NATIONAL BROADCASTING COMPANY

NBC

ENGINEERING DEPARTMENT

INFORMATION SERVICE

NBC FREQUENCY-MODULATION FIELD TEST

By

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Summary—The full theoretical advantages of frequency modulation may be obtained in practice if the transmitting and receiving apparatus are properly designed.

For primary service, amplitude modulation on the ultra high frequencies offers some advantages over standard broadcasting. Frequency modulation offers advantages over amplitude modulation on the ultra high frequencies. The advantages to the listener of frequency modulation on the ultra high frequencies consist of freedom from the 10-kc beat note and side-band interference which result from the frequency allocation of standard broadcasting, and also the reduction of locally generated noise, atmospherics, and interference from distant stations operating on the same channel. Standard broadcasting has the advantage of providing clear channel night-time service to vast areas which would not be served by frequency modulation on the ultra high frequencies.

TWENTY years ago all frequencies above 1500 kc were generally considered to be of such little value that even the amateurs had objections to being confined to them. There is no need to state here what has since occurred on these "useless" frequencies nor to dwell on the fact that the surface has but been scratched. One service after another has wholly or partially transferred the bulk of its activities to them, and a multitude of new and invaluable services have been made possible by their use. So-called "Standard Broadcasting" had a most humble beginning on 830 kc, which was then in the middle of the marine band of 500 kc to 1000 kc. Broadcasting quickly crowded the original occupants out of most of this band. It is not one of the services which have since moved into the high-frequency spectrum. It remains on the former marine frequencies where it started. But there is a possibility that a shift may be approaching.

The use of the ultra-high frequencies for sound broadcasting offers some technical advantages. These advantages consist of escaping the present 10-kc channel limitation, getting away from static and eliminating all except spasmodic long-distance interference. We have known this for many years, have for a decade experimentally operated low power u-h-f stations and at times have had the experience of receiving good service from our low-powered u-h-f transmitters when static ruined reception from our high-powered standard broadcasting plants. Five years ago the FCC had applications for, or had licensed, over 100 u-h-f transmitting stations and it seemed that a trend was developing toward u-h-f broadcasting, but this trend was not sustained. Interest has been revived in recent months through wide-spread discussion of the advantages of frequency modulation on the ultra high frequencies.

Amplitude-modulated u-h-f stations can provide greater coverage than standard broadcasting shared-channel stations limited by night-time interference from distant stations operating on the same channel. This interference usually causes such a station's useful service area to shrink to a small fraction of its daytime area and many of these stations are, in addition, required to reduce power at night to minimize similar interference to other stations. Few such stations are free from night-time interference within their 2000 microvolt contour and many are limited to 8000 microvolts. The ultra high frequencies offer an escape from such limitations by virtue of practical freedom from static and shared-channel interference. Frequency modulation can provide a much greater degree of improvement than can amplitude modulation on these ultra high frequencies.

Purpose of F-M Field Test

The National Broadcasting Company has been one of the groups which viewed realistically the possibilities of the ultra high frequencies and has pioneered in conducting experimental operations in that field for many years. It has been NBC's belief that at some time in the future these ultra high frequencies would come into much wider use. It is the policy of NBC to investigate every technical development affecting its field and apply it where possible to provide better public service. Toward that end 18 months ago NBC formulated plans for an exacting field test of frequency modulation similar to the field test of television which preceded the dedication of that service on April 30, 1939. The purposes of the field tests were to quantitatively evaluate the advantages of frequency modulation over amplitude modulation on the ultra high frequencies, not by confined laboratory measurements which had already been made by others, nor merely by operating a frequency-modulated station, but *by painstakingly measuring and comparing the two systems under all kinds of actual service conditions in the field* and determining how much of the theoretical advantage of FM could be obtained in practice.

The impression has been gained by some, that only by tne use of FM may the public now enjoy high fidelity sound reproduction in the home. With ultra high frequencies, the same fidelity can be provided with either amplitude or frequency modulation. Improved fidelity is made possible by increasing the transmitting channel width beyond the 10-kc channel allocations of the standard broadcasting band and not by using a particular type of modulation. Irrespective of the type of modulation, receivers for "high fidelity" reproduction require equally costly high power, low distortion audio amplifiers and expensive loudspeakers and acoustical systems.

Present-day transmitters of NBC and others in the standard broadcasting band transmit much higher fidelity than is reproduced in moderate-priced receivers. To reproduce sound in the degree of fidelity which is now available, requires more costly receivers. Popular interest has been much more pronounced in low-priced receivers than in high fidelity at more cost. The problems of high fidelity are problems of cost and of widespread public appreciation of improved fidelity and not of a type or method of modulation. High fidelity eventually will receive the recognition it merits. Provision has been made for it in the ultra-high-frequency channel allocations.

In the NBC field test of frequency modulation attention was directed toward the evaluation of the frequency modulation system in the suppression of undesired noise and interference, using the amplitude modulated system as the reference, or standard of comparison.

Scope of the Tests

To carry out this project properly, and for the first time completely, it was decided that:—

1. The same transmitter, transmitting antenna, receiving antennas, receivers and measuring equipment should be utilized for each system of modulation.
2. The transmitter and receiver should be equipped for instantaneous switching to either amplitude modulation or frequency modulation and the transmitter should be of 1000 watts power.
3. The transmitter power should be continuously variable over a range of 10,000 to 1 on frequency modulation, and a means of accurately measuring it should be installed.
4. The most important comparisons should be between amplitude modulation, frequency modulation with a deviation of 15 kc (total swing of 30 kc), and frequency modulation with a deviation of 75 kc (total swing of 150 kc). A minimum of 15 kc deviation was chosen because it represents a deviation ratio (deviation divided by maximum audio frequency transmitted) of 1 and because a 30-kc i-f system would still be required for a smaller deviation, to accommodate the side-bands.
5. Order wires should be used between the transmitting and main

receiving points to expedite the work and insure accurate results.

6. The observations and measurements should be conducted at a number of scattered and representative receiving locations throughout the service area of the station.
7. The observations would include shared channel and adjacent channel operation of F-M stations.

The transmitter was equipped with relays for instantly selecting at will the condition of modulation desired. Since the degree of frequency deviation is directly proportional to the audio input voltage, pads, selected by a relay, served to produce various frequency deviations. Herein, for frequency modulation, the term "per cent modulation" refers to the passband of the system and is the ratio of the total swing being used divided by the total pass-band.

Tone modulation was used for most measurements. For measurements of distortion or signal-to-noise ratios, with modulation present, the tone output of the receivers was cleaned up by passing it through filters and then impressed upon RCA noise and distortion meters.

For brevity the following designations will be used herein:

AM ....Amplitude Modulation.
FM-15 ....Frequency Modulation with a deviation of 15 kc, or total swing of 30 kc.
FM-30 ....Frequency Modulation with a deviation of 30 kc, or total swing of 60 kc.
FM-75 ....Frequency Modulation with a deviation of 75 kc, or total swing of 150 kc.
S/N ....Signal-to-noise ratio.

Preliminary work on this field test was started in April, 1939, and the project was completed on May 4, 1940. The results of this work were submitted to the FCC during the F-M hearings of March, 1940 and presumably were of assistance to that body in formulating rules and standards of good engineering practice covering u-h-f broadcasting.

THE TRANSMITTER

The 1000-watt transmitter was an RCA unit, originally designed for amplitude modulation, which was modified and equipped to meet the requirements for both FM and AM. The receivers, of which there were four, were specially designed and built throughout so as also to meet the requirements.

Special temporary authorization was requested and obtained from the FCC to use either FM or AM on 42.6 Mc, ordinarily an exclusive F-M frequency.

The station was licensed as W2XWG and was constructed on the Empire State Building in New York City. It is shown in Figure 1. This transmitter utilized an FM modulator of the type developed by Murray G. Crosby of the RCA. Some manufacturers of F-M transmitters have adopted this system as standard equipment for commercial F-M transmitters. The transmitter was equipped with a reactance control in the primary circuits of the main rectifier which

Fig. 1

permitted continuously variable control of the carrier power from 1000 watts down to less than 1/10 of one watt during transmission with frequency modulation. A General Radio multi-range vacuum tube voltmeter was provided to measure the transmission line voltage and power accurately at any point over this wide range. Both of these instruments are illustrated by Figure 2.

The frequency modulator consisted of several tubes, including an oscillator, a reactance tube, a crystal beating oscillator, a discriminator and a filter. The operation is as follows:—

The reactance tube produces a change of reactance in its output circuit when the grid voltage is actuated by d-c bias or a superimposed audio frequency such as tone or program. This reactance controls the frequency of a connected oscillator which drives the transmitter. The other items in the unit are provided to maintain accurate average carrier frequency stability. This is accomplished by a series of simple operations. A fixed crystal oscillator beats against the frequency of the modulated oscillator to produce an average difference frequency of 1500 kc. This 1500 kc is brought up in level through an amplifier and impressed upon a discriminator. When the carrier frequency is such that exactly 1500 kc is produced no voltage appears in the output of this discriminator. However, when the reactance tube average frequency changes, 1500 kc is no longer produced and a voltage is developed in the output circuit of the discriminator. A discriminator output filter removes all modulation frequencies to produce a direct current which controls the reactance tube d-c bias and thus the average frequency of the oscillator. The purpose of the filter is to prevent the reactance tube bias from changing with modulation.

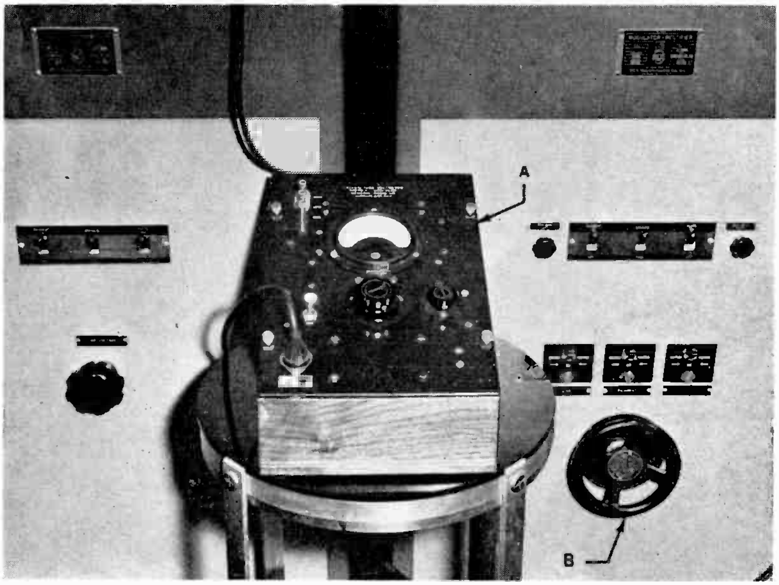

Fig. 2

The transmitter modulation characteristics are shown on Figure 3.

On this curve there are plotted a-c volts as the abscissa and carrier frequency as the ordinate. The audio input to the transmitter is superimposed on the reactance tube d-c bias.

Figure 4 shows the overall frequency response of W2XWG and the Bellmore receiver before pre-emphasis and de-emphasis were inserted.

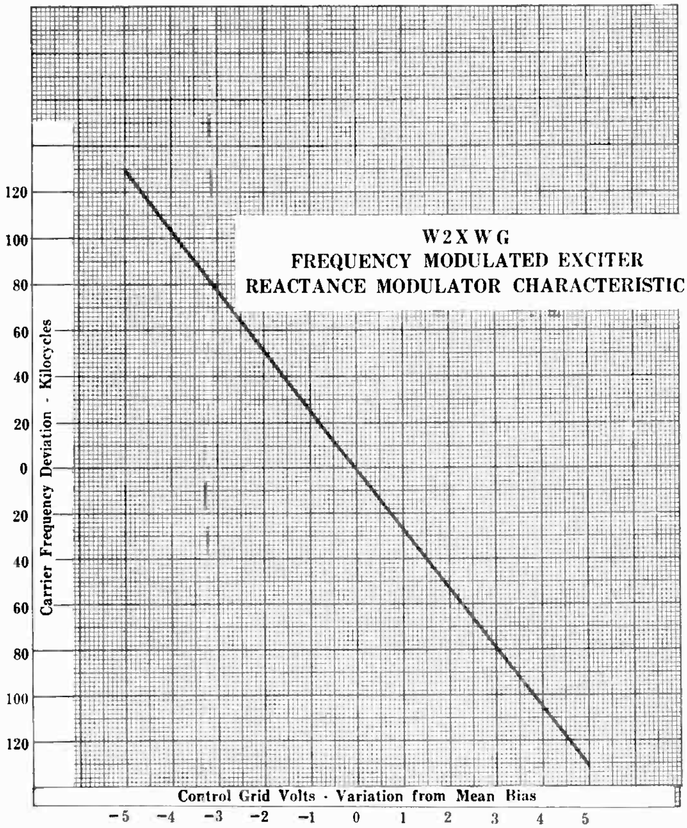

Fig. 3

The antenna normally used for transmitting for the field test was the television video unit on top of the Empire State Building.[1] However, an auxiliary antenna was built consisting of a folded dipole. This was directed eastward towards Bellmore and used when the video antenna was occupied for television schedules.

The photograph on page 5 shows the video antenna, which is 1300

[1] Television Transmitting Antenna for Empire State Building, Nils E. Lindenblad, RCA Review, pp. 387-408, April, 1939.

feet above the sidewalk. Figure 6 shows the folded dipole in operating position.

The circuit arrangement of the special 1000-watt transmitter is illustrated in the form of a block diagram in Figure 7. The frequency modulator comprises the five blocks at the upper right side, containing RCA 6V6, 6K8 and 6H6 tubes.

The degree of frequency deviation was measured by a method recently described in the RCA REVIEW[2]. The method consists of applying a constant frequency tone to the transmitter input terminals and gradually increasing the voltage until the carrier amplitude drops to zero. When this occurs, the frequency deviation is 2.405 times the audio

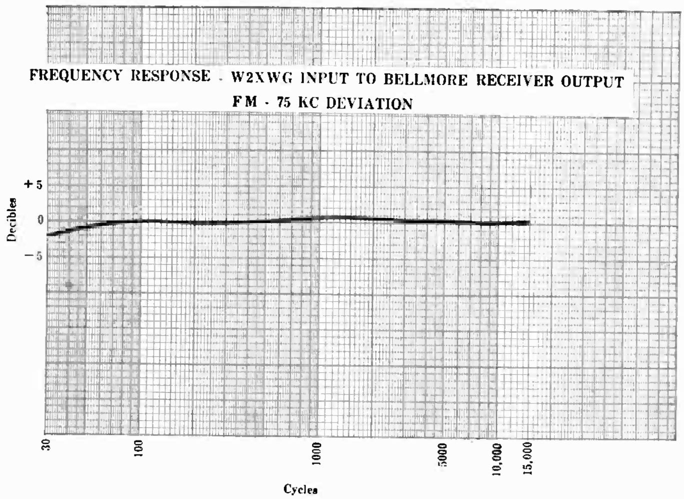

Fig. 4

modulating frequency. This method is simple and very satisfactory if reasonable precautions are taken.

THE RECEIVERS

In order that an exacting comparison of amplitude and frequency modulation can be made, it is very desirable that the receivers for the two systems be as nearly ideal and alike as possible. This practice minimizes otherwise possible errors due to differences in receiver performance. The ideal way to build such receiving systems would be the

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[2] A Method of Measuring Frequency Deviation, M. G. Crosby, RCA REVIEW, pp. 473-477, April, 1940.

common use of as many parts as possible. This was done. They were built on the same chassis. The r-f amplifier, first oscillator and the converter were used to drive two different i-f systems in parallel. Switching and chassis space was provided for a third i-f system but it was not used. The i-f systems were used separately and each was designed particularly for the reception of the modulating system to be tested. Each contained an F-M and an A-M detector and each detector had a separate audio output amplifier. The outputs of these audio

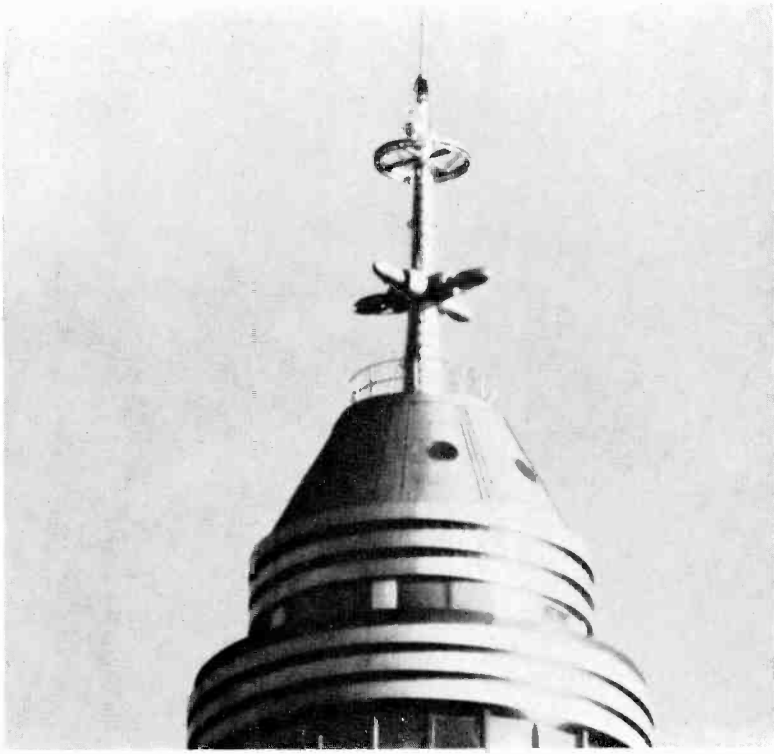


Fig. 5

amplifier tubes were all in parallel, but the system desired was selected by screen grid blocking of the other amplifiers. For AM and FM-15, parts of the same i-f system were used but the detectors and limiters were separate. For FM-75 a separate i-f system was used. This was also provided with a separate A-M detector, but it was little used because the 150-kc i-f passband was not representative of amplitude receivers. One meter was provided to show the diode currents and another was provided to show the discriminator currents. The latter is a zerocenter meter which indicates zero discriminator current when the receiver is exactly tuned for FM. Separate gain controls were provided for the i-f systems and also for the individual audio amplifiers. The receiver output circuit was provided with a very sharp 8-kc low-pass filter with a disconnecting key and the high-frequency de-emphasis circuit at this point was also provided with a disconnecting key. A single switch served to select the type of modulation which it was desired to receive.

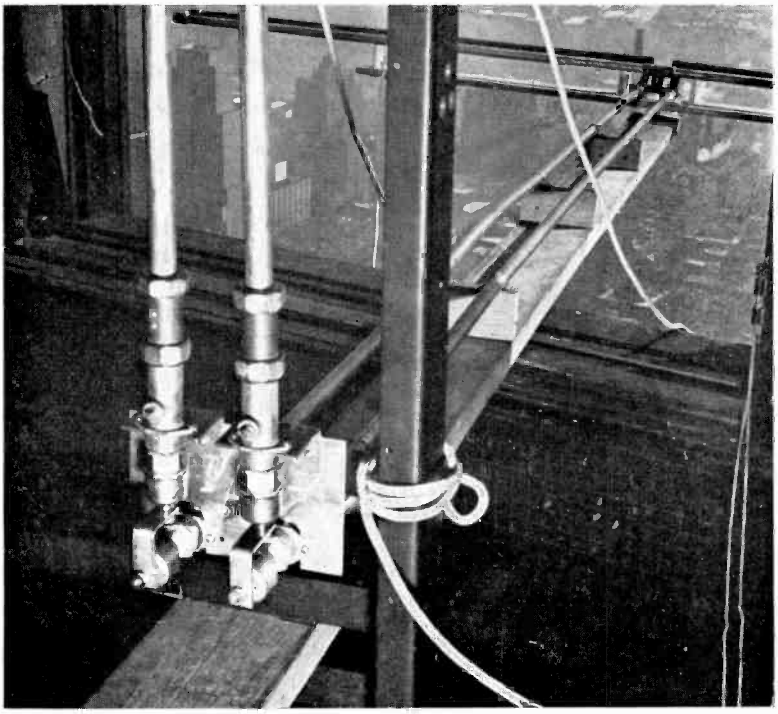
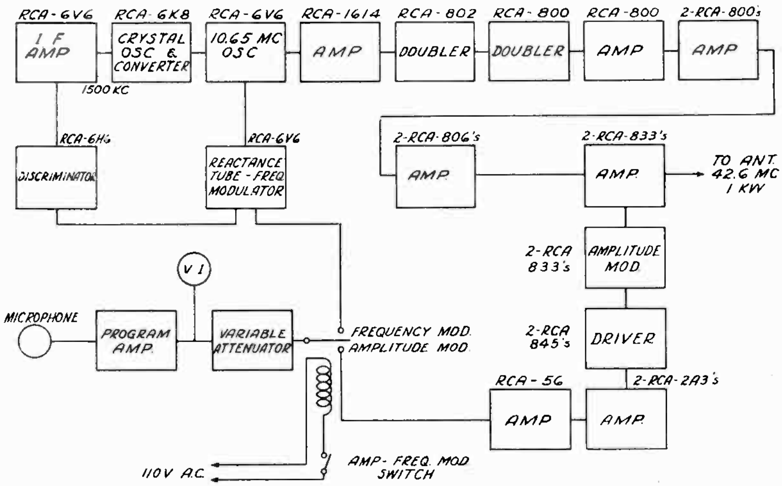


Fig. 6

Four receivers were specially built by the RCA Manufacturing Company for this test and would theoretically give full output with an r-f voltage of only 1/10 microvolt across the input terminals. The hiss level of 1 microvolt peak in these receivers was representative of the best modern receivers and was produced by thermal agitation in the antenna circuits and by tube hiss. They were made as good as receivers can be built in order that the final conclusions concerning frequency modulation as a system would not be erroneous due to apparatus shortcomings. The sacrifice of receiver design to price will not permit



FM-FIELD TEST TRANSMITTER W2XWG

Fig. 7

the full gain of frequency modulation, as reported herein, to be realized.

A block diagram of the duplicate receivers is shown in Figure 8. A photograph of one of the receivers is shown in Figure 9. At Bellmore and also in the NBC laboratory in Radio City there were provided and used a special F-M receiver, dipole antenna and trans-

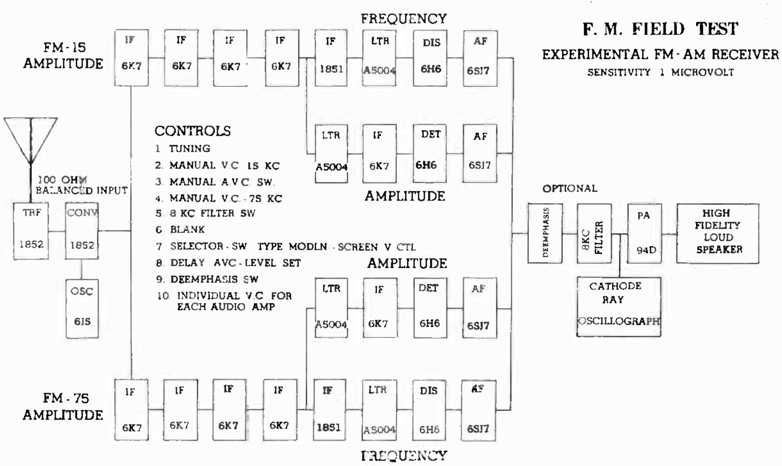


Fig. 8

mission line, commercial receivers of various makes, cathode-ray oscillographs, a special high-fidelity high-power audio amplifier, an RCA audio oscillator, an RCA noise and distortion meter, a harmonic analyzer, disc-recording equipment, a high quality loudspeaker, unweighted volume indicators, volume indicators weighted for ear response, a u-h-f signal generator, a u-h-f field intensity measuring (RCA type 301A) set, r-f transmission line calibrated attenuators, noise-producing devices including automobiles, diathermy machines,

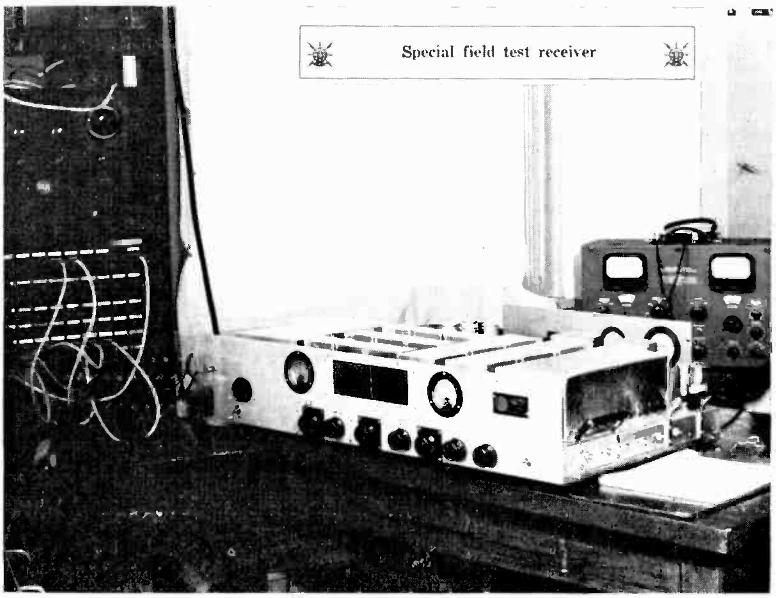


Fig. 9

etc., audio voltage amplifiers, balanced variable pads, and a microphone for recording.

The i-f systems in these receivers were painstakingly designed and adjusted for FM-15, FM-75 and AM, and at intervals during the field tests they were checked with respect to filter characteristics, i-f characteristics, limiter action, discriminator performance, audio frequency response, distortion, etc.

A shielded mutual inductance type antenna attenuator was built and calibrated for controlling the amount of signal or noise voltage reaching the Bellmore receiver input terminals from the antenna. By controlling the power of W2XWG, the antenna attenuator and the noise sources themselves, any desired carrier or noise voltages could be produced. Separate means were provided for controlling the noise amplitudes without changing the character of the noise.

Figure 10 shows measurements made with the special RCA field test receiver and two commercial receivers. Receiver input microvolts are plotted against audio output level. The drop in the commercial receivers is due to r-f gains insufficient to operate the limiters at low input

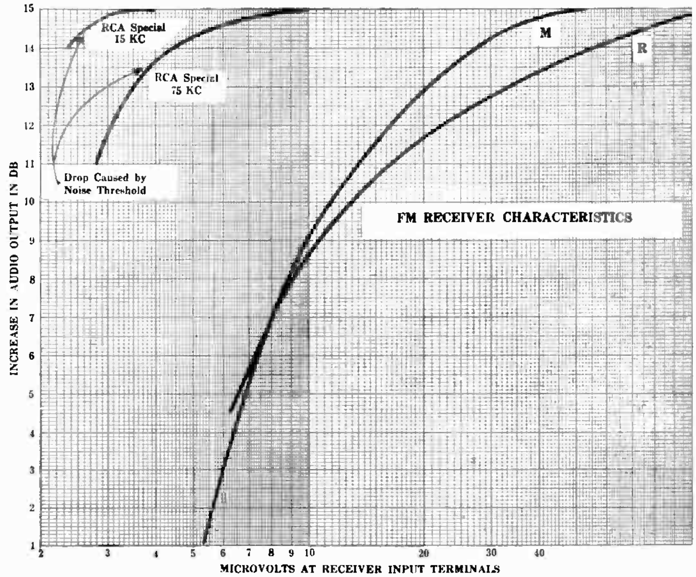


Fig. 10

voltages. The drop in the field test receiver is due to the noise threshold limitation and not lack of r-f gain.

The Field Intensity Survey of W2XWG

At the Bellmore receiving location all observations and measurements were correlated with field intensity in microvolts per meter, and also with the number of microvolts across the receiver input terminals. Similar measurements were also made of the noise voltages. In order that all of these measurements could be directly related to miles service radius, a field intensity survey was made of W2XWG. The measurements were carried out to 3.5 microvolts per meter, corresponding to a distance of approximately 85 miles, as shown on the survey map of Figure 11. The radiation index for W2XWG is 910. This is defined as the product of the antenna height, the antenna gain and the square root of the power in kilowatts.

One of the Radio Facilities engineering cars used by NBC for such measurements is shown in Figure 12. Each of these cars is a passenger sedan in which the body and interior has been modified to house a 75B RCA 500-kc to 20-Mc field intensity measuring set, a 301A RCA 18-Mc to 155-Mc field intensity measuring set, a modified RCA 302A

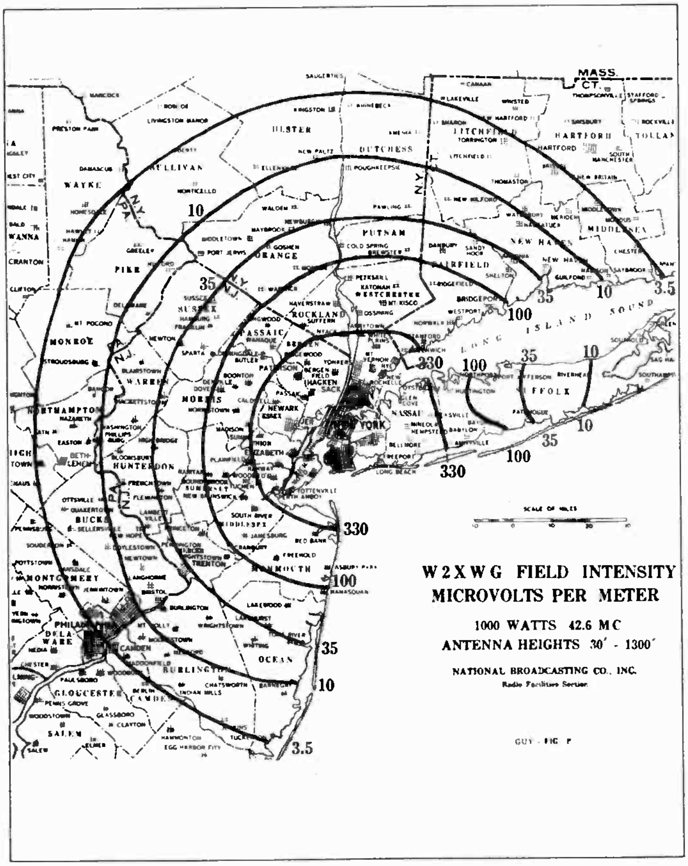


Fig. 11

noise meter, 2 Esterline Angus recorders, a driveshaft-to-recorder gear and clutch system, a special vernier speedometer and distance recorder, an automobile receiver, an aviation type broadcast loop, a u-h-f universally mounted antenna, a swivel-mounted searchlight, a compass and a steel mounting frame with aviation shock absorbers for instruments. Quick-demountable mechanisms permit easy removal of measuring gear.

THE MEASURING LOCATIONS

As a part of this project, field tests and electrical transcriptions were made under a variety of conditions at the following locations:—

Collingswood, N. J.	—85 miles	(temporary station)
Hollis, L. I.	—12 miles	(temporary station)

Fig. 12

Floral Park, L. I.	—15 miles	(temporary station)
Port Jefferson, L. I.	—50 miles	(temporary station)
Commack, L. I.	—36 miles	(temporary station)
Riverhead, L. I.	—70 miles	(temporary station)
Hampton Bays, L. I.	—78 miles	(temporary station)
Bridgehampton, L. I.	—89 miles	(temporary station)
Eastport, L. I.	—65 miles	(temporary station)
Bellmore, L. I.	—23 miles	(permanent station)
NBC Laboratory	— 1 mile	(permanent station)

In addition to making thousands of measurements at the permanent stations, field intensity measurements, listening tests and orthacoustic recordings were made at each of the temporary stations. The recordings compared on one disc, in each series, AM, FM-15 and FM-75. Several discs were recorded at each location under various noise conditions, including the random neighborhood noise encountered. For the observations at the temporary stations a two-car "F-M caravan" was assembled, equipped and moved from station to station. Figure 13 shows the two cars used to transport the equipment and also shows one of the typical locations selected. Figure 14 shows the Bellmore

Fig. 13

receiving station, at which most of the measurements reported herein were made. This receiving station is in a typical suburban neighborhood 23 miles from the transmitter atop the Empire State Building in New York City.

At the Bellmore station a simple horizontal dipole antenna was mounted 25 feet above the ground on a wooden pole. At the temporary receiving stations the receiving antenna consisted of a tripod-mounted dipole. The temporary station locations were selected over a range of distances which covered all grades of service ranging from zero to excellent and a sufficient number of stations were used to insure authoritative conclusions. The observations, orthacoustic recordings and comparisons made at these temporary stations provided a broad overall picture of u-h-f broadcasting without which this thorough field test would have been incomplete. The recordings remain as permanent exhibits of the results.

F-M Theory

The theory of FM has been presented in the literature[3,4,5]. However, since the following pages compare the actual performance in the field with the theoretical, there is presented for the convenience of the reader a very brief review of the reasons why FM is superior, and the nature of the superiority.

The advantages of FM over AM in noise suppression are contributed by three factors:

1. The triangular noise spectrum of FM.
2. Large deviation ratios.
3. The greater effect of de-emphasis in FM compared to AM.

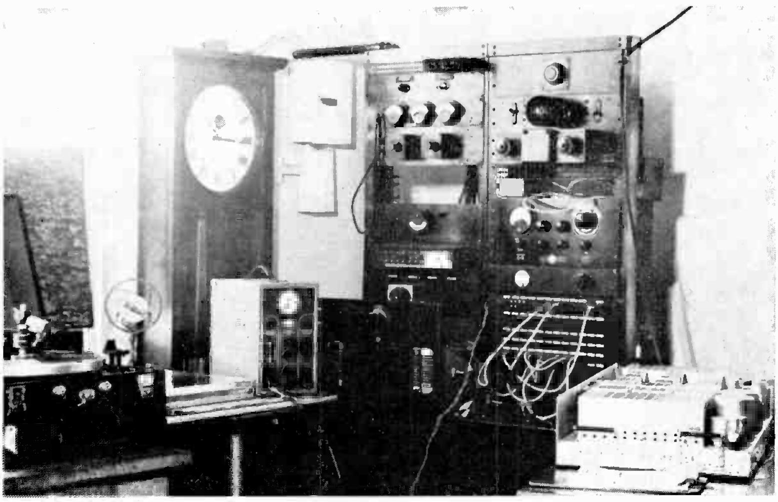


Fig. 14

The Triangular Noise Spectrum

An F-M system with a deviation ratio of one has an advantage in signal-to-noise ratio of 1.73 or 4.75 db for tube hiss or other types of fluctuating noise.

Tube hiss consists of a great many closely overlapping impulses. When combined with a steady carrier of fixed frequency, the noise

[3] A Method of Reducing Disturbances in Radio Signaling by a System of Frequency Modulation, Edwin H. Armstrong, *Proc. I.R.E.*, pp. 689-740, Vol. 24, May, 1936.
[4] Frequency Modulation Characters, Murray G. Crosby, *Proc. I.R.E.*, pp. 472-514, Vol. 25, April, 1937.
[5] The Service Range of Frequency Modulation, Murray G. Crosby, RCA Review, pp. 349-371, January, 1940.

peaks beat with it. In the following it is convenient to consider an individual noise frequency as a separate carrier, of which there are many present at any time.

Since a combination of two station carriers differing in frequency is equivalent to a station carrier and a single noise voltage, both cases may be considered at the same time. The effect is most easily shown and understood by means of a simple vector diagram.

The desired carrier vector continuously rotates through 360 degrees and is indicated in Figure 15. A weaker carrier, or a noise voltage, rotates around the carrier vector at a frequency which is equal to the difference between the two. Amplitude modulation is produced as shown. As the undesired vector rotates around the desired vector,

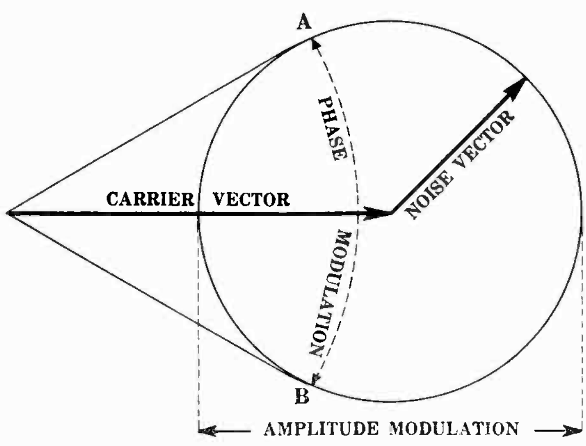


Fig. 15

phase modulation also is produced between the limits A and B. The faster the undesired vector rotates, or the faster the rate of phase change becomes, the greater becomes the momentary change in frequency and, therefore, the greater the frequency modulation becomes, because frequency modulation is a function of the first differential of phase modulation. Therefore, the amplitude of the F-M noise or beat note varies directly with beat frequency. This results in a triangular noise spectrum.

In amplitude modulation there is no such effect as this. All noise components combine with the carrier equally, resulting in a rectangular noise spectrum. The ratio of r-m-s fluctuation noise voltages in FM and AM is, therefore, the ratio between the square root of the squared ordinate areas of these spectrums. This ratio is 1.73 or 4.75 db.

The Deviation Ratio

The deviation ratio, or modulation index, is obtained by dividing the maximum carrier deviation by the highest audio frequency transmitted. For an F-M system, the suppression of fluctuation noise is directly proportional to the deviation ratio. In Figure 16 the A-M noise spectrum corresponds to the total hatched area below 15 kc because the i-f and a-f system would cut off there. The FM-75 receiver i-f system actually accepts noise out to 75 Mc and it has the usual F-M triangular noise characteristic. However, the audio amplifier and the ear respond only to noise frequencies within the range of audibility, around 15 kc, and reject everything else. Therefore, the FM-75 noise we actually hear corresponds only to the small cross-hatched triangle.

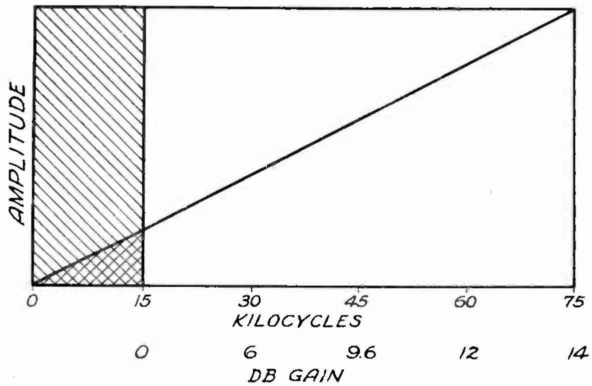


Fig. 16

The maximum height of this F-M triangle, corresponding to voltage, is only one-fifth of the height of an FM-15 triangle or the A-M rectangle. Such being the case, the FM-75 advantage over FM-15 is 5 to 1, or 14 db, and over AM it is 1.73 x 5 or 18.75 db.

De-emphasis

The use of a 100-microsecond filter to accomplish this high-frequency pre-emphasis and de-emphasis has been adopted as standard practice in television and u-h-f sound broadcasting by the Radio Manufacturers Association and recently by the FCC.

It was shown that in FM the noise amplitude decreases as its frequency decreases whereas in AM it does not. Therefore, de-emphasis is more effective in FM. This is shown in Figure 17.

The full rectangle at the left is the A-M noise spectrum. The full triangle at the right is the F-M spectrum. The application of de-emphasis reduces these areas to those combining the hatched and black sections. Squaring those ordinates gives the black areas, corresponding to power. Extracting the square root of the ratios of these black areas gives the r-m-s S/N advantage of FM over AM. It is slightly over 4, corresponding to about 12.1 db. This includes the gains contributed by both the triangular noise spectrum and de-emphasis. The spectrum advantage is 4.75 db. Hence the de-emphasis advantage is 12.1 db minus 4.75 db or 7.35 db. To sum up, for hiss noise the F-M noise spectrum advantage is 4.75 db, the de-emphasis advantage is 7.35 db and the deviation ratio of FM-75 is 14 db, giving a total of about 26 db.

It has been reported[5] that the use of 100 microsecond pre-emphasis produces overswing or overmodulation of from 2.5 to 4.5 db with

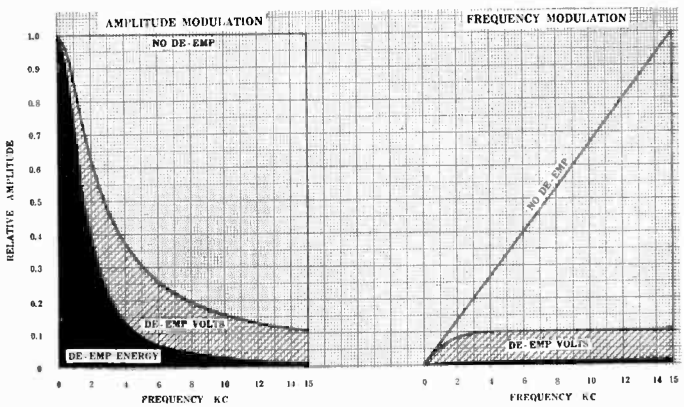


Fig. 17

program modulation, depending upon the character of the sound source. The NBC field test confirmed these conclusions. Therefore, in presetting transmitter gain controls, using low-frequency tone modulation, a 2.5 db correction should be made for program modulation.

Results of the F-M Field-Test Measurements

One of the first facts sought and determined was the lowest field intensity which could provide good service if no external r-f noise were present, and receiver hiss only were the ultimate limiting factor. Figure 18 shows the ultimate limit in service range due to the receiver noise alone, in the complete absence of any noise received on the antenna. The signal-to-noise ratio is shown for the three systems over a significant range of receiver input microvolts, field intensity in microvolts-per-meter and miles-service range. The signal-to-noise ratios were rated by subjective listening tests and the ratings are shown on the right side of the figure. The noise threshold values are indicated in such a manner that they show where the increase of noise with modulation becomes severe but do not indicate the absolute value where an insignificant increase of noise results. The curves are shown dotted below the threshold value because the increase of noise with

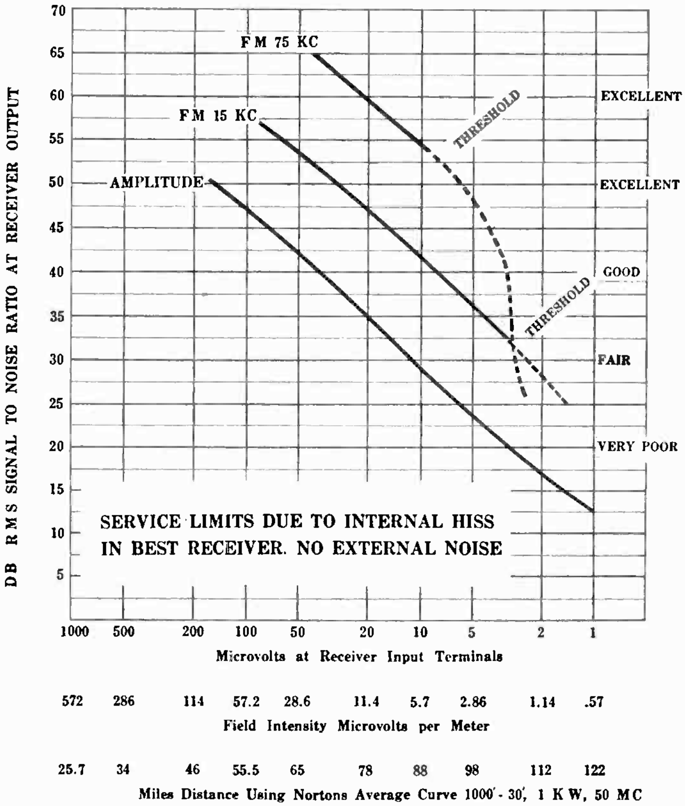


Fig. 18

modulation is very severe. A study of these curves will show the ratio of field intensity or power necessary to produce equivalent performance on the three types of modulation plotted. It is possible to determine directly the distance at which equivalent grades of service may be obtained with the three types of modulation plotted. The three curves may be projected on a straight line toward the upper left corner of the figure if it is desired to compare the results at very high signal-to-noise ratios.

The noise level in the receiver may be read directly from this figure. For instance, where there are two microvolts at the receiver input terminals the signal-to-noise ratio on AM is 17 db. Therefore, the noise is 17 db below two microvolts RMS. This curve was made using a signal generator as a transmitter, feeding directly to the input terminals to block out all external noise. It may be seen that the full theoretical gain of FM-15 and FM-75 over AM was obtained.

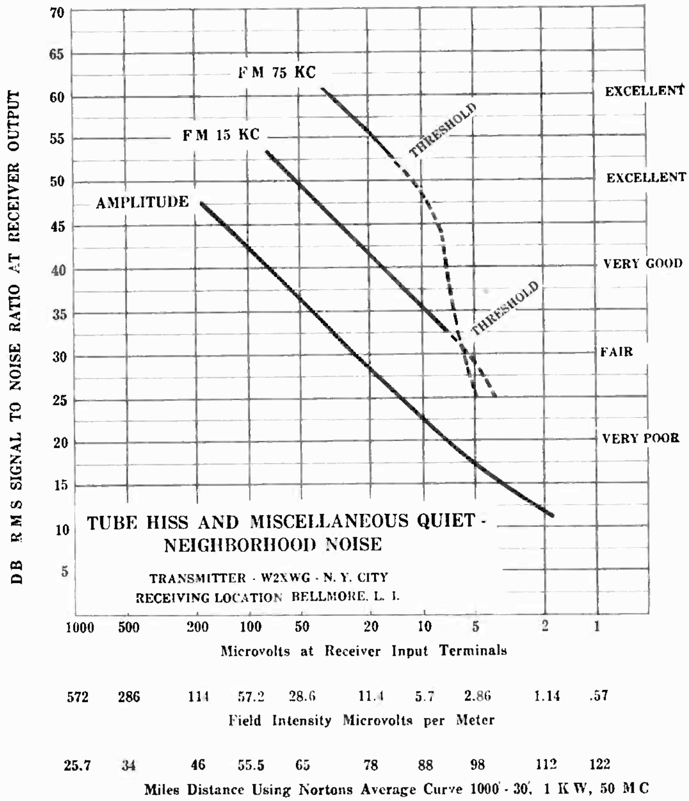


Fig. 19

Figure 19 shows the results of a series of measurements made under conditions which would be representative of a receiver operated in a home. The dipole was used and the noise received was a combination of random Bellmore neighborhood noise plus receiver hiss and thermal agitation. This receiver was located about 400 feet from the nearest public street and there was little automobile traffic in the neighborhood. The measurements were not made during a time when the noise was particularly low but the noise was taken as it existed, at random times. In a location with a higher noise level the three curves plotted on this figure would slide to the left but would otherwise retain their characteristics, if the noise were predominantly steady in character. Here again it may be observed that the full theoretical gain of FM-15 and FM-75 over AM is obtained.

In order that this figure may be more easily interpreted, the same data has been plotted on a bar chart comprising Figure 20. This shows the number of miles service range for the types of modulation shown and also includes calculated values for a frequency-modulation system with a deviation of 30 kc. This also shows the service range with powers of 5 kw and 50 kw, assuming that the same neighborhood noise level existed at all receivers.

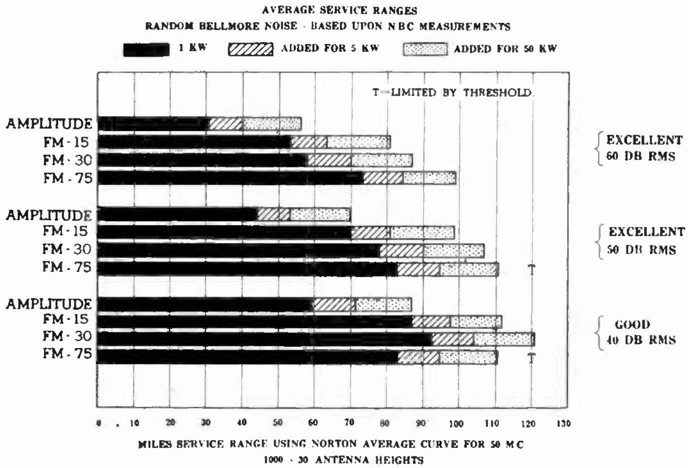


Fig. 20

It will be seen that with a signal-to-noise ratio of 40 db, FM-30 produces a greater service range than any other modulating condition, assuming that in each case the receiver is designed specially for the system being received. This would indicate that if 40 db r-m-s signal-to-noise ratio is considered satisfactory as a minimum, FM-30 would be about the optimum deviation to use. The service range for a swing of 150 kc does not extend beyond the limit imposed by the noise threshold and therefore FM-75 is limited to the distance at which a S/N ratio of 53 db is obtained in all cases.

The threshold effect actually starts on FM-75 at about 60 db but does not become severe until the unmodulated S/N ratio is about 53 db. Therefore, the threshold is indicated on the curves as 53 db.

If neighborhood noise were to be greater than that measured at Bellmore, these bars would all shorten, but would retain their relative lengths. It will be noted that FM-75 is superior, even with the threshold limitation, at signal-to-noise ratios of 50 or more decibels.

Regardless of the carrier-to-noise or the signal-to-noise ratio coming out of the discriminator, the full benefits of FM cannot be obtained unless the audio amplifier hum level is sufficiently low. The advantages of FM do not extend into the audio amplifier.

Figure 21 shows measurements of tube hiss. The figure shows the ratio of r-m-s to peak values using an 8-kc audio band width and a 15-kc audio band width with the triangular F-M noise spectrum and de-emphasis. The hiss levels shown are representative of what can be expected from the best modern high-gain receiver.

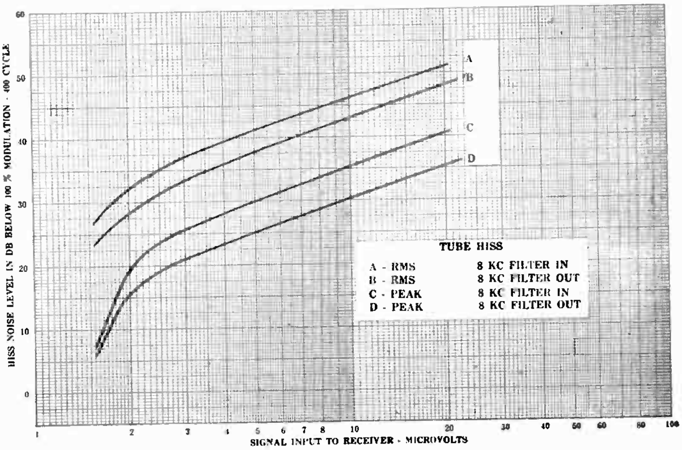


Fig. 21

From the curve, it can be observed that the ratio of peak to r-m-s values with 8 kc is slightly over 10 db. With 15 kc it is slightly over 13 db. It can also be seen that the r-m-s noise is reduced 3 db when the pass-band is reduced from 15 kc to 8 kc. The peak noise is reduced 5 db under the same conditions.

Operation of Two F-M Stations on the Same Channel

By referring to the section covering noise interference it can be seen that the worst condition of shared channel operation occurs when both stations are unmodulated, and a fixed beat note, therefore, results. It will also be seen that the higher this beat note the greater will be its amplitude up to about 5,000 cycles. Figure 22 was made on the basis of the worst conditions, which occur when the difference in carrier frequency reaches approximately 5,000 cycles. Were it not for the effect of de-emphasis in the receiver the beat note amplitude would continuously rise with frequency. However, de-emphasis of the high frequencies prevents that from happening. The effect may be further understood by referring to the section on pre-emphasis and de-emphasis. It will be noted that the noise on the desired station caused by the undesired station varies inversely with the deviation ratio. Here again the theoretical advantage of FM was obtained in our field test.

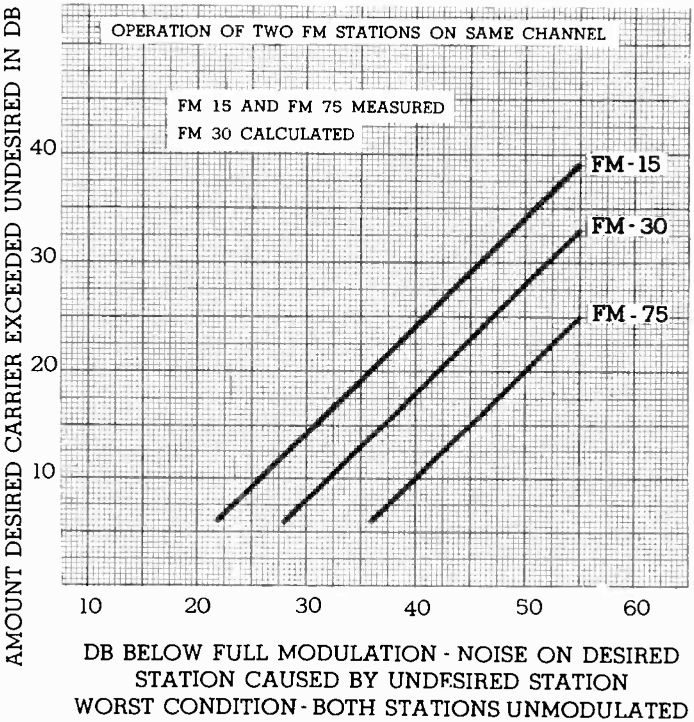


Fig. 22

When either of the stations producing the beat note becomes modulated, the beat note disappears, because one carrier sweeps across the other one. When the desired station is approximately 20 db stronger than the undesired station, all interference and cross talk effects become unnoticeable. At 12 db difference they are noticeable, but it is the opinion of some engineers that the 12 db ratio would be tolerable. Frequency modulation offers a great advantage over amplitude modulation in the allocation of stations on the same frequency. In AM the carrier amplitude of the desired station must be 100 times, or 40 db greater than the undesired carrier amplitude for a 40 db signal-to-beat note ratio. For FM-75 it need be only 10 db, or 3 times greater; for FM-30, 17.5 db, or 8 times greater; for FM-15 24 db, or 10.5 times greater. The result is that F-M stations may be located much closer geographically than A-M stations, and therefore many more station assignments can be made per channel.

Operation of Frequency-Modulation Stations on Adjacent Channels

Figure 23 shows the results of listening tests on adjacent F-M channels using in each case FM-75. On the basis of this information it is

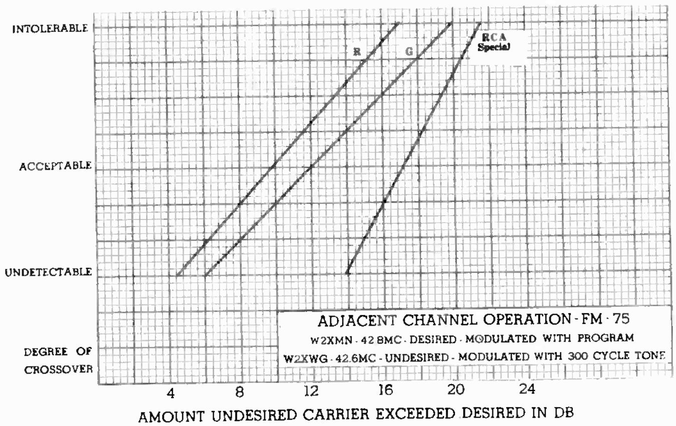


Fig. 23

seen that adjacent channel stations must not be located in the same geographical area. The channels were 200 kc wide and were adjacent, one being W2XMN on 42.8 Mc and the other W2XWG on 42.6 Mc. W2XMN was used as the desired channel, since its field intensity was constant at Bellmore. W2XWG was used as the undesired station. The field intensity ratios were adjusted as desired by varying the power of W2XWG. Observations were made of the special field-test receiver and also of two commercial receivers with the results shown.

The figure shows that the undesired carrier level should be not more than about 10 db greater than the desired carrier level to prevent objectionable cross-talk in the commercial receivers. The RCA special field-test receiver will give equivalent performance at a carrier level ratio of 17 db, but this receiver is more elaborately built and is superior in certain respects to commercial models.

Intolerable cross-talk occurs on all three receivers at carrier level ratios of from 17 to 21 db.

THE NOISE THRESHOLD IN FREQUENCY MODULATION

Crosby points out that an interesting series of events takes place in a frequency-modulated system when the noise peaks equal or exceed the peaks of the carrier.[4] The result is a rapid increase of the noise

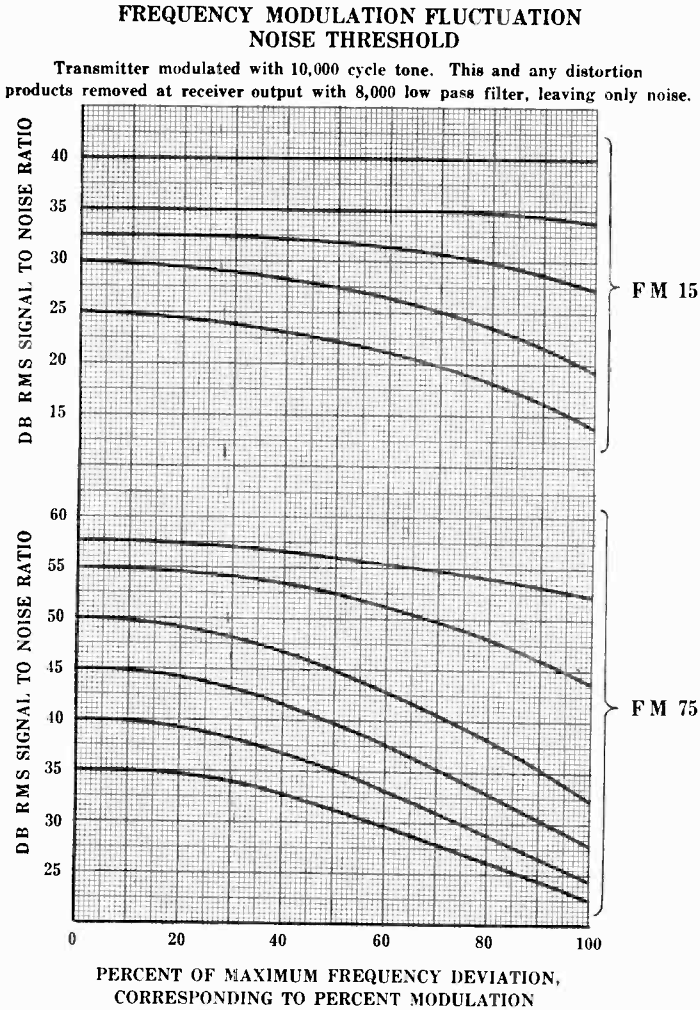


Fig. 24

level or decrease of the signal-to-noise ratio, with modulation. In frequency modulation wherein the maximum swing is 150 kc the point where this begins to occur is reached when the unmodulated signal-to-noise ratio is about 60 db. When the unmodulated signal-to-noise ratio is less than about 60 db, or 1,000 to 1, the noise level rises with modulation, and, as the noise peaks exceed the carrier peaks by a considerable amount, this noise level may increase almost 20 db, or 10 times. When operating above the threshold limit the noise changes little as the

FREQUENCY MODULATION FLUCTUATION
NOISE THRESHOLD

Transmitter modulated with 17,000 cycle tone. This and any distortion products removed at receiver output with 14,000 low pass filter, leaving only noise.

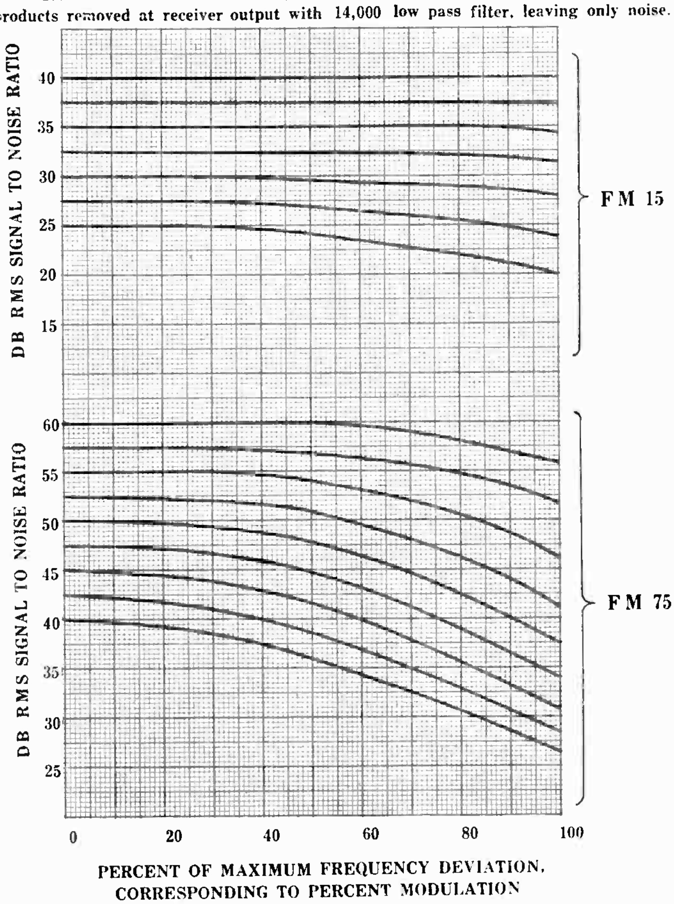


Fig. 25

station is modulated. Below the threshold limit the effect is not unlike severe harmonic distortion in an overloaded A-M transmitter.

In frequency modulation of a lesser swing, such as 30 kc, the same effect occurs. In this case, however, the threshold limit occurs at about 35 db signal-to-noise ratio. Figure 24 shows the results of some of the measurements made at Bellmore. In order that the noise would not be confused with any small amount of inherent distortion in a man-made system, the measurements were made in such a manner that the effects of distortion were eliminated. This was done by modulating the trans-

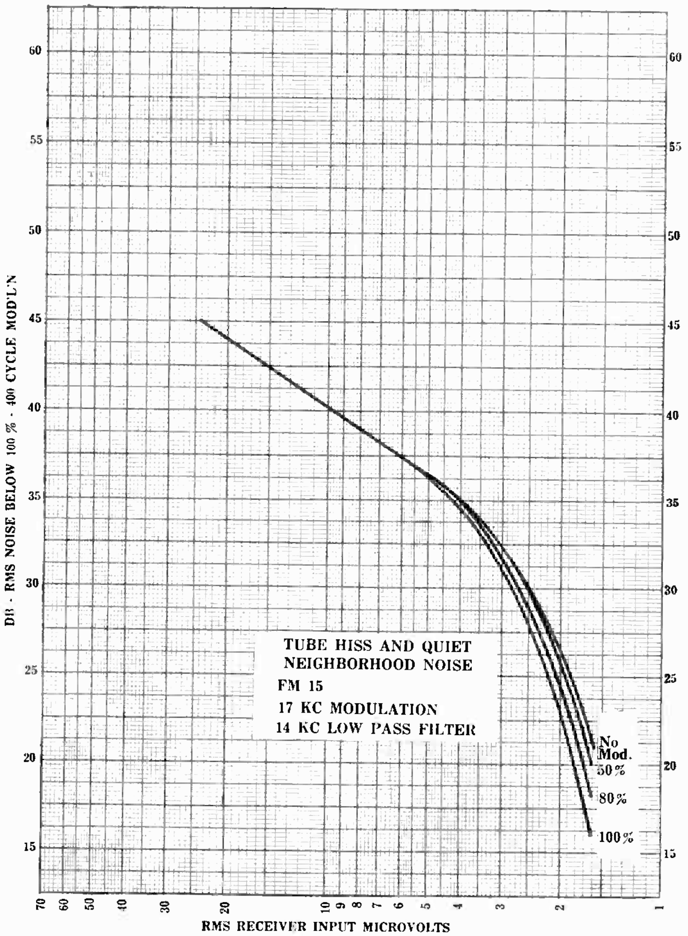


Fig. 26

mitter with a 10,000-cycle tone and eliminating at the output of the receiver, with an 8-kc low-pass filter, not only the fundamental modulating tone but also the distortion products, leaving only the noise. Figure 25 shows the results of another set of measurements made with a 17-kc modulating frequency, and a 14-kc low-pass filter to eliminate the fundamental tone and distortion products.

This effect has no doubt been observed by many without being understood. It is an inherent characteristic of a frequency-modulation system. The noise threshold in the case of an FM-40 system having a

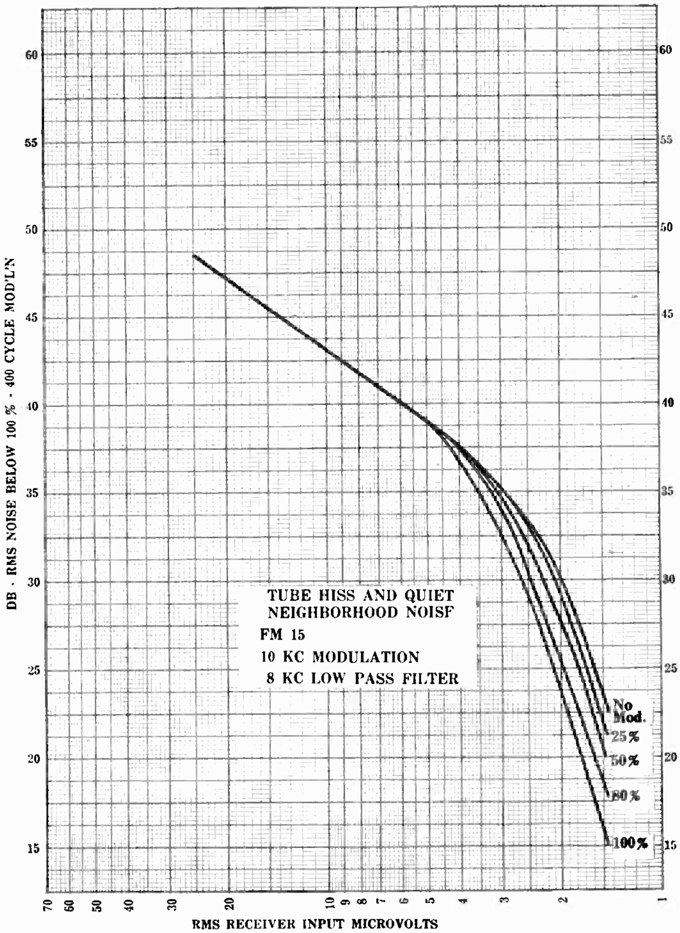


Fig. 27

total band width of 100 kc occurs at about 43 db. This provides a very good signal-to-noise ratio.

Figures 26-27 give additional results of threshold r-m-s measurements showing noise levels plotted against receiver input microvolts, with various percentages of modulation. The signal-to-noise ratio (ordinate) is the ratio of maximum 400-cycle modulation to noise.

MEASUREMENTS OF PEAK IGNITION NOISE

Because of the peculiar wave shape and large crest factor of ignition noise it is preferable to measure the peak signal and peak ignition noise rather than the r-m-s values in order to establish, for one thing, the

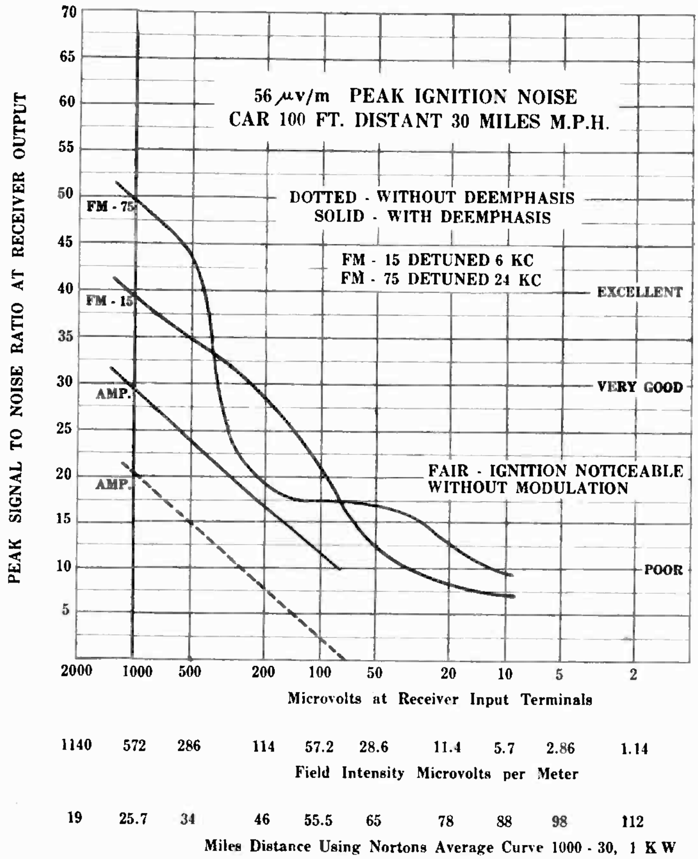


Fig. 28

threshold where they become equal. Because of the infrequent number of peaks, compared with hiss noise, much higher values of peak noise levels can be tolerated from ignition systems. In making measurements of ignition noise an actual automobile was used. Making such measurements is quite difficult because of the variation of peak noise amplitudes from an automobile system over short periods of time. Also, to show what the dynamic noise characteristics of a system would be without actually modulating it, it becomes necessary to de-tune the receiver or resort to some other expedient. This is necessary because high noise peaks, if synchronized with an unmodulated carrier, do not show the existence of the noise threshold. Modulation, in effect, de-tunes the receiver and the threshold becomes evident. De-tuning the receiver in the absence of modulation is one expedient which produces a similar result and was the method used in obtaining the data shown on Figure 28.

Of particular interest in this figure is the rating of the signal-to-noise ratio as shown at the right. A 30 db signal-to-noise ratio, when measured with peak values, is equivalent to a 40 db r-m-s signal-to-noise ratio. Even with as low a signal-to-ignition-noise ratio as 20 db the service is quite fair, although the ignition would be noticeable without modulation. The relative infrequency of ignition peaks produces an audible result which is very deceiving. With signal-to-ignition-noise ratios of 10 or 12 db, service is still not completely ruined but could be tolerated if there were a special interest in the program material.

In general, ignition noise is transient, lasting for only a matter of seconds as a car passes by a residence. During that period the noise is not distressing. Furthermore, over a period of years, it may be expected that automobile ignition systems will be provided with suppres sors which will reduce the u-h-f interference by at least 20 db. Ignition noise is of particular concern and is the predominant noise in suburban areas. In urban areas, the field intensity from a F-M station or an A-M station will ordinarily be high enough to over-ride the higher noise levels experienced. Figure 28 represents some of the results obtained with 56 peak microvolts per meter noise. The method of making these measurements was not ideal in all respects but the data is indicative of the results obtained in the presence of ignition noise. The curve of Figure 29 shows r-m-s ignition noise measurements made without modulation and illustrates that no threshold is found under such conditions. Since a system is of no value until modulated, this curve is shown only to illustrate the point that the noise threshold must be associated with modulation.

Figure 30 presents interesting data showing peak ignition noise measurements made with an 8-kc audio band width. Peak noise input microvolts are plotted against peak S/N ratio, the field intensity of the station remaining unchanged. The signal with which the noise was compared was 100 per cent 400-cycle tone modulation. The noise source in this case was an automobile ignition system built up and mounted on a lathe at Bellmore. The battery power was not varied to produce different field intensities of noise because this method changed the character of the noise. The field intensity was varied over a very wide range, without changing its normal characteristic, by orienting and changing the length of the connected noise transmitting antenna, which was located about 50 feet from the receiving dipole. FM-15 represents a deviation ratio of 1.875 when the audio band width is 8 kc. As Crosby has shown[5], the noise spectrum advantage of FM is 6 db for impulse noise. The FM-15 threshold is shown. The FM-75 threshold is not shown because at the time the measurements were made a-c hum within

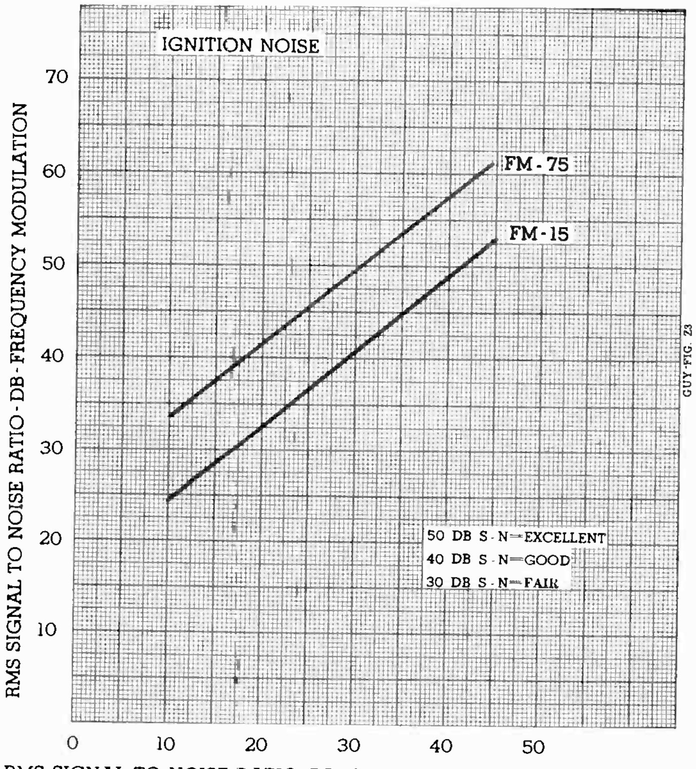


Fig. 29

the system made the accuracy of S/N measurements in the 60-db region uncertain. Of particular interest is the shape of the F-M curves at the lower right side of the figure. The explanation for it is given in the references.

This is to be expected from the character of ignition noise. The impulses are very short in duration, very high in amplitude and relatively widely separated. They literally blank out only small portions of the signal waves, without impairing the remainder. The short blanked out intervals of the signal change little over a wide range in noise peak amplitude. Once an ignition peak has risen to the value required to control the receiver and blank out the signal a further rise in the noise level will not occur until the peak increases in breadth, or duration, or until there is a sufficient rise in certain low amplitude components of ignition noise having fluctuation noise characteristics. The peculiar shapes of such curves below the threshold values are due to the wave shapes and crest factors of ignition noise.

Results of Observations at Temporary Receiving Stations

The observations at the temporary receiving stations confirmed the measurements made at Bellmore. In going to progressively greater distances the FM-75 noise threshold distance was passed and FM-15 became superior. Then the FM-15 threshold distance was passed and AM became superior, although it was very noisy. At the limit of A-M intelligibility both FM-75 and FM-15 were completely smothered by noise. The service limits were all in excellent agreement with those shown by the bar chart, Figure 20, subject to spasmodic interference from passing automobiles. This type of interference was at all stations the predominating one, but was only intermittent and not as troublesome as might be expected.

Observations of Diathermal Interference in AM and FM

Diathermal machines vary considerably in their characteristics, some types using raw a.c. and others using partially filtered power supplies. Observations were made of interference on the three types of modulation using raw a-c machines. It was concluded from these observations that this type of interference is characterized by the transmission of a band of frequencies about 15 kc wide. With amplitude modulation the background interference is essentially equal to the carrier-to-noise ratio. With fairly weak interference from diathermy exactly centered on the desired carrier, FM-75 reception is 20 to 25 db superior to AM and FM-15 is 10 to 12 db superior. However, with the diathermy 5 kc off the desired carrier, AM was approximately equal to FM-15 and was in some cases superior to FM-75. With the diathermy carrier at the edge of the AM and FM-15 passband, the interference is highly attenuated. Under these conditions the FM-75 interference was extremely severe. With the diathermy carrier well outside of the passband of FM-15 or AM, the interference is noticeable only when the diathermy amplitude is extremely high. Under normal receiving conditions it would not be heard. However, if the diathermy under these conditions is within the FM-75 passband, the interference is extremely severe. Thus, under such conditions, FM-75 was the worst of the three types of modulation. It was concluded that in locations having strong diathermy interference, narrow band receiving systems

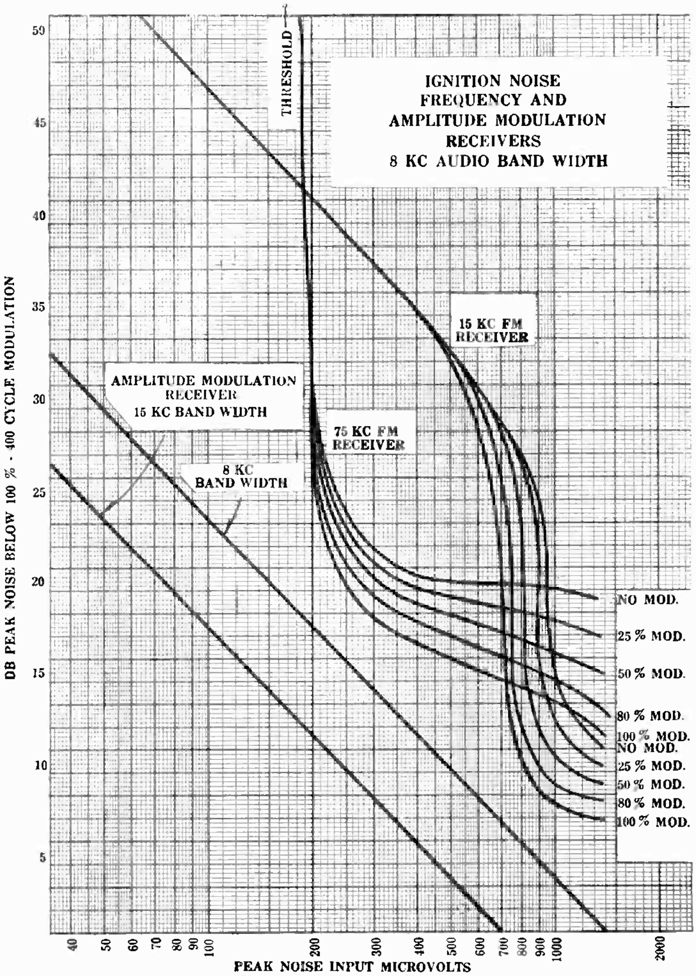


Fig. 30

would be far superior to others. It was also concluded that in locations having weak diathermy interference the wide band system would be much superior.

Noise Levels

In the foregoing, considerable data has been shown to indicate the field intensities which will provide good service for F-M and A-M systems. Figure 31 is shown because it is of particular interest in connection with this field test. It represents an accumulation of noise measurements made over a period of years by various RCA groups. These data were assembled by Dr. H. H. Beverage.

Noise levels vary considerably from time to time and it is not possible to give fixed values for any time or place. However, the informa-

TYPICAL NOISE LEVELS 40 - 50 MC.

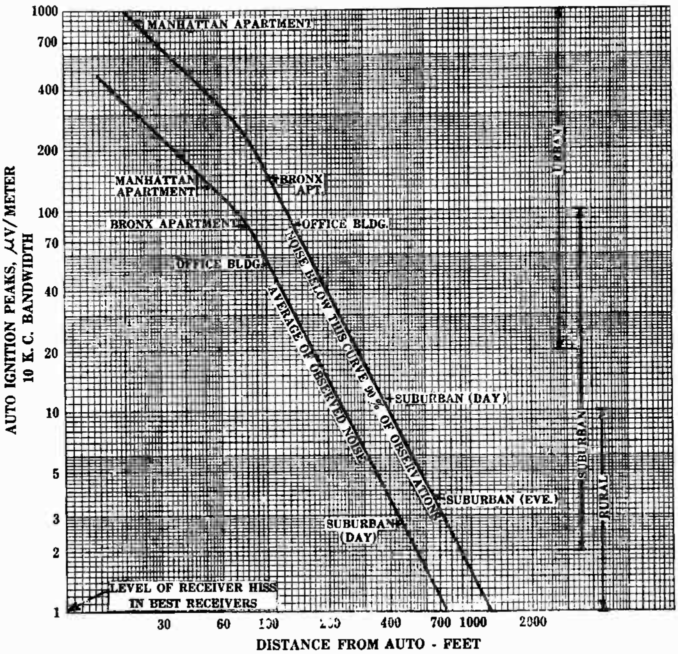


Fig. 31

tion shown on Figure 31 is indicative of the noise levels which may be encountered under a wide range of conditions with a 10-kc audio band width. For peak noise the amplitude varies directly with the frequency band. For fluctuation noise the amplitude varies as the square root of the band width.

ACKNOWLEDGMENT

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