E-1033 (7-47)

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COVER SHEET FOR TECHNICAL MEMORANDA

SUBJECT: Mobile Telephony - Wide Area Coverage - Case 20564

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DATE 11 December 1947
AUTHOR D. H. Ring

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~~ABSTRACT~~

ABSTRACT

In this memorandum it is postulated that an adequate mobile radio system should provide service to any equipped vehicle at any point in the whole country. Some of the features resulting from this conception of the problem are discussed with reference to a rather obvious plan for providing such service. The plan which is outlined briefly is not proposed as the best solution resulting from an exhaustive study, but rather is presented as a point of departure for discussion and comparison of alternative suggestions which may be made.

The discussion in this memorandum is limited to some problems concerned with the efficient utilization of a given frequency allocation for wide area coverage. Only a portion of the total allocation is available at any one point in the plan discussed. It is hoped that a future memorandum can be prepared dealing with the most efficient utilization of the frequency band assigned to a particular small area, i.e., methods of modulation, multiplexing, etc.

In the plan outlined above frequency discrimination is used to avoid interference between adjacent primary areas, and amplitude discrimination due to attenuation with distance is used to avoid interference between like primary frequencies in adjacent secondary areas.

Time and directivity discrimination can be used to advantage in many radio problems, but these methods do not appear to be applicable to broadcast area coverage systems. We might attempt to apply time discrimination by sending pulses from adjacent stations so timed that they do not arrive simultaneously at any one point. It will be found that this is impossible without wasting more than half the time. Since we must cover an area, antenna directivity can only change the shape of the primary station coverage. Interference is most likely around the perimeter of a coverage area, and the normal circular coverage of a non-directional antenna (horizontally) will cover the greatest area for a given perimeter.

There is an interesting speculative possibility in this field, however. In channel sample transmission systems 8000 short pulses per second suffice to carry one telephone channel. If each primary station had a highly directive beam which rotated at 8000 rps, a number of adjacent stations might be operated on the same frequency without serious interference if the instantaneous angular positions of the various beams were coordinated. Since the extra bandwidth required for the pulse system would probably be comparable with the saving due to fewer primary frequencies, and since we do not know how to build a highly directive rotating beam, this does not seem to be a very promising line of attack at the moment.

In order to lay out a system according to the plan outlined at the beginning of this section, we must know how far apart stations operating on the same frequency must be in order to obtain enough attenuation due to distance to avoid interference. With this knowledge we will be in a position to determine how many separate frequency bands will be required.

Amplitude Discrimination Due to Distance

The relative amplitude of two signals received from different transmitters is a function of the ratio of the distances of the transmitters from the receiving point. It is a complicated function involving a number of parameters and it is beyond the scope of this discussion to examine it in detail. Fig. 1 is a plot of the attenuation vs. distance for transmission between

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half wave dipoles. This curve was plotted from the nomographs given by Bullington* for a frequency of 450 mc and antenna heights of 6' and 200'. Using the information from Fig. 1 we can plot a set of curves as shown in Fig. 2 which indicate the amplitude discrimination obtained as function of the ratio of the distances to each transmitter $\frac{D2}{D1}$, and the distance to the nearest transmitter, D_1. For the antenna heights chosen, the horizon just intercepts the direct line of sight at 23 miles. When D_2 is less than 23 miles the amplitude difference is about 12 db for $D_2/D_1 = 2$. As D_1 approaches 23 miles D_2 becomes greater than 23 miles and the amplitude difference becomes greater for a distance ratio of 2, reaching about 24 db when D_1 is just a line of sight path.

The curves of Fig. 2 indicate the way the amplitude discrimination due to distance varies in one specific case under idealized conditions. In practice transmission will be subject to wide variations due to atmospheric conditions and surface irregularities. Most of these variations can probably be included by reducing the values given in Fig. 2 by 20 db, although there will certainly be exceptional times and places where even greater departures will be recorded. These considerations lead to the conclusion that it is desirable that the transmission system be one which has the property of increasing the amplitude discrimination in the audio output as compared with that existing in the antenna circuit. FM and PCM are examples of transmission systems which have this property. Such systems will result in more frequent duplication of similar primary systems, smaller secondary areas, and less complicated switching circuits.

<u>Frequency Plans</u>

As pointed out by W. R. Young in his report to the RMA Systems Committee, the best general arrangement of frequency assignments for the minimum interference and with a minimum number of frequencies is a hexagonal layout in which each station is surrounded by six equidistant adjacent stations. The important dimensions in such a layout are shown in Fig. 3. In this figure the normalized distances to distant transmitters from the edge of the service area of a given transmitter give directly the minimum value of the distance ratio D_2/D_1 which determines the level of an interfering signal. D_2/D_1 is the ratio for a car on the parameter of a service area circle rather than one midway between adjacent stations.

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* Proceedings I.R.E., October 1947.

Wide area coverage can be obtained with minimum interference with a given number of frequencies repeated according to a systematic plan. Such plans can be worked out in which the minimum value of D_2/D_1 has any of the various values indicated in Fig. 3. These values of D_2/D_1 and other possible values can be calculated from the relation derived in the appendix (12).

$$D_2/D_1 = (\sqrt{3i^2 + 2.25j^2} - 1 \qquad (1)$$

In this equation i and j are positive integers, including zero, with the restriction that i and j must both be even or both must be odd for any value of D_2/D_1. It is also shown in the appendix (11) that for any value of D_2/D_1 given by (1) the number m of primary stations required is given by

$$D_2/D_1 = \sqrt{3m} - 1 \qquad (2)$$

$$m = \frac{1}{3} \left(\left[\frac{D_2}{D_1}\right]^2 + 2\,\frac{D_2}{D_1} + 1 \right) \qquad (3)$$

Fig. 9 is a plot of m vs. D_2/D_1 with the possible values of D_2/D_1 from (1) circled. Symmetrical plans can be constructed based on any of the circled points. In these plans each station will be surrounded by 6 stations at a distance $(D_2+1)D_1$ away, and the secondary area covered by the m stations of different frequency will be approximately, from appendix (4),

$$A_S = \frac{\sqrt{3}}{2} (D_2+D_1)^2 \qquad (4)$$

Figs. 4 and 5 show examples of symmetrical coverage plans for 3, 4, 7 and 9 frequencies. These plans yield the minimum value of D_2/D_1 at six symmetrical points on the periphery of the service area. The best plans with 5, 6, and 8 frequencies will have the same minimum value as the next lower symmetrical case, but this minimum will not occur at six points, so the disturbed area will be smaller.

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A study of these plans and Fig. 2 indicates that at least 4 frequencies will be required for a high quality system in which extra suppression is obtained by other than distance discrimination. Probably 9 or more frequencies will be required for systems such as straight SSB where no extra discrimination is available. A great deal of study will be required to ascertain which type of system will lead to a minimum total bandwidth with satisfactory quality.

Channel Coverage

In general, we can see from Fig. 2 that for a given required amplitude ratio the distance ratio must be increased as the service area of a primary station is made smaller. For example, if a particular system required an amplitude ratio of 26 db for channel interference plus fading and shadow effects, a distance ratio of 2.5 would be adequate with a 15 mile service radius, while a distance ratio of 3.6 would be required if the service radius is 5 miles. A distance ratio of 2.5 can be obtained with 4 primary frequencies while 7 frequencies are required for a ratio of 3.6. While these figures are only approximate, they clearly indicate the general trend. We conclude that a large primary service radius leads to a minimum number of primary frequencies.

A minimum number of primary frequencies may not be the best arrangement, however. If more than one primary band is used, means must be provided for switching the car reciever and transmitter to the various bands. Once such means are provided the difference between 4 and 7 positions may not be great, and there may be other reasons for using smaller primary areas. We desire to blanket a wide area so that all parts of the area have service. Another problem is to provide enough channels to take care of the maximum number of simultaneous calls that will be encountered in a primary area. It is obvious that a large primary area covering a large city will require a large number of channels. Therefore, the smaller the primary areas the smaller number of channels and the band required for each primary frequency. For instance, suppose 120 channels are required simultaneously in New York City. We might arrange the primary areas so that 3 of the 15 mile radius areas shared the New York traffic, but they would also extend well into New Jersey, Long Island and Westchester, and probably at least 65 channels per primary area would be required yielding a total of 260 channels. With 5 mile radius primary areas about 5 primary areas could be used to share the New York load and still take in less outside territory. In this case 30 channels per primary area might suffice. With the 7 primary frequencies required for 5 mile radius this gives a total of 210 channels required in the basic plan. These are very crude estimates, but they indicate that the total bandwidth required for a wide area system might be smaller for a smaller primary area radius. Fig. 6 shows how 15 mile and 5 mile radius areas might be used to cover the New York area. The advantage of the 5 mile plan in concentrating the channel capacity of the primary areas is obvious.

It should be pointed out that a large primary radius such as 15 miles will require 4 or more land receivers per land transmitter due to the limited power of the car transmitters. Thus, the area of a 15 mile radius primary area is 708 square miles, and at least 5 station sites would be required, or one site per 141 square miles. The area of a 5 mile radius primary area is 78.5 miles, but in this case a single site could presumably be used for both the land receiver and transmitter. This arrangement will lead to easing some receiver selectivity problems as will be mentioned later.

It may appear that the writer is attempting to build a case for 5 mile radius primary areas. It should be emphasized that this is not the objective, and that the 5 and 15 mile radii are simply round numbers that have been used to illustrate some of the general problems associated with small and large radius systems. It is believed, however, that a number of practical considerations tend to at least partially balance the apparently overwhelming advantage of large radius systems indicated by Fig. 2.

It has already been shown that at least twice, and quite possibly considerably more than twice as many total channels will be required for uniform wide area coverage as will be required in the highly concentrated New York City area alone, if the same plan is used over the whole country. This will result in a great deal of excess capacity in most areas outside big cities. However, there are enough big cities scattered over the country so that most of the frequency space required for the N.Y. area will be required at other points. Most other services that might use this frequency space will also be concentrated in the big cities, and therefore does not seem to be too unreasonable for the telephone company to ask for the allocation of the full band for the whole country rather than on some regional basis.

Serious consideration should be given to the possibility of using the excess capacity of the mobile system in rural areas in the local plant in these areas. For fixed stations directive antennas, higher antennas, and auxiliary power could be used to extend the range of any land station so that a skeleton system confined to main highways and towns would actually cover many remote locations where telephone lines are not available. The mobile system could also be used for temporary and emergency service in many cases. Since this type of service would be complementary to the heavy demand for mobile service in congested areas a much greater public use of a frequency allocation could be made by allocating a band to general common carrier use rather than breaking the allocation into separate bands for mobile and other services.

Even with the expanded concept of a mobile system suggested in the preceding paragraph some excess capacity would remain in wide areas. Here the fewer transmitters of the large radius system would be very desirable. This might be achieved by using two completely independent large radius systems in the congested regions, and dropping one of them in rural areas. This might introduce difficult switching problems and some loss of efficiency in some cases, but is worthy of consideration. Another possible solution to this problem would be to gradually enlarge the basic primary area of a small radius system as lightly settled regions are reached. This might be made feasible by taking advantage of local geography and by dropping some of the excess channels on some stations, but such a plan would be difficult to lay out.

Some Other System Considerations

It has been assumed that the total frequency allocation is divided into two parts; one to be assigned to the land transmitters and one to the car transmitters. These two bands would then be further subdivided between the various primary areas, and each primary area band would be divided among the various channels. In the case of the land transmitters there are large savings possible in both bandwidth and power capacity if some form of multiplex transmission is used with all channels multiplexed on a single carrier. The more channels there are on each primary transmitter the wider the signal band, and, in general, the greater the susceptibility to distortion due to echoes. This may turn out to be a very strong factor in favor of a minimum number of channels per transmitter. The lower peak power required for fewer channels also points in this direction. The bandwidth advantage of multiplex is obtained by close packing of the channels. Thus, the land transmitter bands should be used in blocks with one block assigned to each primary area, and the various blocks packed as closely as possible and adjacent to each other. This minimizes the possibility of interference between land transmitters and car transmitters since only one guard band between land and car frequencies is required.

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In the case of the car transmitters, no way has been devised for obtaining the equivalent of multiplex operation since individual carriers and different transmission times for each car are inevitable. On the basis of individual channels for the car transmitters we can use either of the plans illustrated by Fig. 7. In Fig. 7-a, the car transmitter band is divided into blocks assigned to each primary area and each land receiver must separate individual channels from a completely filled band. In Fig. 7-b the frequencies assigned to cars in different primary areas are interlaced so that each land receiver receives the whole band, but must select a series of widely spaced channels. These two arrangements should be compared on the basis of the receiver selectivity problems.

Two kinds of receiver selectivity are important. One kind involves the separation of adjacent channels. This may call for some 30 to 40 db adjacent channel selectivity for equal input signals on two channels, but when reception of nearby and distant cars must be provided for some 60 to 70 db must be added to the equal level selectivity in the worst case. This is a severe requirement. It can be greatly reduced if the car transmitter power is controlled by the received power from the land transmitter when the land receiver and transmitter are located close together. In the wide radius system with multiple receivers this would be much less effective, and might not give any worthwhile advantage. The second kind of receiver selectivity problem involves overloading from strong signals outside the band of the desired signal. This overloading occurs in the early stages where the selectivity is less than the final channel selectivity. Receivers are subject to this interference due to nearby cars, and such nearby cars can cause trouble in channels well spaced from them. Here again the car transmitter gain control will be effective in small radius single receiver systems. The car transmitter frequency plan of Fig. 7-b has the advantage that, except for fading which will presumably be minimized by diversity reception, the average signals in several adjacent channels on each side of a desired channel will never be greater than the desired signal. They will only be equal for cars at the edges of the service areas when cars using the adjacent channels in adjacent primary areas are also at the edges of their service areas. The probability of this condition is small, so the plan of Fig. 7-b will result in the adjacent signals being lower than the desired signal on the average. This should permit a substantial reduction in the guard bands between channels and a worthwhile saving in total frequency band. With regard to receiver overload, if the land receiver were broken up into several separate receivers each with RF selectivity of say 2 mc then it would be subject to overload from only about 8 car frequencies in a 7 frequency plan with 40 kc spacing and interlacing. Without interlacing the same receiver would be subject to overloading from 50 car frequencies if that many were used in a single area. The interlaced plan plus a partial gain control on the car transmitters and a small radius system with a single land receiver in each primary area will apparently greatly ease the problems of interference and permit closer packing of the car transmitter channels.

It might be noted also that if individual channels with their own carriers were used for the land transmitters instead of a multiplex system, a big average improvement in the car receiver selectivity against adjacent channels could also be realized by interlacing the land transmitter frequencies of the various primary areas.

Conclusions

A satisfactory mobile service must be planned on the basis of wide area coverage rather than local coverage. In this memorandum an attempt has been made to survey some of the general implications of this viewpoint with particular regard to minimizing the total frequency allocation assigned to such service.

It is found that at least twice as many channels may be required for general coverage as are required in the most congested local area such as New York City. With a system set up on this basis, excess capacity will exist in rural areas. It is suggested that this excess capacity be incorporated in the local plant of the rural areas for special point to point service and in particular to provide service at remote points where lines are lacking, and for emergency services.

There are factors favoring high power land transmitters covering wide areas, and other factors favoring low power land transmitters with small service areas. Some of these opposing factors are discussed briefly, but much more detailed study will be required before a definite selection of the best arrangement can be made. It is pointed out that some of the interference and selectivity problems may be eased in the case of area coverage so that somewhat tighter packing of channels can be used than in a strictly local system.

D.H.R.
D. H. RING

Attached:
Figs. 1 - 9
BA-333136 through
BA-333144
Appendix

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APPENDIX

Interference Distance Ratio for m Frequencies.

We assume that an area is to be covered by a large number of stations using m different frequencies. The service radius of each station is D_1 miles, and the stations are located according to a hexagonal arrangement in which each station is surrounded by 6 other equidistant stations. We wish to evaluate the minimum value of the ratio D_2/D_1 for different values of m where D_2 is the distance from the perimeter of the service area of one station to the nearest station operating on the same frequency.

From Fig. 3 the horizontal spacing of the stations is

$$x = \sqrt{3}\, D_1 \tag{1}$$

and the vertical spacing between rows is

$$y = 1.5\, D_1 \tag{2}$$

The hexagonal area served by each station is

$$A = \frac{3\sqrt{3}}{2}\, D_1^2 \tag{3}$$

For the symmetrical plans the same frequency appears at 6 points a distance S from the center of a primary station as shown in Fig. 5.

The lines in Fig. 5 show how this large area may be divided into 3 parallelograms in such a way that it is clear that one parallelogram represents the area that must be associated with each primary frequency number one in order to cover an infinite area. In other words, each parallelogram corresponds to a secondary area. The area of one parallelogram

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or secondary area is

$$A_s = \frac{\sqrt{3}\, S^2}{2} \tag{4}$$

and m is then the ratio of the areas given by (3) and (4)

$$m = \frac{A_s}{A} = \frac{S^2}{3D_1^{\,2}} \tag{5}$$

$$\frac{S}{D_1} = \sqrt{3m} \tag{6}$$

Now S can only have certain values given by the distances between the centers of the various stations. The distance from one station to any other station is given by

$$S = \sqrt{(i\tfrac{x}{2})^2 + (j\ y)^2} \tag{7}$$

where i and j are integers including zero, and are restricted in that if i is even, j is even, or if i is odd, j is odd. This is illustrated by Fig. 8.

Substituting (1) and (2) in (7) gives

$$\frac{S}{D_1} = \sqrt{3i^2 + 2.25j^2} \tag{8}$$

Then from (6)

$$\sqrt{3m} = \sqrt{3i^2 + 2.25\ j^2} \tag{9}$$

$$m = (i^2 + 0.75\ j^2) \tag{10}$$

By substituting for i and j in (10) m, the number of frequencies required for the various symmetrical patterns, can be obtained.

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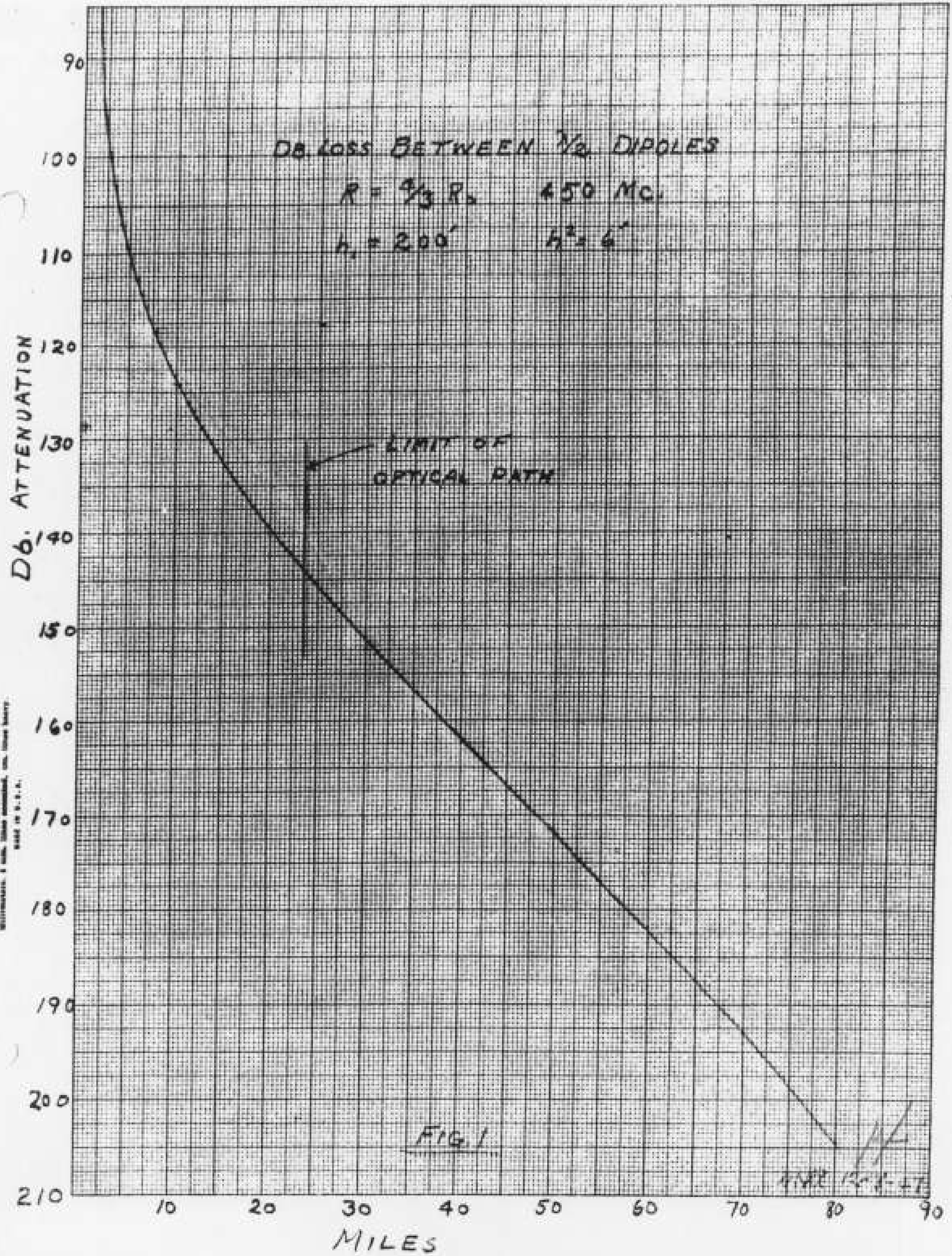

FIG. 1

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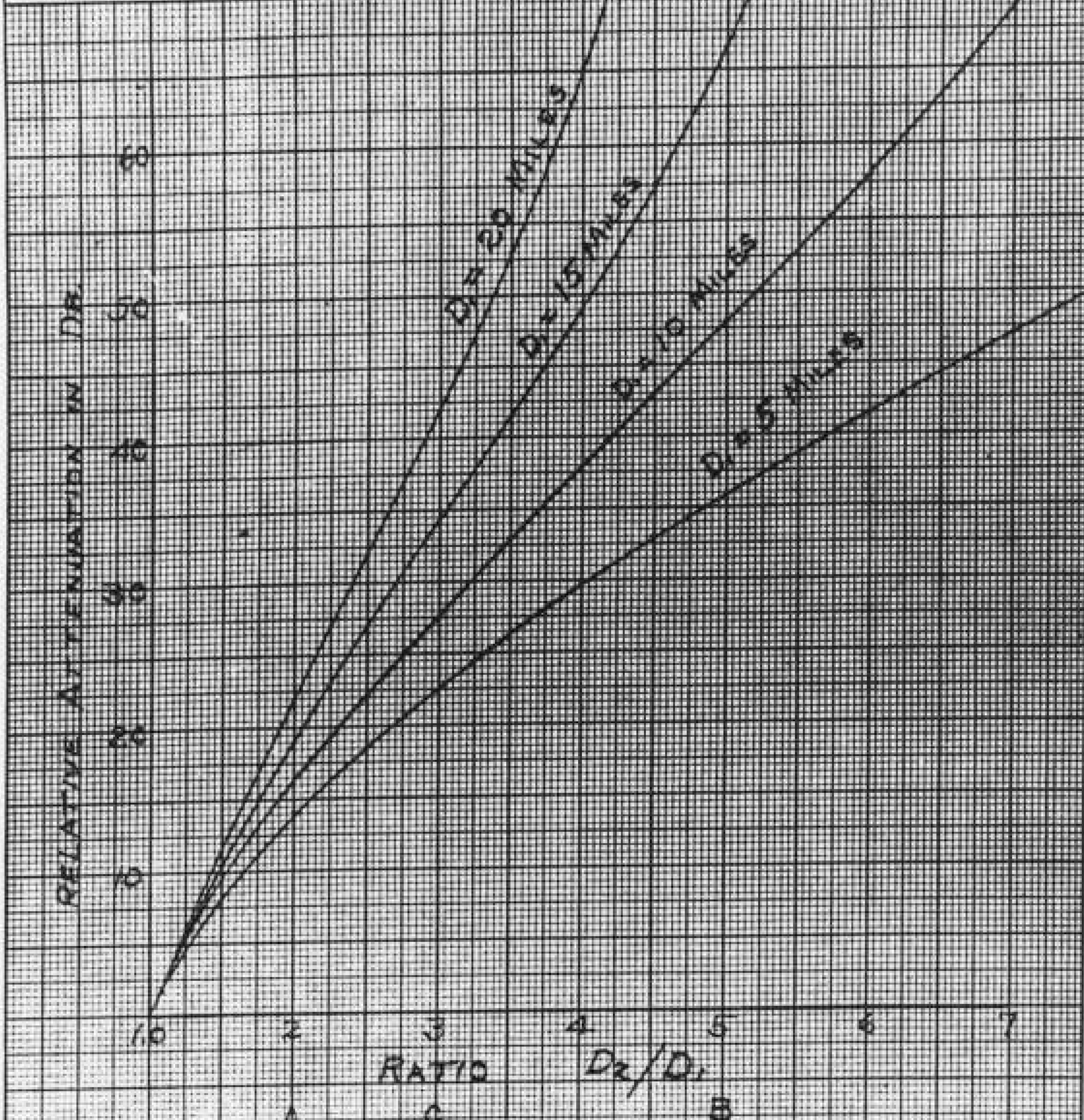

RELATIVE ATTENUATION OF SIGNALS RECEIVED AT C FROM TRANSMITTERS AT A AND B
F = 450 MC., 4/3 EARTH RADIUS, ANTS. A & B = 200', C = 6'

FIG 2

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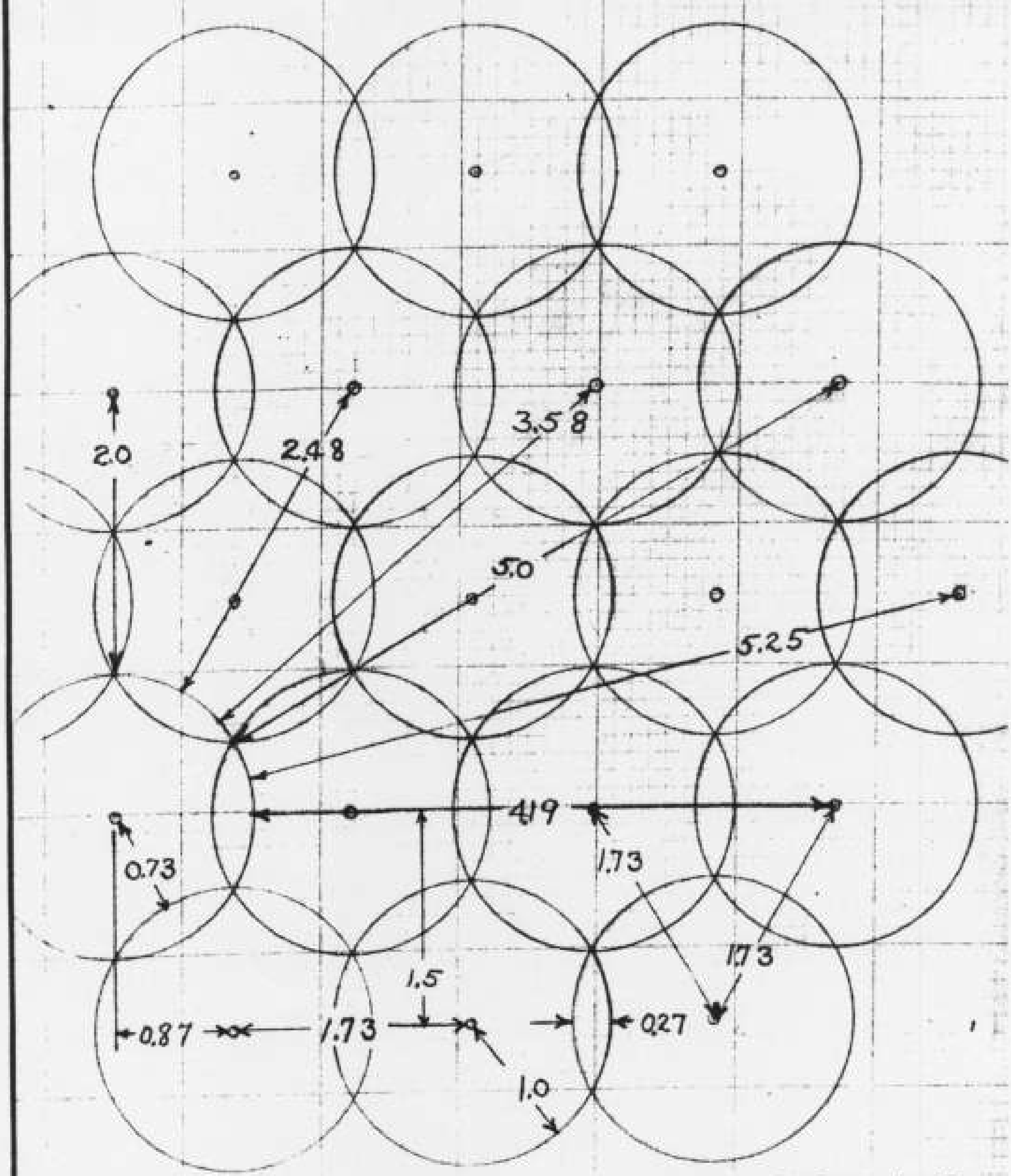

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NORMALIZED VALUES OF IMPORTANT DIMENSIONS IN A WIDE AREA PLAN
SERVICE RADIUS OF EACH STATION = 1

FIG. 3.

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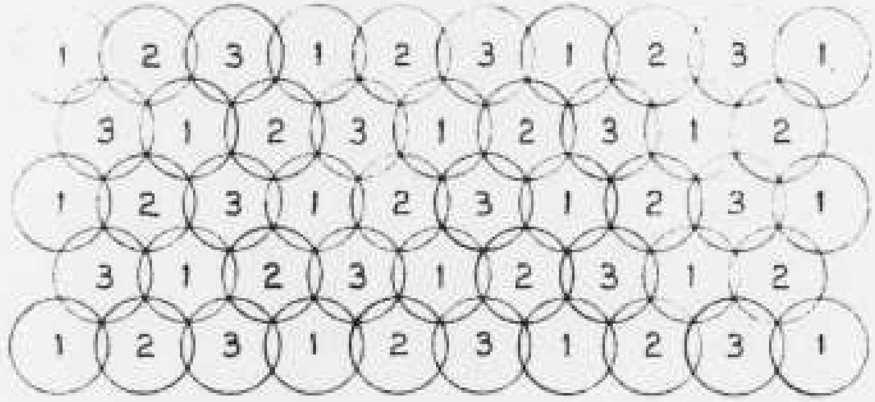
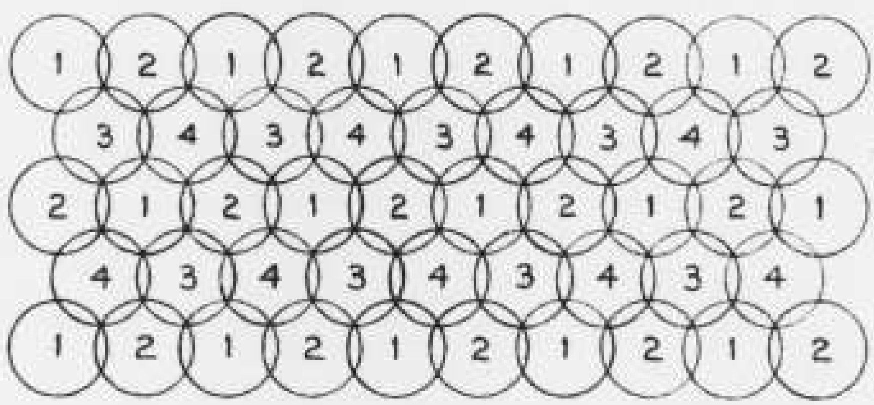


3 FREQUENCIES – MIN VALUE $D_2/D = 2$



4 FREQUENCIES – MIN VALUE $D_2/D_1 = 2.48$

FIG. 4

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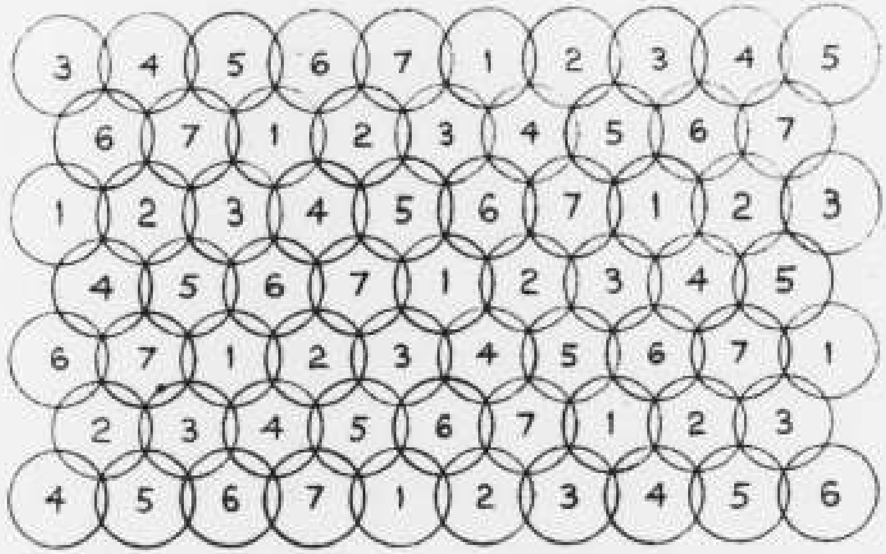
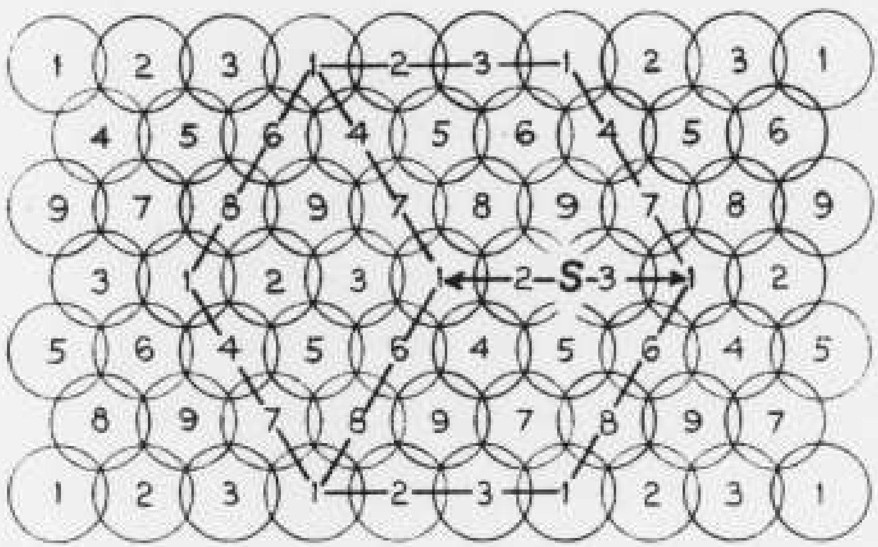


7 FREQUENCIES — MIN VALUE $D_2/D_1 = 3.58$



9 FREQUENCIES — MIN VALUE $D_2/D_1 = 4.19$

FIG 5

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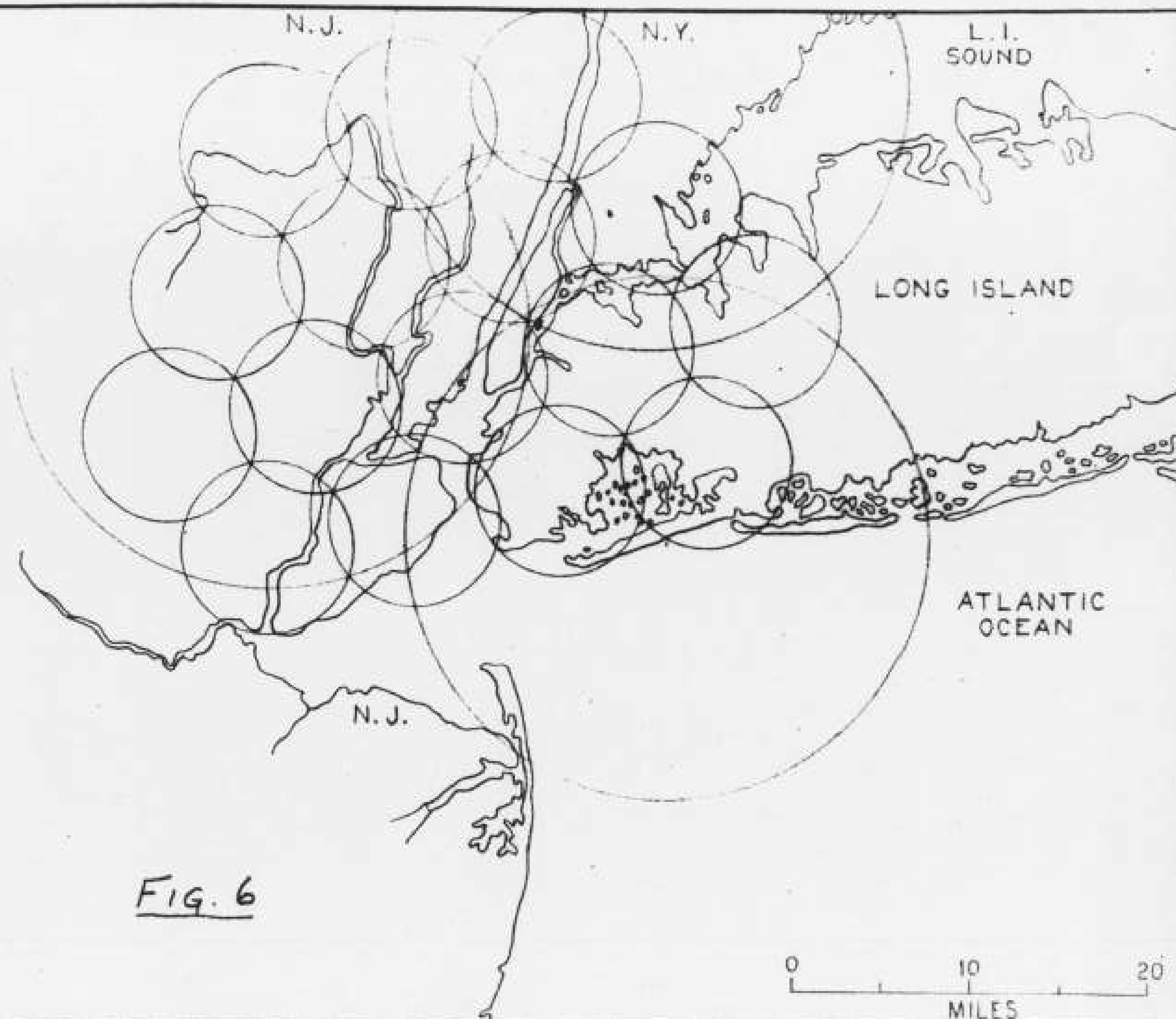

FIG. 6

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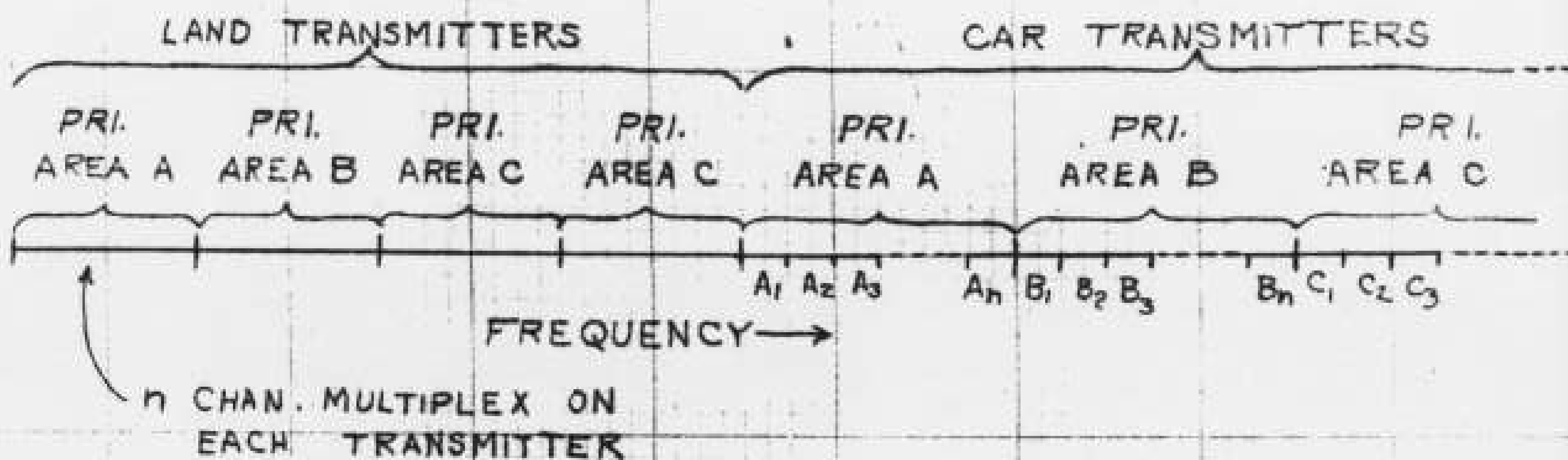
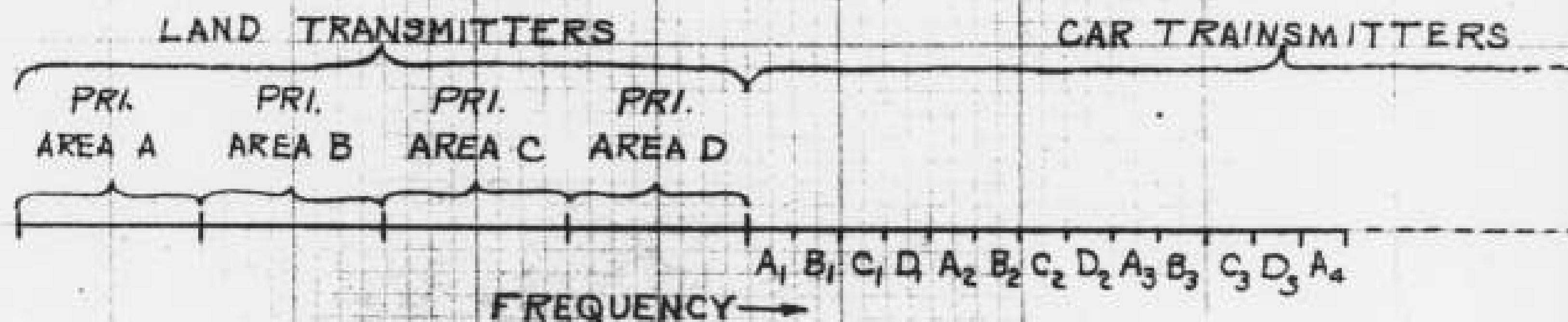


Fig. 7-a



WIDE COVERAGE MOBILE SYSTEM FREQUENCY PLANS

Fig 7-b

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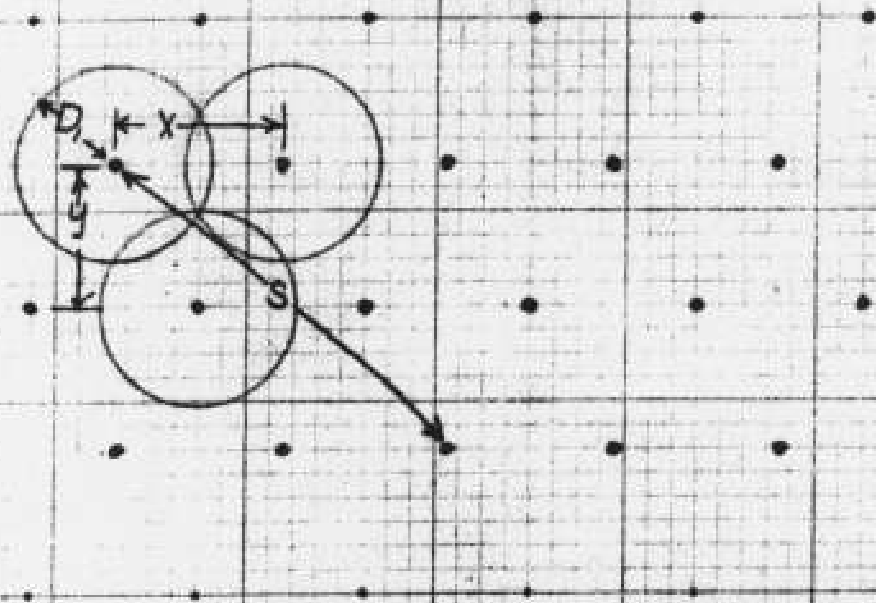

$$s = \sqrt{\left(i\,\tfrac{x}{2}\right)^2 + (j\,y)^2}\,, \quad i \,\&\, j \text{ BOTH EVEN OR BOTH ODD INTEGERS, INC. ZERO.}$$

$$x = \sqrt{3}\, D_1$$

$$y = 1.5\, D_1$$

FIG. 8

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DISTANCE TO ANY POINT IN HEXAGONAL PATTERN

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MINIMUM VALUE OF D_2/D_1 FOR HEXAGONAL PATTERNS OF m FREQUENCIES

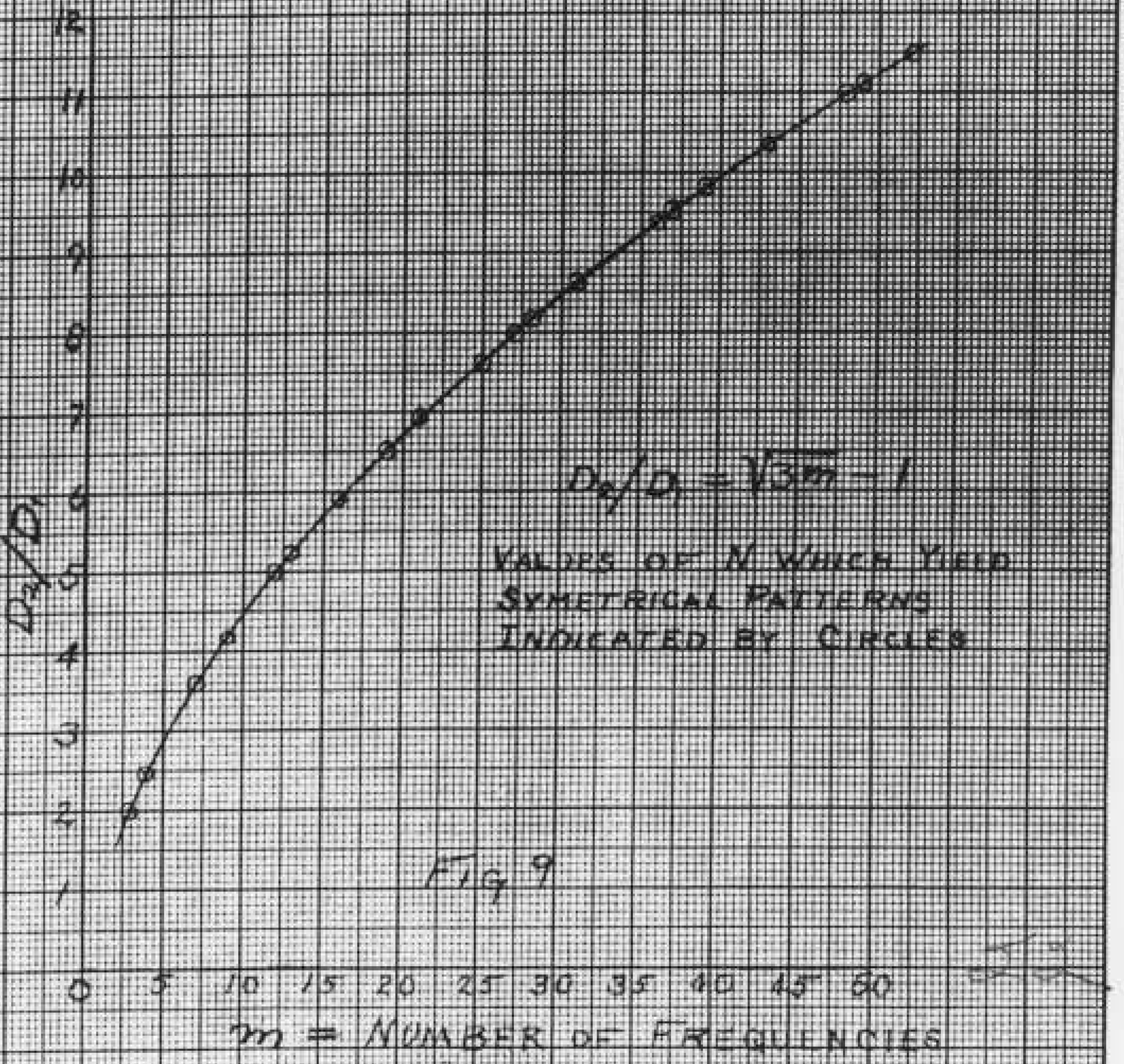

FIG 9