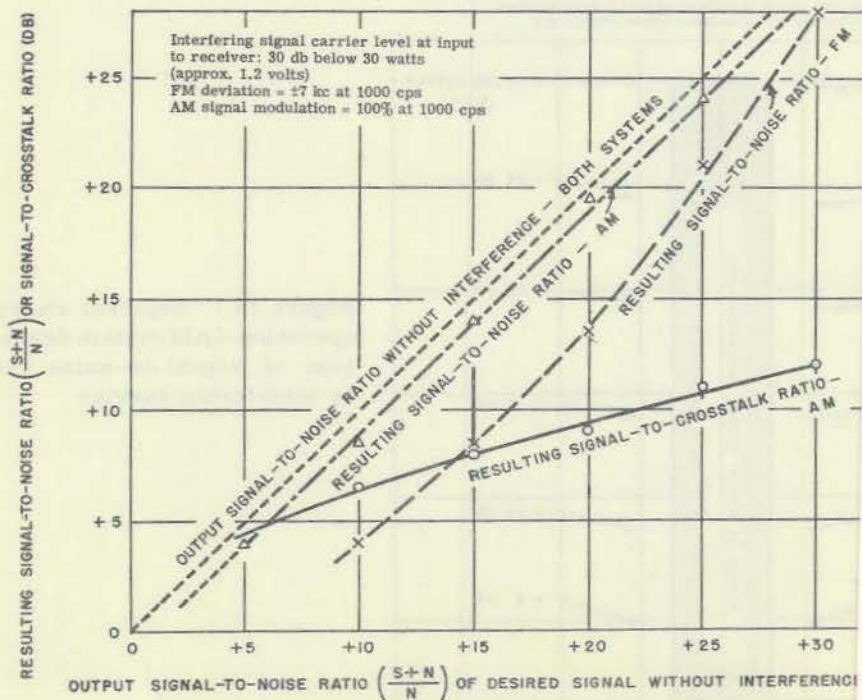


Figure 18 - Adjacent channel operation-both systems-effect of an interfering signal 2.4 Mc below the desired-signal frequency

Figure 18 shows the desired signal in the presence of interfering signal. The relationships which exist are, however, similar to those shown in Figure 17. Limiter performance closer to the theoretical ideal in the FM case could be expected to result in greater output S/N depression effect, with, however, a lower desired-signal level required to produce the indicated output S/N ratios without interference.

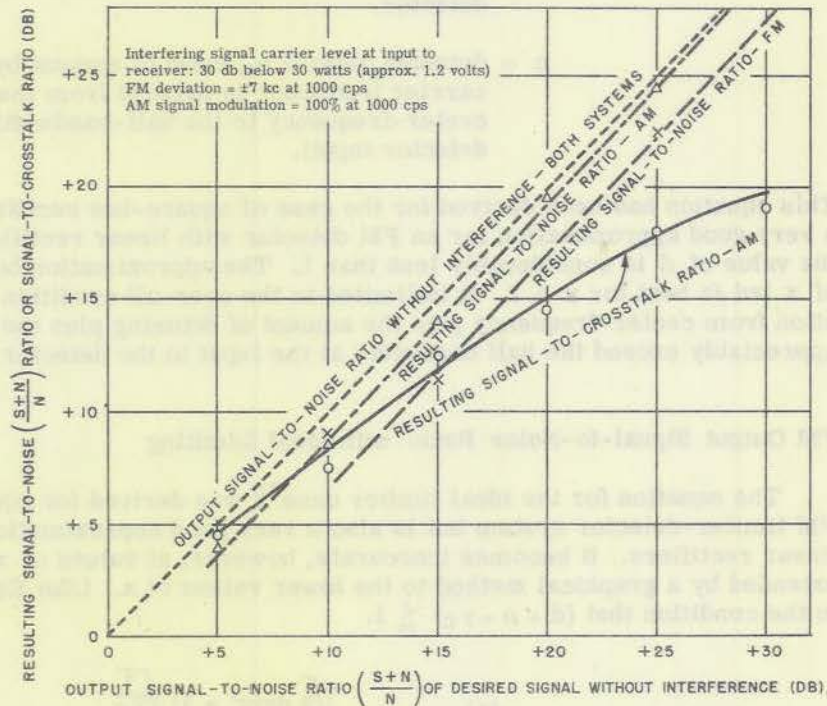
graph<sup>34</sup> similar to Figure 18, but with the interfering signal 2.4 Mc above signal frequency. The curves show less effect on the desired signal by the interfering signal. The relationships which exist are, however, similar to those shown in Figure 17. Limiter performance closer to the theoretical ideal in the FM case could be expected to result in greater output S/N depression effect, with, however, a lower desired-signal level required to produce the indicated output S/N ratios without interference.

In the above board trials, cross-modulation and signal-to-noise ratio depression occurred in only one case, when the transmitting and receiving antennas were closely spaced (10 feet, 36.1 db at resonance). Maximum AM cross-modulation output was observed at 1.6 Mc above resonance and had a value of 10 db cross-modulation output signal-to-noise ratio. Maximum FM signal-to-noise ratio depression was 0.2 db, and occurred at 1 Mc below resonance.

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Figure 19 shows adjacent channel interference effect of an interfering signal 2.4 Mc above the desired signal frequency.

Adjacent channel interference effect of an interfering signal 2.4 Mc above the desired signal frequency.



THEORETICAL PERFORMANCE

FM Output Signal-to-Noise Ratio with No Limiting

The theoretical solutions for output S/N ratio of an FM system with no limiting and with ideal limiting (thematically perfect limiting) were derived in forms capable of providing weak-signal region where the available solutions did not satisfactorily extend.<sup>35</sup> The following equation was obtained for the no-limiter case:

$$\left(\frac{S}{N}\right)_o = \left[ \frac{2x^4 d^2}{\frac{2}{3} - \frac{(2 - \gamma_c)^4}{24} + 2x^2 \gamma_c \left[ 4\rho^2 + 2d^2 + \frac{\gamma_c^2}{3} \right]} \right]^{1/2} \quad (1)$$

<sup>34</sup> This equation was derived from Figures 15, 16, 17

<sup>35</sup> NRL Report R-3231, p. 40-42

where  $\left(\frac{S}{N}\right)_o$  = rms output signal-to-noise ratio (no limiter).  
 $x$  = rms unmodulated carrier-to-noise ratio at the input to the FM detector.  
 $d$  = ratio of maximum carrier-frequency deviation to the half-bandwidth at the input to the detector (e.g., half-bandwidth of the r-f plus i-f amplifier)  
 $\gamma_c$  = ratio of output bandwidth (e.g., audio-amplifier bandwidth) to the half-bandwidth at the input to the detector.  
 $\rho$  = detuning ratio (i.e., ratio of amount by which the carrier frequency is detuned from the discriminator center-frequency to the half-bandwidth at the detector input).

This equation has been derived for the case of square-law rectifiers, but it provides a very good approximation for an FM detector with linear rectifiers, particularly when the value of  $d$  is considerably less than 1. The approximation holds well for values of  $x$  but is best for  $x > 2$ . It is limited to the over-all condition that the deviation from center-frequency plus the amount of detuning plus the audio band does not appreciably exceed the half bandwidth at the input to the detector  $[(d + \rho + \gamma_c) \leq 1]$ .

#### FM Output Signal-to-Noise Ratio with Ideal Limiting

The equation for the ideal limiter case<sup>36</sup> was derived for square-law rectifiers in the FM limiter-detector system but is also a very good approximation for a detector with linear rectifiers. It becomes inaccurate, however, at values of  $x$  less than 10, but can be extended by a graphical method to the lower values of  $x$ . Like Equation (1), it is limited to the condition that  $(d + \rho + \gamma_c) \leq 1$ .

$$L \left(\frac{S}{N}\right)_o = \frac{\sqrt{3} dx(x^2 + 1) \sqrt{\frac{1}{\gamma_c}}}{[12\rho^2 + 6d^2 + (x^2 + 1)^2 \gamma_c^2]^{1/2}} \quad (2)$$

where  $L \left(\frac{S}{N}\right)_o$  = rms output signal-to-noise ratio with perfect input limiting. When the input carrier-to-noise ratio is large ( $x \geq 10$ ), and the input carrier is exact entered on a perfectly symmetrical and balanced discriminator characteristic ( $\rho = 0$ ), Equation (2) assumes the simpler form:

$$L \left(\frac{S}{N}\right)_o = \sqrt{3} x R \sqrt{\frac{1}{\gamma_c}} = x R \left(\frac{3f_i}{2f_a}\right)^{1/2} \quad (3)$$

<sup>36</sup> NRL Report R-3231, p. 42-43

where  $f_c = f_{\Delta}/f_a =$  deviation ratio (or the modulation index,  $(m_f)$  when the modulating frequency equals the audio cutoff-frequency),

$f_{\Delta}$  = frequency deviation from the center-frequency,

$f_i$  = input bandwidth at the final detector,

$f_a$  = output bandwidth (or audio cutoff-frequency at the high end)

Equations (1), (2), and (3) are based on such ideal assumptions as a perfect rectangular input activity curve, a perfect limiter with no threshold level, and ideal slope filters for the frequency-discriminator, with perfect symmetry and balance throughout.

AM Output Signal-to-Noise Ratio

The output S/N equation for the AM case<sup>37</sup> is based on square-law detection but is also a good approximation for linear detection. Its accuracy is greater for the lower values of modulation percentage.

$$\left(\frac{S}{N}\right)_o \cong mx^2 \left\{ \frac{f_i}{f_a [1 + x^2 (2 + m^2)]} \right\}^{1/2}, \quad (4)$$

where

$(S/N)_o$  = rms output signal-to-noise ratio,

$m$  = modulation depth ( $m = 1$  for 100 percent mod.)

$x$  = rms unmodulated carrier-to-noise ratio at the input to the final detector

$f_i$  = input bandwidth at final detector

$f_a$  = output (a-f) bandwidth (or audio cutoff-frequency at the high end)

For values of  $C/N > 3$ , Equation (4) may be simplified to:

$$\frac{S}{N}_o \cong 0.707 mx \left( \frac{f_i}{2f_a} \right)^{1/2}. \quad (5)$$

The input activity curve is assumed to be a perfect rectangle.

Theoretical "Range" Curves

Figure 10 shows the computed AM and FM output rms signal-to-noise ratios<sup>38</sup> corresponding to increasing values of input rms carrier-to-noise ratio for the conditions of

<sup>37</sup> The factor 0.707 was inadvertently omitted from Equation (25) of NRL Report R-3231, p. 38.

<sup>38</sup> NRL Report R-3231, p. 43; obtained from Equations 1-5.

the subject AM/FM investigations. The output values with perfect limiter for ratios below +6 db were derived as follows. The  $\pm 7$  kc deviation FM no-limiting curve was constructed, using Equation (1), for C/N ratios from -10 to +40 db. As stated previously, Equation (1) holds quite closely for all values of x. It was then assumed that the noise energy for C/N ratios of -6 db and less could be considered as an equivalent signal exhibiting the same capture or depression effect on the desired signal as the signal exhibited with regard to noise for C/N ratios of +6 db and above. The FM perfect limiter case was then drawn as much below the no-limiting curve for C/N = +6 db, -6 db, -10 db, etc., as it was above the no-limiting curve for C/N = +6 db, +10 db, etc. The two curve sections resulting were then joined by extension, passing through the no-limiting curve at C/N = 0 db, which was considered the capture transition point. The computed values for C/N =  $\pm 3.5$  db have been plotted as a guide to construction.

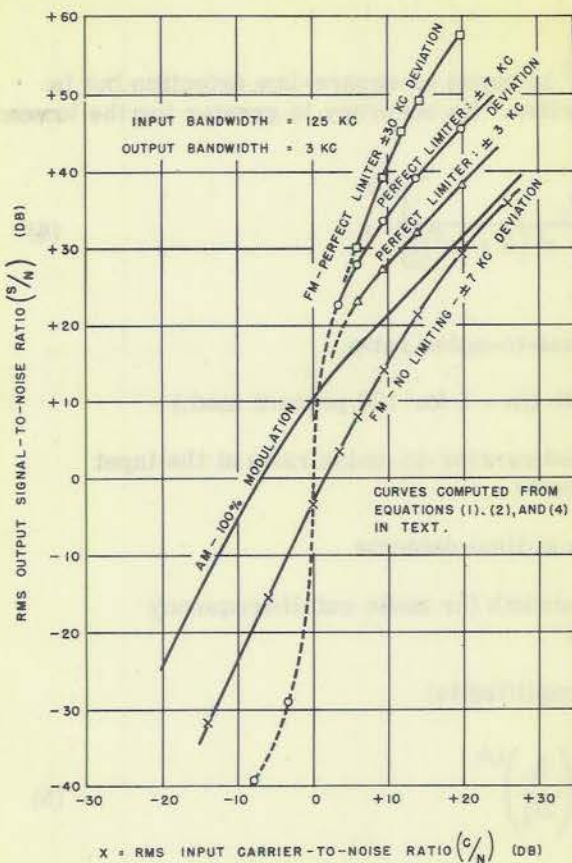


Figure 20 - Theoretical AM and FM "Range" Performance

which were in terms of input C/N ratio, by assuming that the experimental was substantially identical with the perfect theoretical case at about +20 db. This assumption was supported by previous measurements of i-f amplifier o

The FM perfect limiter  $\pm 7$  kc deviation crosses the AM theoretical curve for 100 percent modulation at an output signal-to-noise ratio of +11 db. These two curves were used for comparative theoretical "range" comparison in Figure 11. Increasing the maximum deviation from  $\pm 7$  to  $\pm 30$  kc ( $m_f = 10$ ) changes the limiter AM/FM crossover point very little, as shown by the 30 kc deviation curve. On the other hand, the increased modulation results in improvement of output signal-to-noise ratio for input C/N ratios above about +5 db. Decreasing the deviation to  $\pm 3$  kc ( $m_f = 1$ ) affects mainly the output levels corresponding to C/N ratios of +2 db, with the AM/FM crossover as occurring at about +12 db.

Experimental "Range" Curve

A series of signal generator measurements were made on an FM receiver of the same type as used in the comparison trials discussed above, to verify the theoretical curves of Figure 20 and to determine the relative position of the ratio within the no-limiting/perfect-limiting area. Companion AM measurements were made on the same receiver, after rewiring the detector for AM operation. Theoretical curves, which were plotted in microvolts input from the signal generator, were matched to the theoretical curves,

for C/N ratios below +6 db were derived as follows. The  $\pm 7$  kc deviation FM no-limiting curve was constructed, using Equation (1), for C/N ratios from -10 to +40 db. As stated previously, Equation (1) holds quite closely for all values of x. It was then assumed that the noise energy for C/N ratios of -6 db and less could be considered as an equivalent signal exhibiting the same capture or depression effect on the desired signal as the signal exhibited with regard to noise for C/N ratios of +6 db and above. The FM perfect limiter case was then drawn as much below the no-limiting curve for C/N = +6 db, -6 db, -10 db, etc., as it was above the no-limiting curve for C/N = +6 db, +10 db, etc. The two curve sections resulting were then joined by extension, passing through the no-limiting curve at C/N = 0 db, which was considered the capture transition point. The computed values for C/N =  $\pm 3.5$  db have been plotted as a guide to construction.

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receiver in  
for  $\pm 7$  kc  
laboratory  
S/N ratio,

in microvolts. The resultant overlay<sup>39</sup> is shown in Figure 21. The curve  
with the ratio-detector without added limiting (the condition for the  
field trials) shows the experimental AM/FM crossover at +18.5 db output  
use check with the average crossover of the laboratory trials (see Figure 8).

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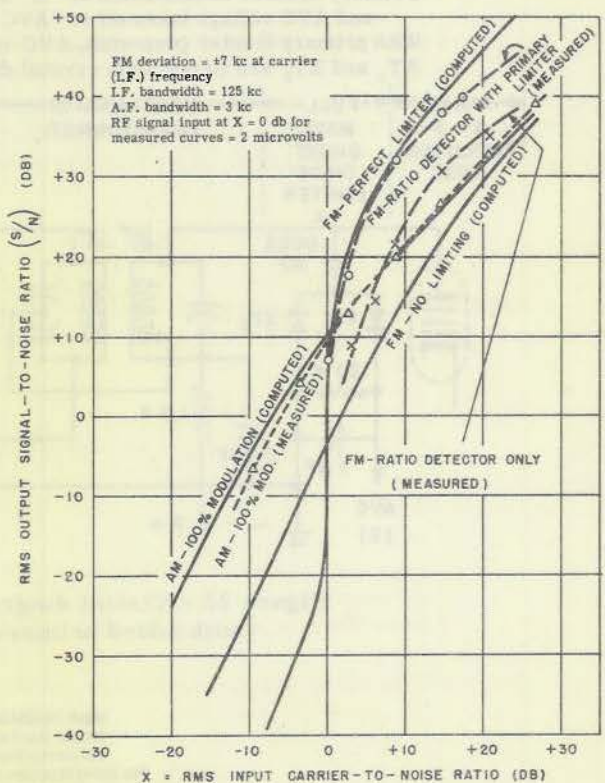


Figure 21 - Comparison of experimental "range" performance to theoretical limits

Computed

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(1) and (2) were also solved at various C/N ratio levels for values of  $\rho$   
ctor) up to about 90 percent of the half-bandwidth of the i-f system. Two  
lting curves, for C/N ratios of +9.5 and 20 db,<sup>40</sup> are plotted in Figure 23.

<sup>39</sup> NRL R

R-3231, p. 43-45

<sup>40</sup> Derived

m graphs in NRL Report R-3231, p. 47

These show the deterioration of output S/N ratio with increase in detuning; that with no limiting, the deterioration is substantially independent of the C/N ratio. With perfect limiting, however, detuning is much more damaging at the lower C/N at the higher C/N values, detuning causes little S/N deterioration.

Primary-limiter disconnected at "X" for ratio-detector only measurement and AVC voltage taken off at "AVC (1)"  
 With primary limiter connected, AVC voltage is taken off at "AVC (2)"  
 XT<sub>1</sub> and XT<sub>2</sub> are Germanium crystal diodes

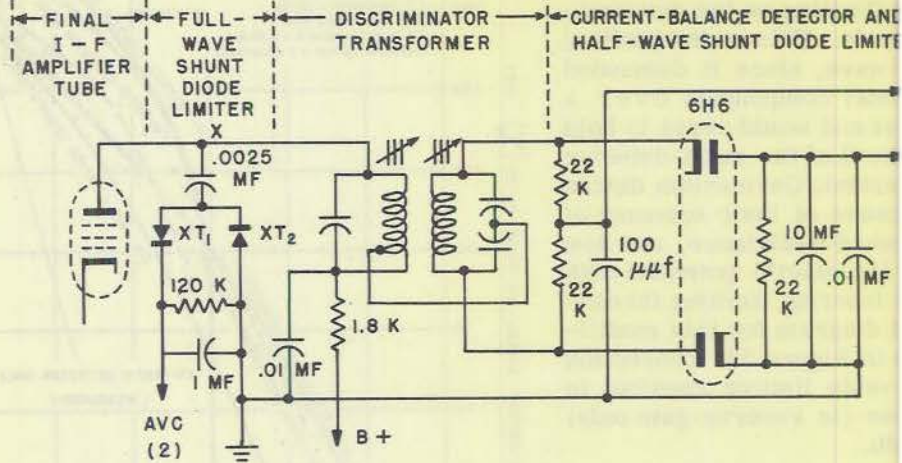


Figure 22 - Circuit diagram of ratio-detector with added primary-side limiter

Input bandwidth = 125 kc  
 Output bandwidth = 3 kc  
 FM deviation = ±7 kc  
 No deterioration of AM output S/N for any detuning to limit of input bandwidth

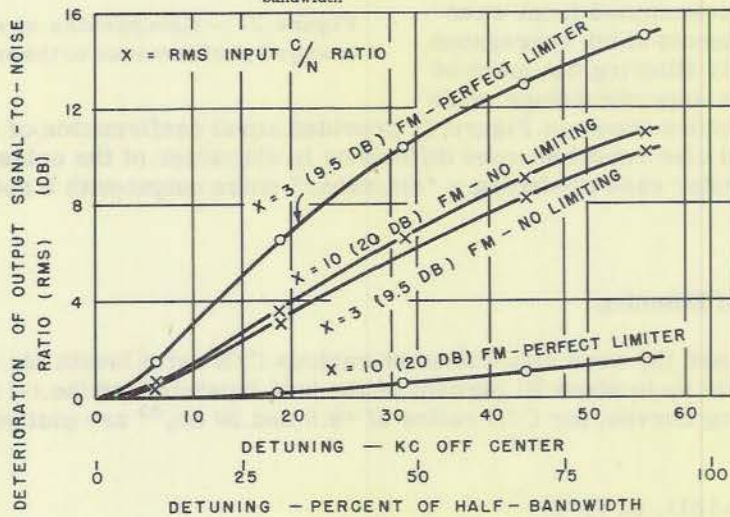


Figure 23 - Theoretical deterioration of output S/N ratio with detuning

Figure 24 shows the measured effects of detuning both the AM and the FM versions of the receiver used in the experimental confirmation of the theoretical "range" data.<sup>41</sup> The measurements were taken at a signal input level corresponding to a C/N ratio very close to the theoretical limits. The theoretical limits for detuning with this C/N value are also shown in the graph. The departure of the experimental curves from these limits above about 25 kc (40 percent) detuning can be ascribed in part to the difference between the rectangular selective curve postulated in the mathematical treatment and the more nearly trapezoidal actual selectivity characteristic.

The ratio-detector with its imperfect limiting is less affected by the more nearly ideal limiter with the added primary limiter. The crossover between the two curves occurs at 28 kc detuning. Magnetic records confirmed that up to about 28 kc off center, the ratio-detector limiter sounded better than the ratio-detector alone, with considerable character of noise output. The performance of the ratio-detector with the added primary limiter is shown in Figure 23 by an amount of improvement largely by the difference between the actual and mathematical curves.

Effect of Improved Limiting on Performance with Impulse-Noise

Measurements were made of FM output S/N with and without the added primary limiter in the presence of impulse interference.<sup>42</sup> These showed the improvement in output S/N ratio with additional limiting that was obtained with only fluctuation noise present was also obtained in the presence of impulse interference. The improvement in performance was equivalent to approximately 2 to 5 db less required FM transmitter power to produce given output S/N ratios from -5 to +25 db. This decrease of required transmitter power will make the FM under conditions as shown in Figure 12 more nearly equal to AM performance with LIMITER ON. The FM impulse-noise reduction was, however, much more dependent on perfect symmetry and centering on the discriminator characteristic, and the results with impulse noise closely resemble those for fluctuation noise (Figure 23).

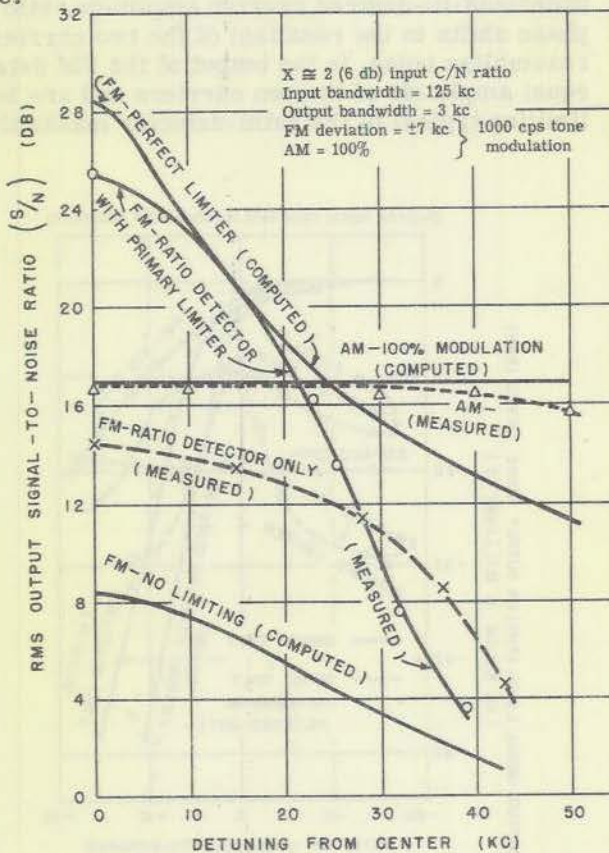


Figure 24 - Comparison of experimental detuning measurements to theoretical limits

<sup>41</sup> NRL Report R-3422, p. 31 and 34

<sup>42</sup> NRL Report R-3422, p. 38

Influence of Limiting on Common- and Adjacent-Channel Performance

Figure 25 shows the desired-signal depression and noise-exaltation effect in co-channel operation, as measured at a desired-carrier input level +20 db output S/N ratio from the AM receiver.<sup>43</sup> The noise curve obtained with added primary limiter shows the peak which is characteristic of an FM system with limiting approaching theoretical optimum. This peak occurs in the close vicinity of an undesired-to-desired carrier amplitude ratio of 1. The noise increase is caused by abrupt phase shifts in the resultant of the two carriers, which produce sharp bursts resembling noise, in the output of the FM detector. These phase shifts are of equal amplitude of the two carriers and are less on either side of equality. The limiting typical of the ratio-detector masks this peak, as shown by the curve

encountered which provided the FM case system with the energy, minimum for half-wave

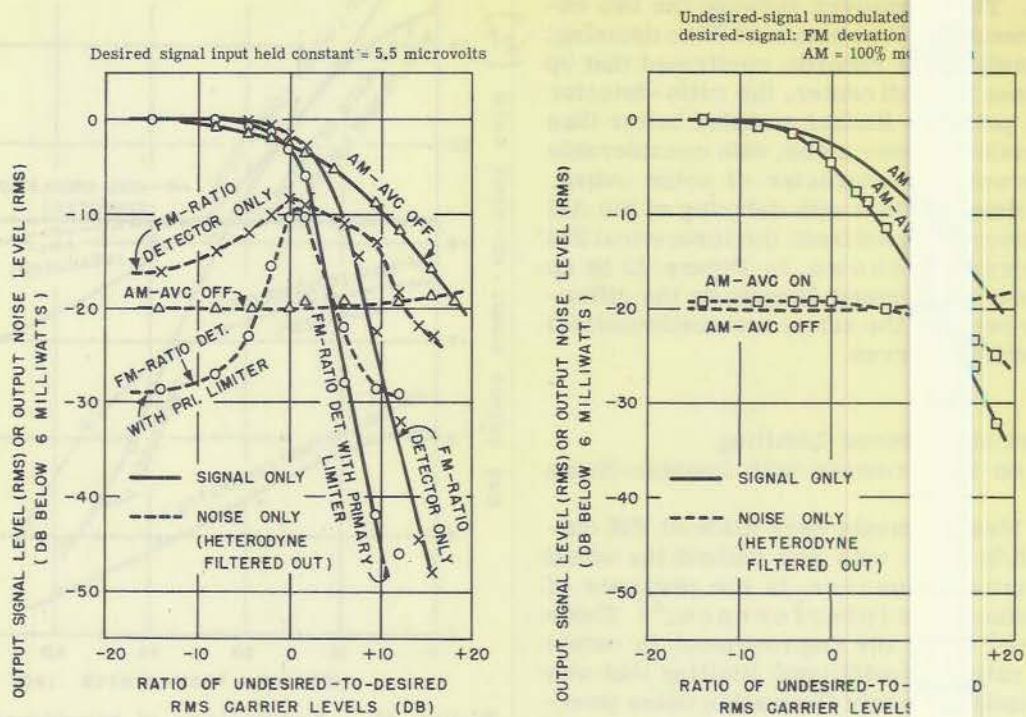


Figure 25 - Comparison of measured AM and FM co-channel (two-signal) performance (desired-signal depression and noise variation)

The low contact-potential of the germanium-crystal diodes used to obtain improved limiting results in a decreased capture threshold. Thus the FM curve for a +20 db output S/N ratio depression for the "ratio-detector alone" case (Figure 13) shows that an undesired-to-desired carrier level ratio is required to produce such a depression for a desired input signal level corresponding to +30 db output S/N with a primary limiter. With the added primary-limiter, however, only a +4 db undesired-to-desired carrier level ratio is required to produce the same depression (Figure 25A). As previously

mentioned, improved output a +7.5 db depression-interference. carrier level mentioned,

<sup>43</sup> NRL Report R-3231, p. 60-61; NRL Report R-3422, p. 35-38

the intelligibility comparison curve (Figure 14), with better limiting and the same initial (interference-free) output S/N ratio, can be expected to show a greater downward tilt toward 0 db undesired-to-desired carrier ratio.

The slope of the desired-signal output curve in the region where capture is well understood is a function of the degree of capture. In Figure 25, the slope for the FM case with limiting alone is  $76^\circ$ , while with added limiting, it is  $78^\circ$ ; the AM curve with AVC off has a slope of about  $50^\circ$ , which becomes about  $60^\circ$  with AVC on. Perfect capture would be indicated by a slope of  $90^\circ$ . It should be noted that the AM capture-slope with AVC off will increase with increasing input signal level as the amplifier stages preceding the final detector begin to exhibit saturation effects. With linear detection, no saturation effects, and no AVC, the AM capture curve should have a slope of  $45^\circ$ , i.e., one db of desired-signal depression for each db of increase in interfering signal. With square-law detection, however, usually no AM capture should occur.

As Figure 25 shows, the AM system exhibits very little change in output noise with increasing interfering carrier level, while large noise changes occur in the FM system. The output signal-to-noise ratio depression effects observed in the adjacent-channel trials are caused by phenomena essentially identical with those occurring in the common-channel case. With limiting approaching the ideal, the depression effects in the FM system will be intensified. For any given initial (interference-free) value of output S/N, as the interfering carrier approaches the desired-carrier frequency; the curves of Figure 17 can therefore be expected to take a steeper downward tilt toward 0 Mc frequency separation.

## DISCUSSION OF RESULTS

### Range

It is generally considered desirable to restrict the distance or range rating of a communication system to a "safe-communication range" which provides not less than about +15 to +20 db output signal-to-noise ratio for peak or 100 percent modulation, but the usefulness of such S/N ratios must not be overlooked. It has been established by the series of tests represented in Figure 26 that a range limit below which 300 to 3000 cps voice message systems must, in general, never be allowed to fall. Figure 26 shows the horizontal or azimuthal radiation pattern for a typical uhf vertical dipole antenna installation on shipboard.<sup>44</sup> The outstanding characteristic of such patterns, despite all precautions, is rapid and large variation in signal strength with bearing. Vertical patterns for the same antenna would also reveal large variations with elevation. The maneuvering of ships and planes with transmitting and/or receiving antenna patterns such as shown would result in large fluctuations of signal input to the receiver, even though the range or distance were maintained constant. Thus, at the "safe-communication" range limit, radical variations of output S/N could be expected to occur in the FM system, with the signal abruptly disappearing and reappearing as the bearing and inclinations from the vertical varied with pitching, rolling, banking, and turning of the communicating craft. The less abrupt range "cutoff" characteristic of the AM system would be particularly advantageous under such conditions; its relative freedom from downward AM limitations would also be desirable.

<sup>44</sup> NRL Report R-3234, p. 11, Figure 10

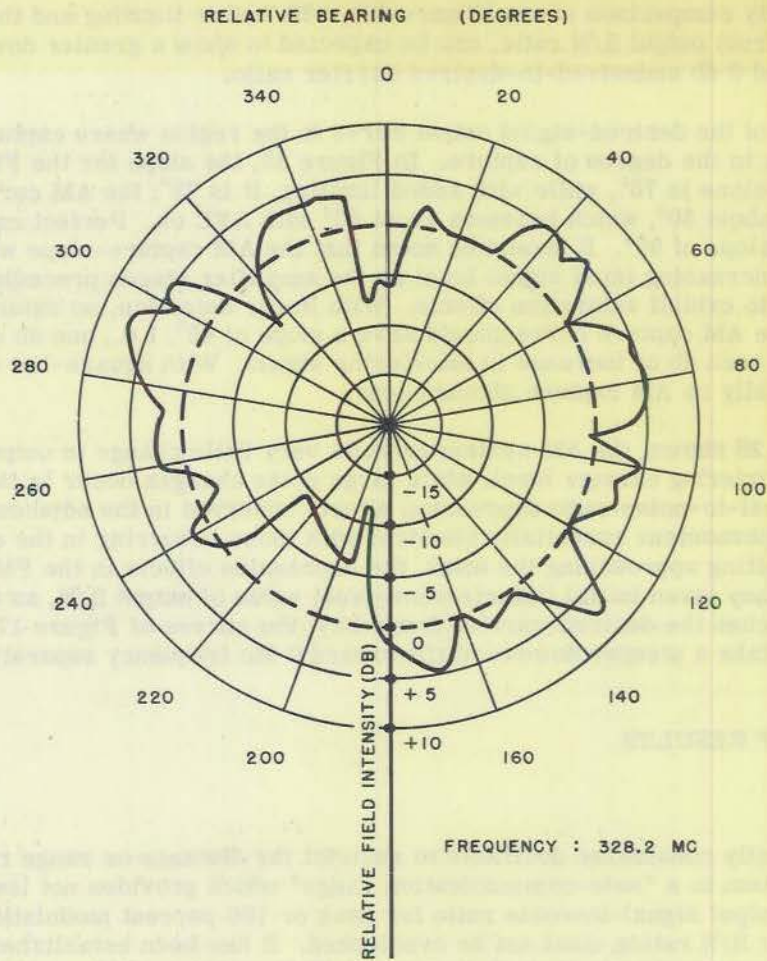


Figure 26 - Horizontal radiation pattern of a good uhf vertical dipole antenna installation on ship ( $f = 328.2 \text{ Mc}$ )

Figure 27 is a plot<sup>45</sup> of the output S/N ratio variation for both types of receivers (with perfect receiving-antenna patterns assumed) move through a sector of 170° to 240° bearing relative to the radiation pattern shown in Figure 26. The 0 db circle on the pattern represents approximately the average radiation level that would be applicable for "safe-communication" range estimation. The curves of Figure 27 are plotted for that constant distance or range at which the AM system provides a constant S/N ratio for a radiation level corresponding to the 0 db circle on the antenna pattern. The unmodulated carrier power output of the FM transmitter is the same as that of the AM transmitter in this comparison. The graphs show that the AM output S/N ratio holds up better than the FM S/N in the antenna pattern "hole" from about 170° to 225° relative bearing. At no time does the AM output signal drop below the +5 db level, the noise limit of intelligence.

<sup>45</sup> Derived from Figures 21 and 26 of this report

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0 db relative field intensity = 20 db output S/N ratio with AM  
 Plot based on perfect receiving antenna pattern  
 AM = 100% modulation  
 FM = ±7 kc deviation

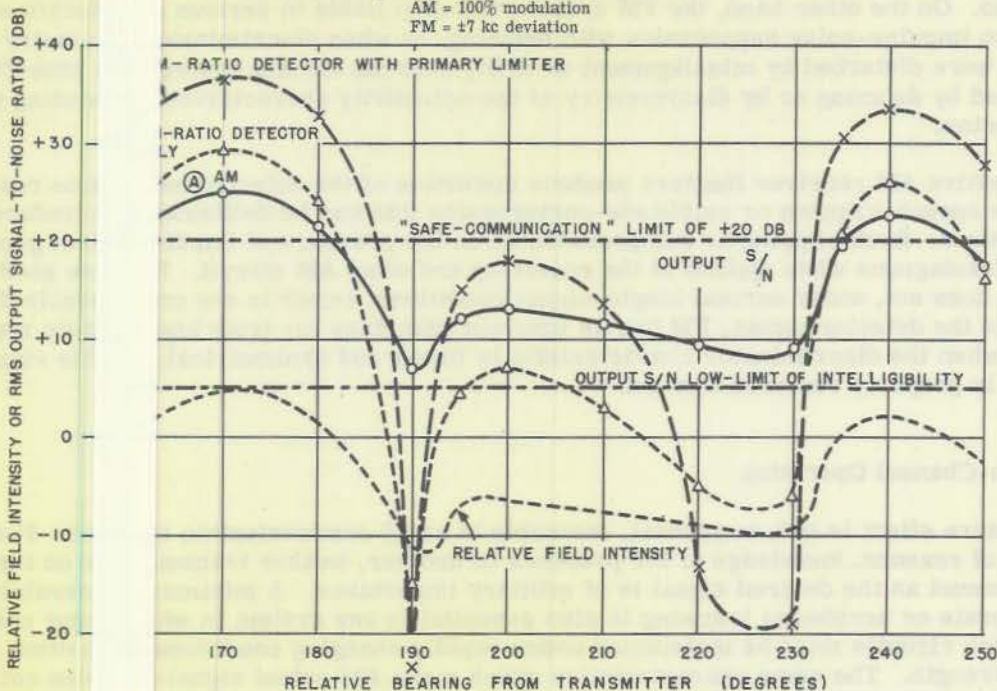


Figure 27 - Output S/N ratio variation in 160°-250° sector of antenna pattern of Figure 26

Curve (A) represents the performance of an AM system under very carefully maintained and controlled conditions which, unfortunately, are not to be expected when normal service conditions prevail. Slight misalignments and drifts of the discriminator circuits; receiver and transmitter oscillator displacements and subsequent drifts, with resultant detuning; changes in tube aging that have consequent influence on limiter levels; etc., will all combine to reduce the FM advantage at received signal levels above the AM/FM crossover point where it would otherwise be much better than AM.

Figure 27 approaches the theoretical limit of performance. It, however, is not to be expected when normal service conditions prevail. Slight misalignments and drifts of the discriminator circuits; receiver and transmitter oscillator displacements and subsequent drifts, with resultant detuning; changes in tube aging that have consequent influence on limiter levels; etc., will all combine to reduce the FM advantage at received signal levels above the AM/FM crossover point where it would otherwise be much better than AM.

Noise Interference

The signal (range) investigations revealed the relative performance of the two types of modulation in the presence of fluctuation noise. Amplitude-limiters (noise-peak class) which are applicable to voice-modulated AM systems have little or no reduction in effect on such noise, particularly when fairly broad r-f (or i-f) bandwidths precede the AM detector. Best results are normally obtained in receivers operating at the higher radio-frequencies, although excellent performance has been obtained even in the VLF range with some of the simplest types of limiters.

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The interference-noise studies showed that the AM system with a simple series-diode noise limiter was at least as good as the FM system in the weak-signal range, even when the FM equipment approached the theoretical-ideal limit. The FM system was, however, inherently capable of better performance above about +20 db output

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S/N ratio. On the other hand, the FM system was also liable to serious distortion with regard to impulse-noise suppression with detuning, or when discriminator balance were disturbed by misalignment or drift, whereas the AM system is unaffected by detuning or by dissymmetry of the selectivity characteristic of the AM detector.

Effective AM receiver limiters produce distortion of the detected modulation resembling the speech-clipping or amplitude-compression that can be deliberately introduced in transmitters. Such clipping or compression is, in the presence of impulse noise, generally more advantageous when applied at the receiving end of an AM circuit. But excessive limiting does not, under normal single-signal conditions, result in any considerable distortion in the detector output, FM has an inherent advantage for truly high fidelity reproduction when the discriminator characteristic is linear and symmetrical, and the carrier is properly centered thereon.

Common-Channel Operation

Capture effect is not, in general, desirable in naval communication systems. A number of reasons, knowledge of the presence of another, weaker transmission in the same channel as the desired signal is of military importance. A minimum level of deliberate or accidental jamming is also essential in any system in which communication circuits must be maintained under rapidly changing conditions of signal strength. The same characteristics which make FM output signal-to-noise ratio superior to AM above the weak-signal region of operation also tend to make FM systems more vulnerable to jamming and capture. Deliberate reduction of the FM S/N ratio to mask masking effects to approach AM performance in this regard will usually result in a loss of much of the FM S/N output advantage above the weak-signal region.

On the other hand, capture can be put to good use in FM communication systems in which the transmitting and receiving terminals are relatively far apart, geographical location and the receivers are well-designed, carefully maintained and operated. Although anomalous propagation may at times work havoc with geographical allocations are based on capture as a consideration, the average performance, except in the fringe area of nearly equal field intensities, should be good. Broadcast systems are an example of such an application; by proper choice of frequency and geographical allocations, the fringe area can be at a distance between two systems such that capture very seldom occurs.

Audible-tone heterodyne interference will occur in both AM and FM systems when the frequency separation between two carriers is less than the upper audio-frequency cutoff of the receivers. In addition to heterodyne beats, the FM system output will exhibit fluctuation-noise increase and "swish" effects due to modulation as the undesired carrier increases toward equality with the desired-signal carrier at the input of the limiter-detector system. The feasibility of detecting a weak signal in the presence of a much stronger signal is indicated in Table 1. This tabulation presents the results of listening tests.

The detection of the weaker signal is dependent on interference produced by the audible beat notes or "swish". As is evident from the figures in Table 1, there is no significant difference between the two systems in this regard for the conditions shown.

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TABLE I  
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 Carrier Level Necessary to Obliterate Weaker Signal (db)
	13	62
	38	69
	12	60
	38	68

\* From Report R-3233, p. 23

### Adjacent-Channel Operation

Cross-modulation effects in AM systems usually determine the minimum channel-separation frequency which can be tolerated when transmitting and receiving antennas working in adjacent channels are located very close to each other, as on a ship. Output S/N depression in an AM system is usually negligible compared to cross-modulation. The cross-modulation interference takes the form of crosstalk in the receiver output; it can be reduced by additional selectivity preceding the first tube of the receiver, use of cutoff tubes, and various other means. FM systems are generally free of cross-modulation but are subject to output signal-to-noise ratio depression effects produced by co-channel capture. Increased selectivity preceding the FM detector is about the only practical means of reducing this effect without sacrifice of FM performance in other regards.

The crosstalk due to cross-modulation in speech communication will usually consist of a lower conversation; it will always be at a lower average level than the desired message under normal conditions, with the usual breaks and pauses, and can be segregated from the desired message to some extent by concentration on the part of the listener. The S/N depression effect with FM is, however, a function of the relative interfering carrier level and is essentially unaffected by the modulation of the undesired signal. It has no breaks or concentration so long as the undesired carrier is on, and the listener's ability to concentrate on the desired message through continuous fluctuation noise will determine how much intelligence he can obtain from the desired signal. The absolute low-limit without repeats will be the same as for single-signal operation; about +5 db peak output S/N ratio for the condition of this problem.

An intelligibility comparison<sup>46</sup> of the two communication systems (Figure 28) indicates that for equal word-list intelligibility of received signals, the frequency separation between adjacent signals must be about 50 percent greater for the AM than for the FM system. For this comparison the desired carrier was adjusted to produce a receiver output signal-to-noise ratio of 5 db before the undesired modulated signal, having a level of 30 db below the desired carrier, was applied.

<sup>46</sup> NRL Report R-3233, p. 40-42

R-3233, p. 40-42

DECLASSIFIED

Desired signal input = 12 microvolts (approx.). Output S/N (with no interfering signal) = +25 dB  
 Interfering signal carrier level = 30 db below 30 watts = 1.2 volts; modulation = 100% on vol-  
 peaks for all signals. Average results are for ten auditors (word-list tests) modulation on  
 desired carrier and continuous prose on undesired carrier.

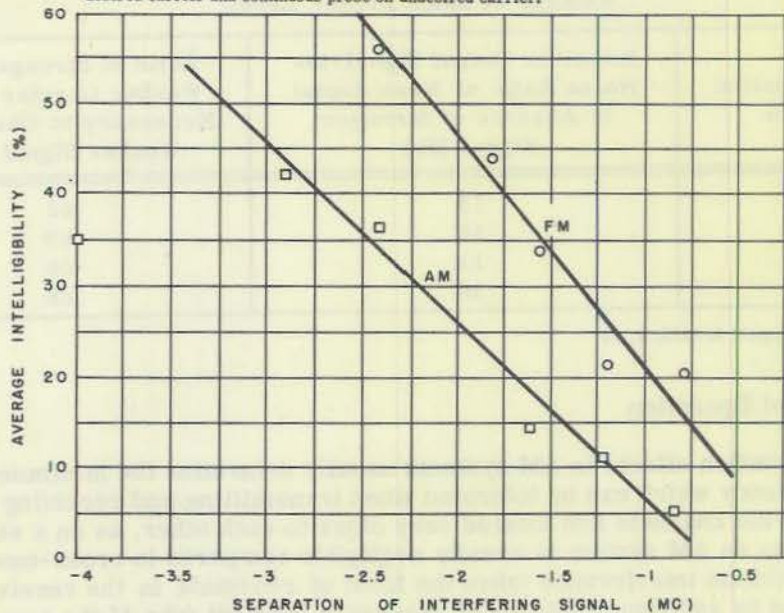


Figure 28 - Comparative intelligibility of the two communications systems during adjacent channel operation

## OTHER FACTORS CONSIDERED

### Multi-Path Propagation

In general, multi-path reception of an FM signal with its resultant phase effects can produce more output distortion than similar multi-path reception with an AM signal. As the frequency-deviation is increased for a given modulation frequency, the number of significant interference points in the spectrum of the signal increase, making wide-deviation FM even more vulnerable to multi-path propagation effects. While no specific tests for multi-path reception were made in this report, a considerable body of contract research reports and other technical literature on this aspect of radio communication was studied, leading to the above generalization. One of these reports,<sup>47</sup> for instance, gave AM an intelligibility score of 82.1 percent under the same system and propagation conditions, while FM gave 57.2 percent. The field test data has also indicated that more marked and severe fluctuations in signal output from the receivers were experienced with FM than with AM. A comparison was made for signal input levels which eliminated, insofar as possible, the signal region where FM begins to exhibit its abrupt "cutoff" effects with decreasing signal level; the FM output fluctuations observed could, however, have been partially due to the downward-AM capability limitations of the ratio-type detector. This limitation appears to be characteristic to some degree of all practical FM detector systems and

interference experienced. It is noted that, while the effect of multi-path propagation is a problem, a comparison of the two systems shows that, while the effect of multi-path propagation is more marked for FM than for AM, the effect is less marked for FM than for AM in a comparative sense. The effect of multi-path propagation is less marked for FM than for AM in a comparative sense. The effect of multi-path propagation is less marked for FM than for AM in a comparative sense.

<sup>47</sup> "Final Report: Engineering Research Study of High-Frequency Communication Methods," Paul Godley Co., Great Notch, N. J. (Signal Corps Contract Number W-39-sc-32244) April 1, 1948

with low signal input levels, where the limiter circuits are usually operating near their threshold re-  
characteristic

It is obviously undesirable under the conditions of signal "fading" multi-path propagation.

The use of an elaborate low-threshold limiter (e.g., eight cascaded stages) in a high-gain receiver circuit, with a wide pass-band immediately preceding the final FM detector, will result in much better system performance under multi-path conditions. This would be, however, an expensive and impractical type of design for most naval applications other than shore stations.

ns.

#### Pre-Emphasis

#### and De-Emphasis

Standard broadcast pre-emphasis would have contributed very little to the performance of either system used in the subject comparison, due to the 6 db cutoff at 3000 cps already provided in both systems. Some tests<sup>48</sup> were, however, made with 400 cps tone-modulation and de-emphasis in the experimental receiver starting at 500 cps; the results obtained are shown in comparative form in Figure 29. Considering the effect of de-emphasis in terms of the reduction it allows in input C/N ratio for a given value of output S/N ratio, the improvement with FM with limiting approaching the theoretical ideal is not more than 1 db reduction in C/N ratio until the detector input C/N ratio exceeds about +3 db with the ratio detector, however, the improvement is considerably greater. The AM system benefits most, particularly in the linear region above C/N = 0 db. One result of de-emphasis, which is due to the relative slopes of the AM and FM curves, is an increase of about +5 db in output S/N ratio at the AM/FM crossover, which becomes about +15 db instead of about +11 db for the nearly ideal case of the ratio-detector with primary limiter, and de-emphasis characteristic used was one which leads to a practicable transmitter pre-emphasis characteristic, since, with male voices, the peak speech energy region in frequency occurs below 500 cps. The improvements afforded by emphasis in a system are, of course, primarily due to the de-emphasis element. Pre-emphasis contributes only to the restoration of the original over-all frequency response. Besides an improvement in output S/N ratio, de-emphasis provides a reduction in receiver output noise as well as a less irritating noise spectrum.

on in the input C/N ratio required for a given value of output S/N ratio, made possible by de-emphasis, is equivalent to a decrease in transmitter radiated power required in the communication system. Taking +20 db output S/N ratio as the reference value, de-emphasis as incorporated in the tests would permit 1 db (about 20 percent) reduction in transmitter power rating for the FM system with near-ideal limiting, 3 db (30 percent) reduction for FM with the imperfect limiting of the ratio-detector only, and about 4 db (40 percent) reduction for AM.

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In a practical system, some reduction in average speech modulation level is necessary at the transmitter when pre-emphasis is used. Tests made on a complete AM TDZ-RDZ circuit in the laboratory<sup>49</sup> indicated a net improvement due to emphasis of about 2.5 db equivalent to a decrease in transmitter power.

<sup>48</sup> NRL Report R-3422, p. 29-30

Report R-3422, p. 29-30

<sup>49</sup> NRL Laboratory Report R-3910-64/49 of 27 May 1949

Report R-3910-64/49 of 27 May 1949

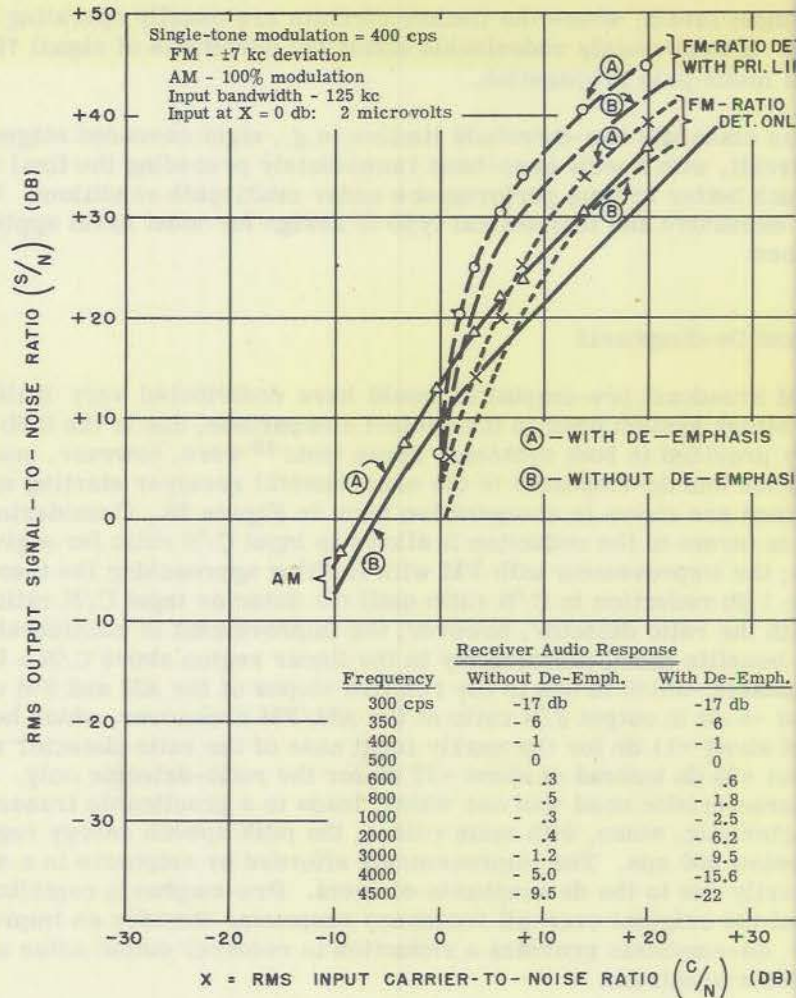


Figure 29 - Comparison of measured performance of both systems with and without de-emphasis

Theoretical Improvement Afforded by Emphasis

The following equations have been derived<sup>50</sup> for the computation of the theoretical improvement afforded by emphasis in AM and FM systems:

$$I_{AM} (db) = 10 \log_{10} \frac{\left\{ 2 + 2x^2(2 + m^2) \right\} (\gamma_c - \gamma_1) - \frac{1}{2}(\gamma_c^2 - \gamma_1^2)}{\gamma_d^2 \left[ \frac{\left\{ 2 + 2x^2(2 + m^2) \right\} (\theta_2 - \theta_1)}{\gamma_d} - \frac{1}{2} \log_e \frac{\gamma_d^2 + \gamma_c^2}{\gamma_d^2 + \gamma_1^2} \right]} \quad (6)$$

<sup>50</sup> NRL Report R-3231, p. 47-51

$$I_{FM}(db) = 10 \log \frac{\frac{2}{3}(\gamma_c^3 - \gamma_1^3)(x^2 + 1)^2 + (\gamma_c - \gamma_1)(8\rho^2 + 4d^2)}{\gamma_d \left[ 2(x^2 + 1)^2 \gamma_d \left\{ (\gamma_c - \gamma_1) - \gamma_d(\theta_1 - \theta_2) + (8\rho^2 + 4d^2)(\theta_1 - \theta_2) \right\} \right]}, \quad (7)$$

where

$I_{AM}(db)$  is the improvement in db for the AM case,  
 $I_{FM}(db)$  is the improvement in db for the FM case;

$\gamma_c$  = rms unmodulated carrier-to-noise ratio at the input to the final detector,

$m$  = modulation depth ( $m = 1$  for 100 percent modulation),

$\rho$  = ratio of maximum carrier-frequency deviation to the half-bandwidth at the input to the detector (e.g., half-bandwidth of the r-f plus i-f amplifiers),

$d$  = detuning ratio (i.e., ratio of amount by which the carrier frequency is detuned from the discriminator center-frequency to the half-bandwidth at the detector input);

also

$\tan^{-1} \frac{f_{ah}}{f_d}$ , and  $f_{ah}$  = high audio cutoff frequency in receiver,

$\tan^{-1} \frac{f_{al}}{f_d}$ ,  $f_{al}$  = low audio cutoff frequency in receiver,  
 $f_d$  = frequency at which response of de-emphasis network is 0.707 of its maximum value,

$\frac{2f_{ah}}{f_i}$ ,

$\frac{2f_{al}}{f_i}$ ,  $f_i$  = input bandwidth at final detector.

$\frac{2f_d}{f_i}$  ;

GENERAL DESIGN CONSIDERATIONS

Transmitter

In addition to performance considerations, a comparison of AM and FM systems must take into account circuit and other physical differences in the transmitters and receivers. For the transmitters, it can be stated that, in general;

- (a) The modulating power required for an AM transmitter is greater than that required for an FM transmitter. High-level plate modulation of an AM transmitter requires audio power approximately equal to 50 percent of the dc power input to the final carrier amplifier. The use of FM can result in a reduction of transmitter primary input

power and elimination of many of the circuit components necessary to high level modulating power output. The saving for an FM transmitter generally becomes a greater absolute value in terms of the total weight, and space as the output power rating of the transmitter is increased. In the case of the 30-watt transmitters used in the subject AM/FM comparison trial it is estimated that this saving would amount to between 10 and 20 percent in primary power input, and in total weight and space.

(b) The saving listed in (a) is partially offset by the necessity of providing phase-modulator and integrating circuits or other frequency-modulating means in the FM transmitter.

(c) Distortion-free modulation of FM transmitters is not simple to achieve, particularly in crystal-controlled designs. It may require use of orders of multiplication higher than would be necessary in an equivalent AM transmitter, particularly with large deviations, and thereby tend to abrogate transmitter and spurious response improvements such as are possible with harmonic mode crystals. In fact, FM, because it represents a controlled frequency-instability, tends to oppose the frequency-stabilization incorporated in a transmitter.

(d) The advent of effective and simple low-level AM modulation tends to reduce the FM advantage listed in (a). At peak (100 percent) modulation requires 1.8 db additional radiation power for its sidebands as compared to the zero modulation condition. Since, however, peak modulation occurs only part of the time with speech transmission, various devices may be used to reduce the average modulation required by the AM transmitter.

### Receivers

In general, FM receivers require two elements not normally necessary in AM receivers:

- (a) some means of minimizing or eliminating the amplitude variations present in the received signal before final detection,
- (b) some means of converting low-percentage frequency variations to equivalent amplitude variations for detection.

The means for minimizing amplitude variations usually takes the form of amplitude limiters. Many of these devices possess serious shortcomings in that they exhibit threshold effects, peculiarities with respect to transient response, etc. Even the best of them force compromises and/or circuit additions in receiver design not normally necessary in an AM receiver. Conversion of low-percentage frequency variations into directly proportionate amplitude variations requires linear phase discriminators which are highly sensitive to very small changes in carrier frequency. In the UHF system under consideration, the average carrier-frequency deviation due to speech modulation was less than  $\pm 0.001$  percent. With good limiting, the discriminator in this case requires a frequency stability for optimum performance which approaches quartz-crystal tolerances. Since maintenance of this high degree of precision is a practical impossibility under operational conditions, some form of automatic centering means (such as AFC) must be considered. Such devices, if used, result in added complications which tend to further compromise the FM system.

AM receivers require some form of amplitude-limiter to provide impulse-noise reduction comparable to FM receiver performance. Several simple and effective circuits which are unaffected by detuning are available for this application, but their use generally involves added output-harmonic distortion at high modulation levels not usually present in limited-power FM receiver output.

## SUMMARY COMPARATIVE AM/FM PERFORMANCE

The relative performance of AM and FM systems approaching the ideal theoretical limits, compared on the basis of equal unmodulated radiated-carrier power, may be summarized (Table 2). It is based primarily on the conditions set up for the subject problem, but also has general applicability.

## CONCLUSIONS

It has been concluded from the results obtained that:

- (a) AM is preferable to FM for the highly mobile terminal conditions characteristic of the U.S. Navy Service, due to better weak-signal performance and relative freedom from cross-channel and adjacent-channel capture effects, as well as to generally lower susceptibility to multi-path propagation difficulties.
- (b) AM is preferable from the standpoint of spectrum occupancy, increasingly so as the carrier frequency is reduced because the receiving system's bandwidth can decrease almost directly with carrier frequency in the AM case.
- (c) AM is preferable from the standpoint of ease of equipment alignment, freedom from detector symmetry and centering limitations, and tolerance of severe detuning with negligible impairment of performance.
- (d) AM is preferable from the standpoint of circuit simplicity, particularly in the receiving equipment.
- (e) FM may be advantageous for geographically fixed communication and broadcast systems, particularly if the receiving equipment is carefully designed, operated, and maintained.
- (f) FM is generally preferable for truly high-fidelity reproduction of speech or music, with the same limiting conditions as given in (e).
- (g) FM permits adjacent-channel spacing in frequency about 2/3 of that feasible with AM on the basis of equivalent signal deterioration due to FM signal-to-noise depression effects as compared to AM cross-modulation.
- (h) FM, in general, can permit a smaller transmitter with less required primary power for a given transmitter carrier output rating than AM. By use of various techniques in AM transmitter design, the difference can be reduced, if continuous high-power AM output is not required.
- (i) FM poses a difficult problem of transmitter modulation in crystal-controlled systems, increasingly so as the required deviation increases, and may force a higher order multiplication not otherwise required or desirable.

TABLE 2  
Summary of Comparative AM/FM Performance

Factor	AM	FM	Factor	AM	FM
1 Spectrum Occupancy*	Needs only bandwidth of twice the highest modulating frequency (or one-half this for single-sideband).	Usually requires several times the bandwidth of AM system to realize FM advantages effectively	7 Output Distortion	Can be better than FM in presence of interfering signals or multi-path reception. With noise-limiter, not as good for truly high-fidelity reproduction under single-signal conditions.	With single-signal reception, capable of exceptional fidelity.
2 Propagation	Susceptible to multi-path effects, particularly "carrier fading."	Susceptible to multi-path effects, particularly "side-band fading."	8 Pre-emphasis and De-emphasis	Can be applied; more feasible at higher carrier frequencies. Increases cross-over output S/N about 5 db, due to fairly constant improvement of S/N ratio. (equivalent to about 3 db increase in carrier power).	Improvement for same conditions less than with AM for input C/N ratio < about 3 (equivalent to about 1 db increase in carrier power with "perfect" limiting).
3 Inherent Fluctuation Noise	Output S/N ratios rather low; signal intelligible but noisy.	Output S/N ratios usually very low; substantially no intelligence.	9 Detuning (off-centering and drift)	Affected very little, up to limit of selectivity preceding AM detector.	Very vulnerable except with strong signals; can be helped considerably by AFC.
(a) Weak Signals (C/N ratio $\leq 1$ )	Output S/N ratios about minimum range design values.	Output S/N ratios can be well above minimum range values.	10 Tuned-Circuit Misalignments	Not much affected, except in reserve gain and possible broadening of selectivity curve.	Very vulnerable to discriminator unbalance and dissymmetry. Affected by selectivity curve irregularities in peak-response region.
(b) Medium Signals (C/N = 2 to 3)	Output S/N ratios good but about 10 db less than FM.	Output S/N very good.	11 Equipment Simplicity	Probably simplest of all systems, when double-sideband type.	More complex; reception requires suppression of AM, then conversion of FM to AM for detection.
(c) Strong Signals (C/N > 10)	With effective AM noise-limiter, can be better than or equal to FM. Alignment and detuning effects negligible.	Greatly affected by alignment and centering on desired carrier.	12 Size, Weight, and Primary Power Requirement	May be greater for transmitter with any given carrier power rating. Can be somewhat the lesser in	Transmitter may be better in this regard than AM; receiver requires more circuitry and com-
4 Impulse-Noise Interference	Not as good as properly adjusted and centered FM.	Very good. Not very critical to detuning.			
(a) Weak and medium signals	Much less than FM.	Serious capture effect.			
(b) Strong Signals	Mostly heterodyne beat-note (if audible frequency).	Heterodyne beat-note (if audible frequency), "swish," noise.			
5 Co-channel Operation	Cross-modulation present; very little output S/N ratio depression.	Serious output S/N ratio depression possible; no apparent cross-modulation.			
(a) Capture					
(b) Masking					
6 Adjacent-Channel Operation					

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## RECOMMENDATIONS

It is recommended that:

- (a) AM used wherever possible in Naval applications involving mobile stations.
- (b) FM considered for communication circuits with both terminals essentially fixed geographical location, each case on its own merits.
- (c) Further investigations of relative AM/FM performance utilize the theoretical approach first, employing a mathematical treatment such as outlined in this report and described more fully in NRL Report R-3231.\* This will allow the experimental work to be limited to a minimum of time and effort, or even eliminated entirely in some cases.

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\*An examination of such an approach is embodied in the paper "The Case for Amplitude Modulation of Very-High-Frequency Marine Communications," by Emerick Toth. An abridged version of this paper was presented at the Fall Assembly Meeting of the Radio Technical Commission for Marine Services (RTCM) at Cleveland, Ohio, on October 25, 1949, with the full version distributed subsequently to the RTCM membership.

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\* \* \*

#### APPENDIX A Background Information

In July 1939, the Naval Research Laboratory undertook a field comparison for the Bureau of Ships of the relative performance of AM and FM communication systems in the vhf range. Performance tests were made at a frequency of about 80 Mc. The equipment used were manufactured by the General Electric Company and were capable of rapid switching from AM to FM or reverse. The test installations were on three destroyers which operated in the Chesapeake Bay area. Engineers of the General Electric Company were present to aid in making the tests.

Data was accumulated on comparative range of reception, effects of interference signals and noise, and various other factors, following, in general, a procedure similar to that used in the shipboard trials\* of the subject investigation. The results obtained indicated that AM was the more advantageous type of modulation for naval operations under the conditions investigated, and that FM presented some serious disadvantages which precluded recommendations for its employment in interfleet communications.

The question of AM versus FM arose again in 1946, when the Bureau of Ships requested that the Naval Research Laboratory undertake another comparison of the two types of modulation, this time in the 225- to 390-Mc range. In October 1946 a conference was held at the Bureau of Ships concerning the conversion of Models RDZ TDZ receiving and transmitting equipment for FM operation. The RDZ TDZ was in a series of receivers of standardized design which have been mechanically arranged with the view of easy conversion to FM reception, if desired. The NRL recommended that a ratio-type FM detector system be employed, since it required no additional i-f amplifier gain over that already provided for AM, and also was less critical as regards accurate centering of the receiver passband on the carrier frequency. It was suggested, however, that the National Company, which was to make the conversions, should initially convert two receivers, one to ratio detection and the other to the standard Armstrong-type of FM detection system (several stages of saturation limiting by a Foster-Seeley type of phase detector). The National Company found that the i-f gain required for satisfactory limiting in the latter type of system resulted in a high degree of i-f amplifier instability. The receiver was also extremely critical as to proper centering of the detector passband on the carrier, with a very large rise in distortion level resulting from slight detuning by even a few kilocycles. As the result of the National Company's tests with both types of FM detector system, it was decided to convert the ratio-type detector in the 12 RDZ's which were modified for this problem.

The conversion of the TDZ transmitters was handled by the General Electric Company at Syracuse, New York. The only type of FM modification practicable in the case, without very extensive redesign, involved use of a phase-shift type of modulation preceded by

\* NRL Report R-3234

an audio-in-ating network. The maximum frequency modulation feasible with such a circuit was the order of plus and minus 30 kc at the carrier frequency of 328.2 Mc which was employed in the tests. The maximum deviation possible, without serious distortion, was estimated to be about plus and minus 15 kc. There was considerable discussion to the limit of deviation to be used in the project. The final decision was for plus and minus 7 kc, a compromise which allowed minimum distortion, with no need of increased receiving system bandwidth in order to accommodate the maximum frequency modulation as well as the system frequency drift.

Initial measurements of the project plans contemplated field trials only, preceded by equipment and standardization in AM-FM pairs. The final plans included:

- a. Theoretical studies to determine the limits of ideal system performance.
- b. Measurements of equipment performance, and standardization of equipments to be used in the tests.
- c. Laboratory trials under conditions simulating those in the field tests.
- d. Field trials employing ships at sea.
- e. Field trials employing aircraft and shore installations.

The order in which the work was done was based on the availability of equipment, field facilities, and manpower. Of necessity, most of the theoretical work was actually done last rather than first. The laboratory trials were conducted in the early spring of 1947, with the shore tests taking place in May and June of 1947, and the air tests in June and July of 1947.

The details of each phase of the investigations were worked out in committee prior to actual execution, so as to insure that all interests were taken into account and no pertinent items were overlooked. The "committee" consisted of all parties directly interested in the particular details under discussion, with NRL, BuShips, OpDevFor, and other organizations represented as needed. The group met on an average of about once a week, until such time as the investigations became unnecessary.

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