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Effects of Local and Skywave Interference on CB Radio Range

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EFFECTS OF LOCAL AND SKYWAVE INTERFERENCE ON CB RADIO RANGE

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The combined effects of local interference, skywave ("skip") interference, and radio noise on Citizens Band radio range are calculated. If the ionospheric reflectivity is normal or above normal during the next solar cycle, and CB use does not decrease, the operational range of CB users in cities of under 100,000 will be less than half its present value during daylight hours of nonsummer days for 3 years at the peak of the cycle. CB'ers in metropolitan areas with more than a million residents will probably not be bothered much by skip interference.

Key words: CB radio; electromagnetic compatibility; skywave interference; spectrum engineering

1. INTRODUCTION

The proliferation of Citizens Band radio has fortunately occurred during a low period of the 11-year solar cycle. During this period, long-distance transmission of 27 MHz signals via reflections from the ionosphere ("skip") has been relatively rare, occurring most often on summer afternoons and evenings when sporadic-E layers are present perhaps 5 percent of the time (Smith, 1976).

As Lucas (New York Times, 1976) pointed out, CB skywave propagation will be more likely near the peak of the solar cycle, expected in 3 or 4 years. His warning that skip signals might cause enough interference to decrease the average CB range ("talk distance") to less than a mile caused considerable consternation to the CB industry.

Two important questions need to be answered: Will skip interference really be important in the face of the increasing

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local congestion on CB channels in urban areas? And, if so, for how long and for what hours of the day will the interference be troublesome?

This report answers those questions. If the ionosphere's reflection properties near the peak of the next solar cycle are about the same as they have been for the four cycles for which we have data, and if CB use remains at its current level or increases, then for about 8 daylight hours per day for 8 months of each of the 3 years near the peak of the cycle, the operational range of CB'ers in cities with about 100,000 population or less will be reduced by more than half by skip interference. The range of CB'ers in sparsely populated rural areas may be only one-sixth of their present range. About one-third of the population of the United States live in such small cities and rural areas. In metropolitan areas with more than one million residents, local interference limits the operational range of CB so much that increased skywave interference will probably not be troublesome. About half the population of the U.S. live in such cities.

The next section of this report explains the philosophy and assumptions of the computer model used to reach these conclusions. Section 3 shows the computed operational ranges. I intend these sections to be comprehensible to any diligent reader. The appendices of the report describe the model mathematically, so that engineers can judge its validity.

2. THE MODEL USED TO CALCULATE CB RANGE

2.1 Approach

More than 20 million CB sets have been sold in the U.S. These sets are attached to many different kinds of antennas installed in all kinds of vehicles, boats, and homes. They operate on flat plains and in the Rocky Mountains, on water and in urban "canyons." Sometimes operation is hindered by automobile ignition noise or static from thunderclouds, and sometimes by interference from other CB's. It is clearly inadequate to use measurements or calculations made for one (or several) "typical" situations to answer questions about the performance of all these sets. It is better to consider the entire range of possibilities and to answer in terms of the average performance, or the performance achieved on, for example, 10 or 75 percent of the attempts. This "probabilistic" or "statistical" approach will not predict success or failure for any specific attempted CB call, but will produce an overall picture of the results obtained by the entire population.

The statistics of CB performance can be accumulated in two ways. One way is to calculate performance for not just a few typical cases, but for millions of attempted CB contacts, each one representative of some specific set of circumstances, and to count the number of successful contacts. Although conceptually simple, this approach requires so many calculations that it is expensive even on a large computer and places a heavy burden on the person who must devise all the cases.

A less costly approach is to compute the performance statistics directly by using probability theory to manipulate the statistical distributions of the contributing factors. This probabilistic approach is described in detail by Berry (1977) and outlined in Appendix A.

2.2 Measures of Performance: Operational Range

How satisfactory a CB message exchange is depends on several factors: whether the desired person can be contacted, how clearly the talker can be understood against the background noise, and whether or not the conversation is interrupted by an overpowering transmission from a third party. However, analysis and comparison is easier if a single number can be used to represent communications satisfaction. Popular literature and CB advertisements show that "talk power" or "signal reach" is important to CB'ers. I call this distance over which two CB'ers can communicate the "operational range" and give it a precise, computable definition.

First, the range depends on the quality of the reception we are willing to accept. Other things being equal, the range at which every word is heard "loud and clear" is much shorter than the range at which a message can just barely be understood through the static and interference. So operational range must be computed for a fixed quality of service. Even then, the range that a CB radio can reach is not fixed, but depends on location, noise, interference, and other variable conditions. At best, we can talk about the average range, or the range that can be achieved for some percentage of the attempted calls.

So, in this report, the distance at which CB'ers receive a signal of specific quality (or better) on 50 percent of the transmissions is called the "50 percent operational range" or the "average operational range." The distance at which they receive the specified quality of service (or better) on 75 percent of the transmissions is called the "75 percent operational range," and so forth. Naturally, the 75 percent operational range is smaller than the 50 percent operational range.

The tables and figures showing operational range in this report are for top quality reception. CB'ers willing to tolerate some noise and interference can reach further. However, the conclusions about the effect of skip interference on operational range would be the same for any fixed quality of service.

2.3 Signals, Noise, and Local Interference

Generally, a voice signal from a CB transmitter can be understood if it is sufficiently stronger than the radio noise or interference. The situation is analogous to ordinary conversation in the presence of noise or competing conversation. If there were no noise or interference, the signal would have to be greater than the receiver's internally generated noise, but this is rarely a limitation.

In the early days of CB and on uncongested channels still, the limitation is noise ("static"). In sparsely populated rural areas, CB radio noise comes primarily from radio sources in the galaxy, or sometimes from nearby electrical storms. The average level is so low that CB signals often can be received from 20 or more miles away. In cities or on busy interstates, automobile ignition systems and other electrical equipment cause man-made se perhaps 100 times stronger than natural noise, cutting CB nge to 5-10 miles or less.

In large cities, interfering transmissions from other CB sets on the same channel may be 10 to 100 times stronger than the man-made noise, and range may be a mile or less.

Estimating the range of a CB radio consists of estimating the distance at which the signal-to-noise and signal-to-interference ratios are large enough to permit conversation. The signal strength depends on how much power is radiated from the transmitter antenna and how much is lost between the transmitter and receiver. Although most CB transmitters have about the same rated power (3 or 4 W), the strength of the signal produced depends on the type and mounting location of the antenna and its height above the ground. In this report, I assume that the average CB is mounted in a vehicle (a "mobile") and is attached to a 40 inch whip mounted in the middle of the vehicle roof, with some mobiles having better antennas and some having less efficient antennas.

The average base station is assumed to have a 5/8 wavelength whip mounted 30 ft above the ground. Some base stations have antennas installed at heights up to 60 ft, and some have lower antennas. The exact distribution of effective radiated power used in the calculations is shown in the appendix. For the conclusions reached in this report, I assume that 20 percent of the stations are base stations and 80 percent are mobiles, but the appendix shows that the results would be almost the same if 10 or 30 percent of the stations were base stations.

Radio signals get weaker the farther they get from the transmitter. How much weaker they get depends on the terrain they pass over and to some extent on other conditions. CB signals carry much farther over water than over land and farther over smooth farmland than over rocky mountains or high-rise urban centers. The location of both CB radios is important. If both are on high points with no obstructions between them, signal loss is small, but if hills or high-rise buildings are between the two antennas, most of the signal may be blocked off. In this report I assume that the <u>average</u> transmission passes over slightly rolling terrain of average soil conditions with either no buildings or suburban residential buildings. But the calculations do not include only average conditions; they include a wide range of other possibilities for transmission paths. The mathematical description of the distribution of transmission loss is given in the appendix.

The source and qualitative levels of natural noise have already been mentioned. The average noise levels and the distributions about those averages are given in the appendix and are those recommended by an international group of experts (CCIR, 1969).

The amount of interference competing with the signal on congested channels depends on the number of other stations transmitting on that channel and on their distance from the desired receiver. The operational range of CB radios in the presence of local interference has been computed for a variety of operating conditions and published in another report (Berry, 1977). The results of interest here are summarized in Table 1. The table shows the ranges of mobile stations and base stations separately when they are operating against local interference and against two levels of noise. Citizens band radios are assumed to be scattered randomly over a metropolitan area that can be enclosed in a circle 24 mi across. (Other calculations have shown that the size of this circle is not critical to this report's conclusions.)

Notice that the range against one interferer is much less than the range against noise, and that the range decreases as the number of interferers increases. However, the larger the number of interferers, the smaller the difference made by

Table 1. Operational Ranges of CB Radio in Different Radio Environments

(OR_x is the distance in miles that a high quality signal is received on 100x percent of the attempted calls. See Appendix A for precise definition of terms.)

	Typical Base Station			Typical Mobile Station		
	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
Natural Noise	18.3	23.2	29.8	8.4	10.5	13.0
Urban Noise	6.3	9.3	13.6	2.2	4.1	6.0
1 Local Interferer	3.5	6.6	10.2	1.6	2.7	4.4
3 Local Interferers	2.0	3.1	4.9	0.8	1.4	2.1
6 Local Interferers	1.3	2.1	3.2	*	0.9	1.4
10 Local Interferers	1.0	1.6	2.4	*	0.7	1.0

*Calculations are not dependable for operational ranges less than 0.5 mi.

additional interferers. For example, the operational range is decreased more going from one to three interferers than it is by going from six to ten interferers, even though twice as many interferers have been added in the latter case. This is an important characteristic and will help explain why the addition of skip interference does not affect operational range much in large cities.

2.4 Skywave Interference

Skywave or "skip" signals are signals radiated towards space from a transmitter and reflected back to earth by the ionosphere, a layer of the atmosphere 60 to 180 mi high (see Figure 1). Because signals traveling this path encounter no obstacles (not even the curvature of the earth), they lose less strength with distance than signals that travel near the earth, and sometimes can be heard 500 to 2000 mi away.

The ionosphere, like the weather, is always changing and does not reflect CB signals all the time. There are two different

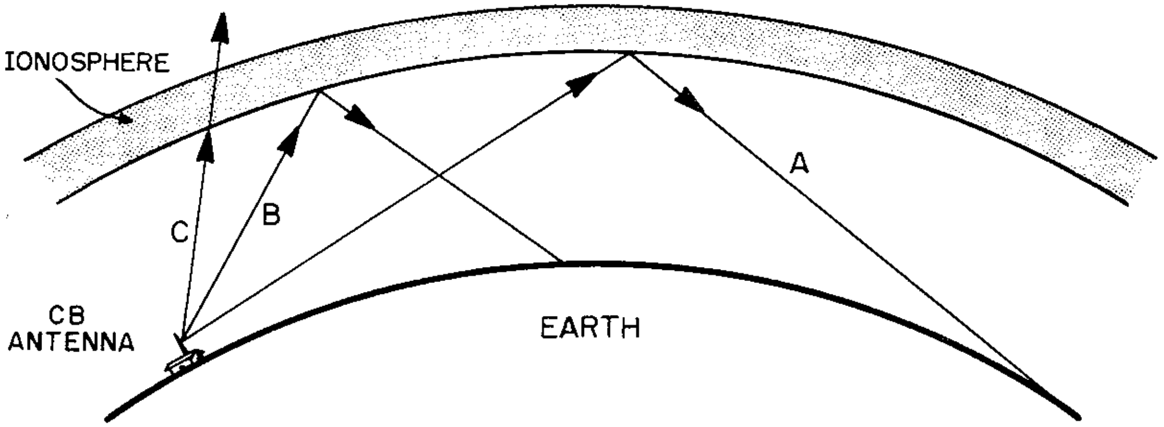

Figure 1. Illustration showing how CB skywave, or skip, signals travel beyond the line-of-sight by reflection from the ionosphere. Signals like A that hit the ionosphere at a glancing angle go farther than signals like B that hit at a sharper angle. If the angle is too sharp, the signal goes through the ionosphere (like C). During solar cycle minimum, the ionosphere reflectivity is so weak that even CB signals like A go through without reflection.

layers that cause skip, and they have different time variations. At a height of about 60 mi, there are sometimes reflecting patches called "sporadic-E." As the name suggests, the appearance of the patches is erratic in time and space, but the percent of time they occur is predictable. During the winter and spring, patches that reflect CB signals occur one percent of the time or less over the United States. During the summer and early fall, this rises to as much as five percent of the time, with a peak higher than that during the afternoon and early evening (Smith, 1976)1. Although this allows CB'ers to (illegally) work long distances at times, and causes some irritation to others, the patchiness of the reflector in both space and time limits the extent of the problem. The effect of sporadic-E skip interference on CB operational range is not included in this report because: (1) it occurs only a small percentage of the time, and

(2) it does not change systematically from year-to-year so that future problems will be much like those experienced now.

The main reflecting layer of the ionosphere, at a height of about 120 to 200 mi, is called the F layer. Its reflecting power varies from low to high to low over a period of about 11 years and then repeats (Davies, 1965). The periods of low reflecting power coincide with periods of few spots observed on the sun, and periods of high reflecting power coincide with periods of many spots on the sun, so skip is correlated with the sunspot cycle. This correlation is useful because we have records of sunspot numbers for over 250 years and records of ionospheric reflectivity for only the last 45 years (Davies, 1965). Figure 2 shows the yearly average sunspot number compared to a measure of the ionosphere's reflecting power (a parameter called foF2) from 1935 through 1976.

The sunspot cycle was at a minimum in early 1976, and the F layer has generally been too weak to reflect CB signals for the last 5 years. The last time that the F layer reflected CB signals with any reliability, there were so few CB users that the presence of skip was more an interesting novelty than a major problem. So we have no direct historical evidence of how much F-layer skip will interfer with CB use during the next sunspot maximum.

It is highly likely, but not certain (Eddy, 1977), that the number of sunspots will increase to a high point within the next 2 to 4 years. How high that peak will be is unpredictable, but although the ionosphere's peak reflective power coincides in time with the sunspot peak, the reflective power itself seems to be only weakly dependent on the peak sunspot number. For example, the 1957 sunspot number is nearly twice that of 1968, but the 1957 foF2 is only 25 percent greater than that of 1968 (Figure 2). In this report, I assume that the next sunspot cycle will be "normal"--like the ones that peaked in 1937 and 1968. The next cycle is expected to be at least that big (Sargent, 1978; Solar Geophysical Data Bulletin, 1977).

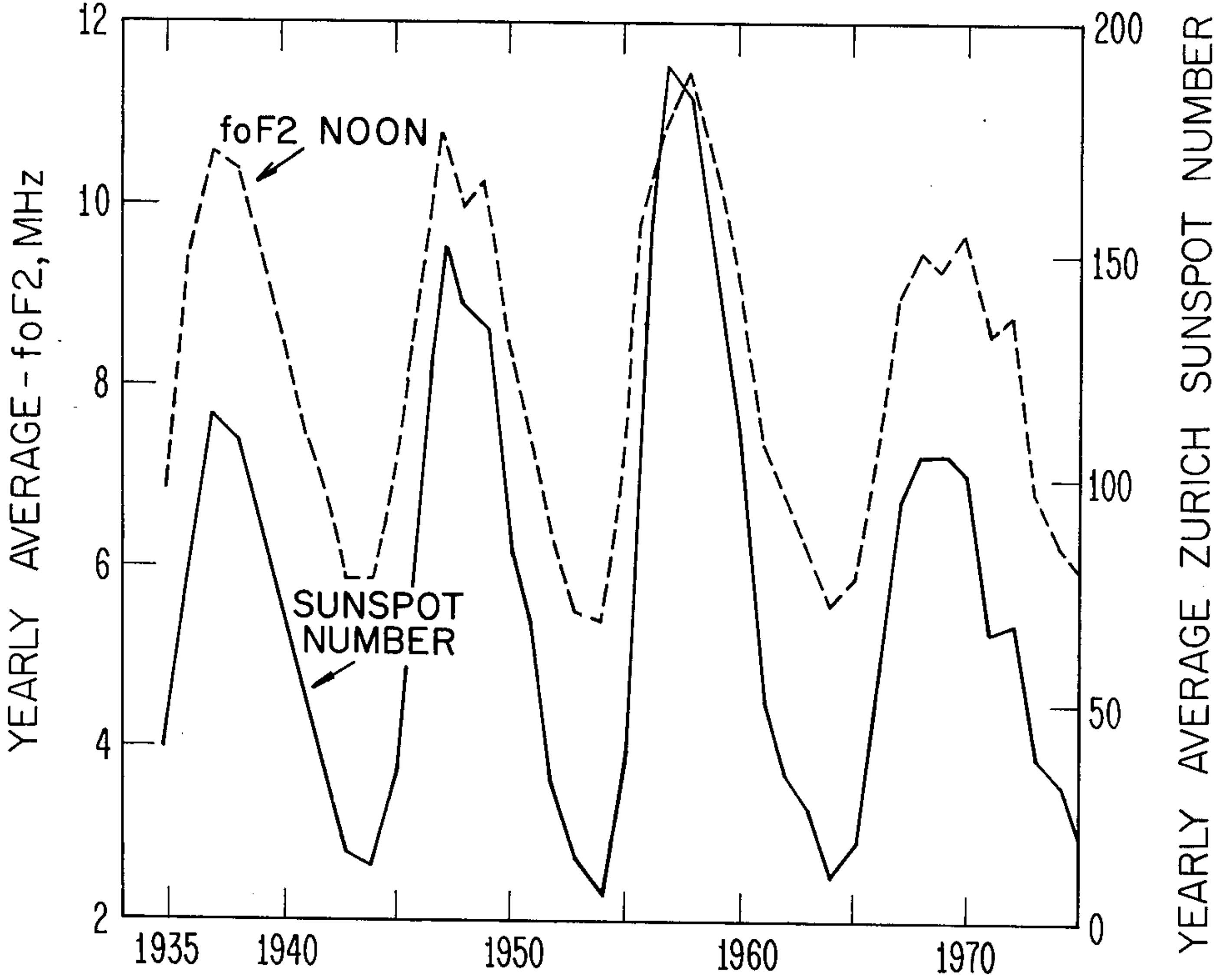

Figure 2. Yearly average sunspot number (solid line, right scale) and yearly average foF2 (dashed line, left scale) at noon near Washington, D.C., from 1935 until 1976. The ionospheric reflectivity is high during the peak of a sunspot cycle and is lower during the minima of the sunspot cycle.

The F layer of the ionosphere, like the atmospheric temperature, cannot be predicted long in advance for a particular hour of a particular day. However, the average behavior, and the extremes, for a given time of day for a given month can be predicted fairly well. Using these predictions (Roberts and Rosich, 1971), the number and strength of skip interferers can be computed.

The number of interfering signals from a given distance depends on the likelihood that CB signals will propagate from that distance, the number of people living at that distance, and the fraction of the population transmitting on the channel. The probability of CB skywave propagation for different distances was calculated with a widely used computer program developed for this purpose (Lucas and Haydon, 1966; Barghausen, et al., 1969). The program's validity has been proven by over 10 year's use by U.S. and foreign government agencies, private companies such as press agencies, and international broadcasters.

Population density was determined using 1970 census data (U.S. Bureau of the Census, 1976). Because skip interference comes from all over the country, the model does not require fine spatial resolution of density, so shifts in population density since 1970 can be ignored. Population growth between 1970 and the next sunspot maximum in the early 1980's will make skip interference marginally worse than shown in this report. However, the operational range will be about the same because of the "saturation effect" explained later in this report (section 4).

The distance a signal travels determines the strength of the signal. The strength of all skip interference signals from all geographically possible distances are added together to get the total skip interference on a channel. The mathematical details of this calculation are given in Appendix A.

The resulting total skip interference is added to the local interference on the channel and compared with the strength of the desired CB signal to see if the readability is as good as desired.

3. CB OPERATIONAL RANGE NEAR THE PEAK OF THE SOLAR CYCLE

In the figures in this section, the effect of combined local and skip interference on operational range of CB radios is shown as a function of the most important causes. This relationship is used to estimate the amount of time that skip interference will be troublesome and the fraction of the U.S. population that will be bothered.

The calculations given in detail in Appendix C show that the most important variables are the number of people in the local area, the fraction of the population that is transmitting on the CB channel of interest, and the reflection characteristics of the ionosphere. The variation of the last two characteristics with time of day and with season is used to estimate how long skip interference will be a serious problem. Separate calculations are shown for the western and eastern parts of the U.S. because of the different population densities of the two regions.

The extension to all locations and times of the results calculated for a few specific locations and times introduces an error estimated as less than 20 percent. This uncertainty is small compared to the computed reduction in operational range.

3.1 Mean foF2 and the Ionosphere's Reflective Power

Interpolation of operational ranges calculated for specific times to all other times requires finding a parameter with known time variation that is directly related to skip interference. After experimenting with several possibilities suggested by experience with skywave propagation, I chose a parameter I call "mean foF2." Technically, foF2 is the highest radio frequency the ionosphere will reflect if the radio wave is transmitted straight up. Contour maps of foF2 are available for different phases of the solar cycle (Roberts and Rosich, 1971). The values for New York, Missouri, and Southern California were read from the maps and averaged to get "mean foF2."

Mean foF2 is logically related to the probability of skip interference because the ionosphere's reflective power is proportional to foF2 (Davies, 1965). When foF2 is small (less than about 6 MHz), the ionosphere is so weak that CB signals pass through it and are not reflected back to earth--there is no skip interference except that from sporadic E. At intermediate values of foF2 (about 8 MHz), CB signals that strike the ionosphere at a glancing angle are reflected, but CB signals that strike the ionosphere at a sharp angle are not reflected. As Figure 1 shows, the shorter the distance between transmitter and receiver, the sharper the angle on the ionosphere. So for intermediate values of foF2, only signals from very far away (about 1500 mi or more) cause skip interference. As foF2 increases above 10 MHz, CB signals from nearer and nearer the receiver are reflected from the ionosphere and cause interference. The amount of skip interference increases quickly as foF2 increases because the signals lose less of their strength traveling the shorter distance, and because there are more potential interfering signals (signals from more CB radios are reflected back to earth).

Table 2 shows mean foF2 for the peak of an average solar cycle (Roberts and Rosich, 1971). The values are the average for each 2-hour time block for each month and are arranged so that the high values are in the center of the table. Notice that around the edges of the table, mean foF2 is well below 6 MHz, and there will be no CB skywave propagation; but near the center of the table, mean foF2 is over 11 MHz. After looking at the effect of different values of mean foF2 on CB operational range, we will return to Table 2 to figure out what part of the time skip interference is a significant problem.

3.2 CB Operational Range as a Function of Mean foF2

Figure 3 shows a typical base station's 50 percent operational range, $OR_{.5}$, as a function of mean foF2. Recall that $OR_{.5}$ is the maximum distance at which a high quality signal will be received on at least 50 percent of the attempted calls. The calculations leading to Figure 3 were made assuming that two CB

Table 2. Mean foF2, MHz, for a Normal Year at Solar Cycle Maximum

(The average of monthly median foF2 for New York, St. Louis, and Los Angeles; from Roberts and Rosich (1971).)

UT*	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
8	4.7	4.7	4.8	4.8	4.0	3.8	4.0	4.5	5.2	5.3	5.5	5.3
10	4.3	4.3	4.5	4.3	4.2	3.7	3.5	4.2	4.5	5.2	5.2	4.8
12	5.2	5.3	5.7	5.8	4.7	4.0	3.8	4.5	5.5	6.2	5.5	5.3
14	6.0	6.3	7.2	8.2	7.7	6.8	6.7	6.7	7.7	7.3	6.5	6.0
16	6.5	7.2	8.7	10.3	10.8	10.0	9.2	9.8	10.2	8.7	7.3	6.5
18	7.0	7.3	9.2	11.2	12.0	11.7	10.7	10.8	11.0	9.5	7.5	7.2
20	7.3	7.5	9.5	11.5	11.8	11.5	11.0	11.0	11.2	10.0	8.3	7.3
22	7.3	7.8	9.5	11.0	11.0	10.3	9.8	10.3	10.8	10.0	8.3	7.3
0	7.3	7.3	8.5	9.3	8.8	8.3	8.3	9.3	9.8	9.5	8.3	7.3
2	6.7	7.0	7.2	7.2	6.2	5.8	5.8	7.2	7.8	8.2	7.7	7.2
4	6.3	6.2	6.0	5.7	5.3	4.3	4.2	5.3	6.5	6.7	6.5	6.3
6	5.5	5.3	5.3	5.3	4.2	3.8	3.8	4.5	5.5	6.0	5.8	5.7

*UT is universal time which is sun time at Greenwich, U.K., EST = UT-5, CST = UT-6, MST = UT-7, PST = UT-8.

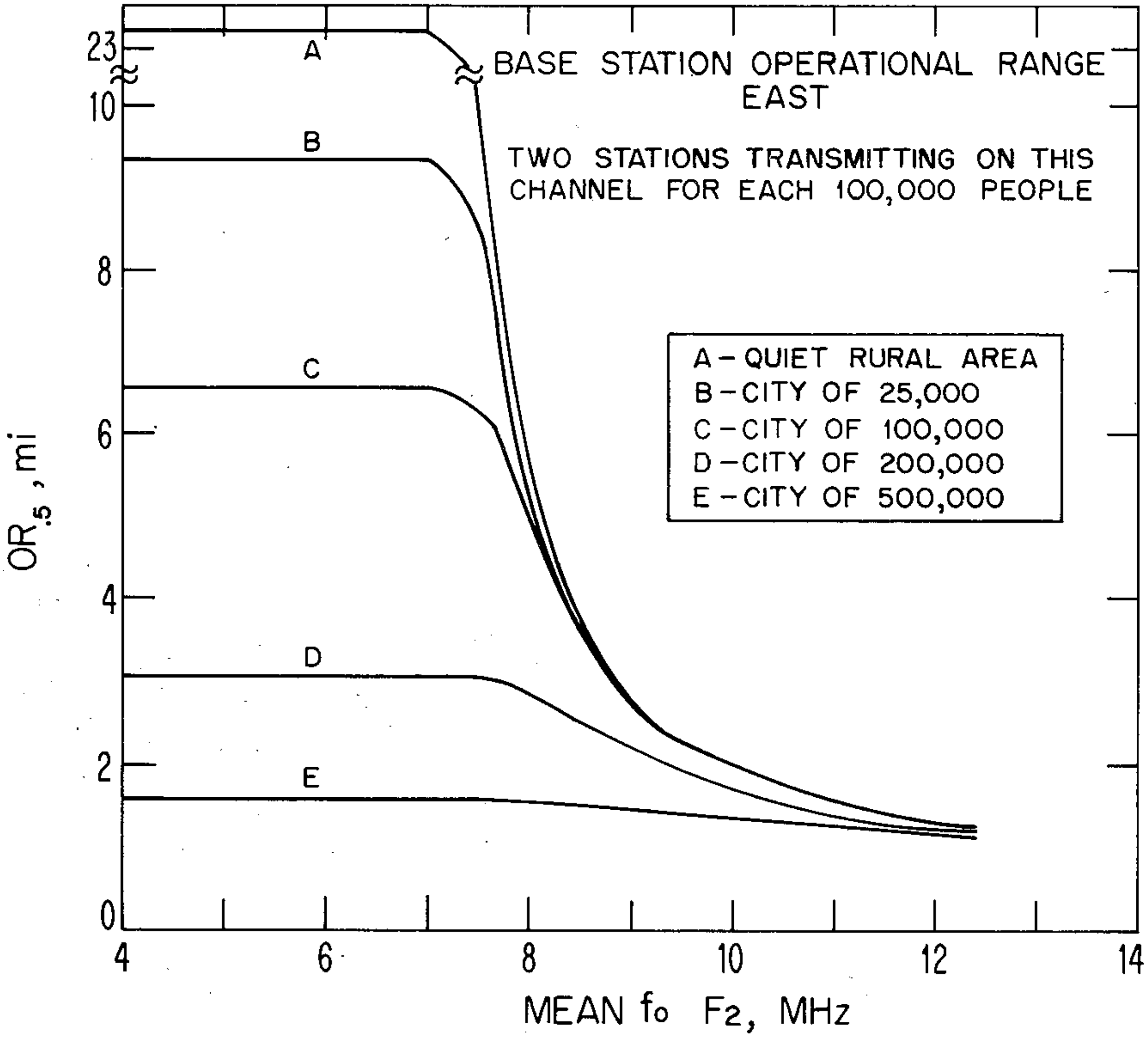

Figure 3. Average operational range of a typical CB base station for the conditions described on figure, as a function of the ionospheric reflectivity parameter, mean foF2. The left side of the figure corresponds to low solar activity; the right side is representative of winter daytime conditions near the peak of a solar cycle. Mobile station operational range is less than half base station range.

stations are transmitting on this channel for every 100,000 population, both in this eastern metropolitan area and all across the country. (This would be the case, for example, if eight percent of the population have 40-channel CB radios, each CB'er transmits one percent of the time (36 s per hour), and all channels are used equally.)

The middle curve in Figure 3 is the base station operational range in a metropolitan area containing 100,000 people. Notice that this curve is level at 6.6 mi for mean foF2 less than about 7 MHz, as it was in 1976. In this region, there is no skywave interference, and the operational range of one of the transmitters is limited by the interference caused by the other local transmission. Skip signals start to interfere as foF2 gets larger than about 7 MHz and the operational range decreases. As foF2 increases, the number of interfering skip signals increases rapidly, so the operational range decreases rapidly at first. However, there is a saturation effect, and the curve flattens out beyond 12 MHz, a value predicted for December during a solar cycle maximum. Notice that the operational range for this case is down to 3.3 mi (half its value for no skip interference) for mean foF2 = 8.75 MHz.

Before continuing, let's illustrate the meaning of operational range using the middle curve in Figure 3. Suppose we picked 1000 base stations in eastern cities with populations of about 100,000. These stations would have different kinds of antennas installed at different heights. Some would be in the middle of the built-up urban core; some would be on the outskirts of the area. Some would be on top of hills; some would be in low spots surrounded by hills; some would be on flat plains. At a time when the ionospheric mean foF2 is less than 6 MHz (say in the winter of 1976), we would have each station try to contact another CB stationed 6.6 mi away. These CB's also would be randomly located (except for the distance). Another (base or mobile) CB radio would be transmitting somewhere in the city on the same channel at the same time. The middle curve in Figure 3 says that 500 of these CB's would receive a high quality signal from the base station and 500 would receive a signal of lower quality.

We want to see how much difference skip interference makes in the range at which we receive a signal of that quality. So at a time when mean foF2 is 9 MHz, say a fall day near solar cycle maximum, we repeat the experiment. Now CB radios must be stationed only 2.6 mi from the base station in order for 500 of them to receive a signal of the same high quality as before. For the conditions mentioned, the 50 percent operational range has been reduced from 6.6 mi to 2.6 mi by the skip interference.

Figure 3 does not show what happened to the signal quality of the stations 6.6 mi away during solar cycle maximum, but the computer model used to make the calculations gives some indication. Figure 4 shows the percentage of CB's receiving a high quality signal at various distances with and without skip interference. The curve including skip interference falls below one percent at about 5.3 mi. So less than 10 of the 1000 stations at 6.6 mi receive a high quality signal in the second experiment. The curves in Figure 3 show the average range of CB base stations under the stated conditions, but the range of some stations is greater than average, and the range of others is smaller.

If there are two CB'ers transmitting on this channel in a city of 100,000, chances are there is only one on the channel in a city of 25,000, so he will not encounter local interference. His operational range for small foF2 is limited by ambient radio noise caused by vehicle ignitions and other electrical and electronic equipment in the city. Figure 3 shows base station range in this city is 9 mi. But once skip interference starts coming in, a small city CB receives as much as one in a large city (since skip is coming from all over the country), and operational range drops to the same low value as in a larger city.

The relative effect is even greater for a CB user in a sparsely populated rural area (top curve in Figure 3). His

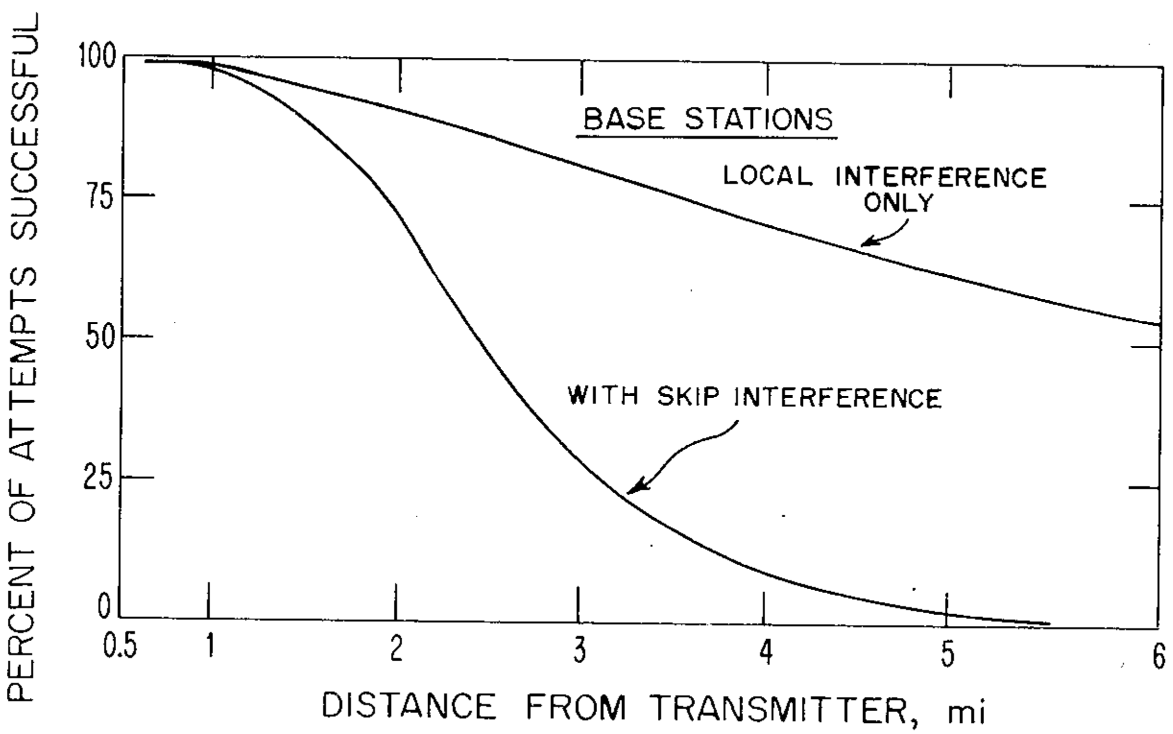

Figure 4. Percent of attempted CB base station calls that would be successful as a function of distance to the desired receiver. It is assumed that the station is in a city with population 100,000 and that there are two transmitters transmitting on this channel for each 100,000 people. The skip interference curve is for an eastern city when mean foF2 is 9 MHz.

range has been limited only by atmospheric and galactic radio noise, which is much lower than the radio noise in a city, so his base station operational range has been 23.2 mi. But he gets the same skip interference as others in the east, so his operational range quickly drops below 3 mi and approaches 1.2 mi for foF2 greater than 12 MHz.

The curve second from the bottom in Figure 3 is the operational range of a base station in an eastern city with a population of 200,000. There are four stations transmitting on this channel in this city, so each is being interfered with by three others, and as a result the average operational range is only 3 mi even without skip interference. When the mean foF2 gets large enough to support skywave propagation, the skip interference decreases the operational range to about 1.2 mi.

The bottom curve in Figure 3 shows the situation in a city of 500,000 or more. So many stations are transmitting on this channel in this city that the average operational range is only 1.6 mi even when there is no skip interference (foF2 less than 6 MHz). The local interference is so high that the skip interference has little effect on the operational range, although it does decrease to 1.2 mi for mean foF2 greater than 11 MHz. So for the conditions of Figure 3, skip has little effect on operational range in large cities, but drastically reduces the CB operational range in small cities and rural areas.

Figure 5 shows $OR_{.5}$ under the assumption that only two stations are transmitting on this channel for each 500,000 people and represents a much more lightly used channel. The general observations made above still apply, but to larger metropolitan areas. Even in this lightly used channel, skywave interference has little effect in metropolitan areas with one million population or more. Half the population in the U.S. live is such areas.

Figure 6 shows base station $OR_{.5}$ for the same conditions as in Figure 3, except for areas in the western U.S. Skywave interference begins at a lower value of mean foF2, and the

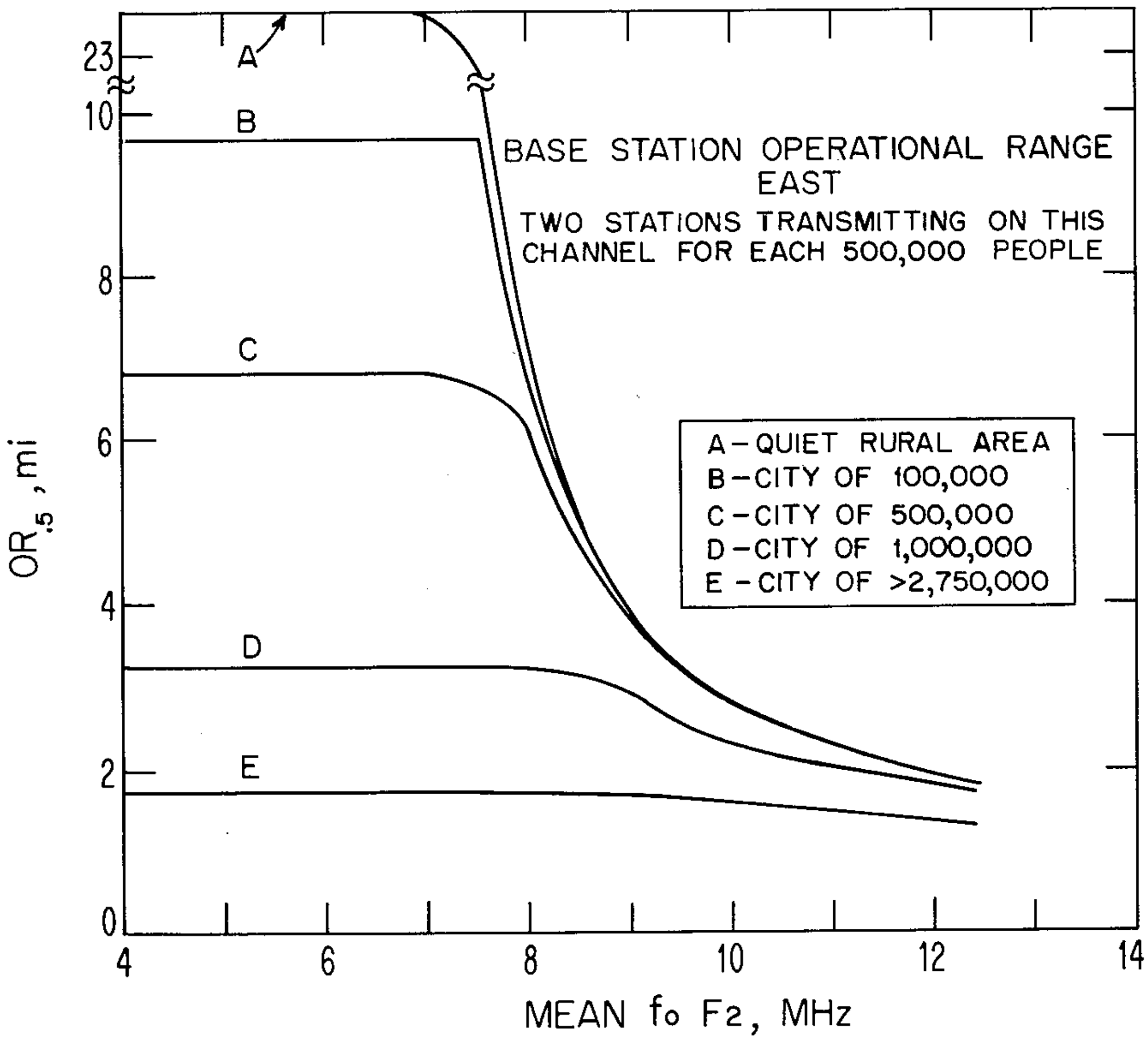

Figure 5. Average operational range of a typical CB base station for the conditions described on the figure. Mobile station operational range is less than half of base station range.

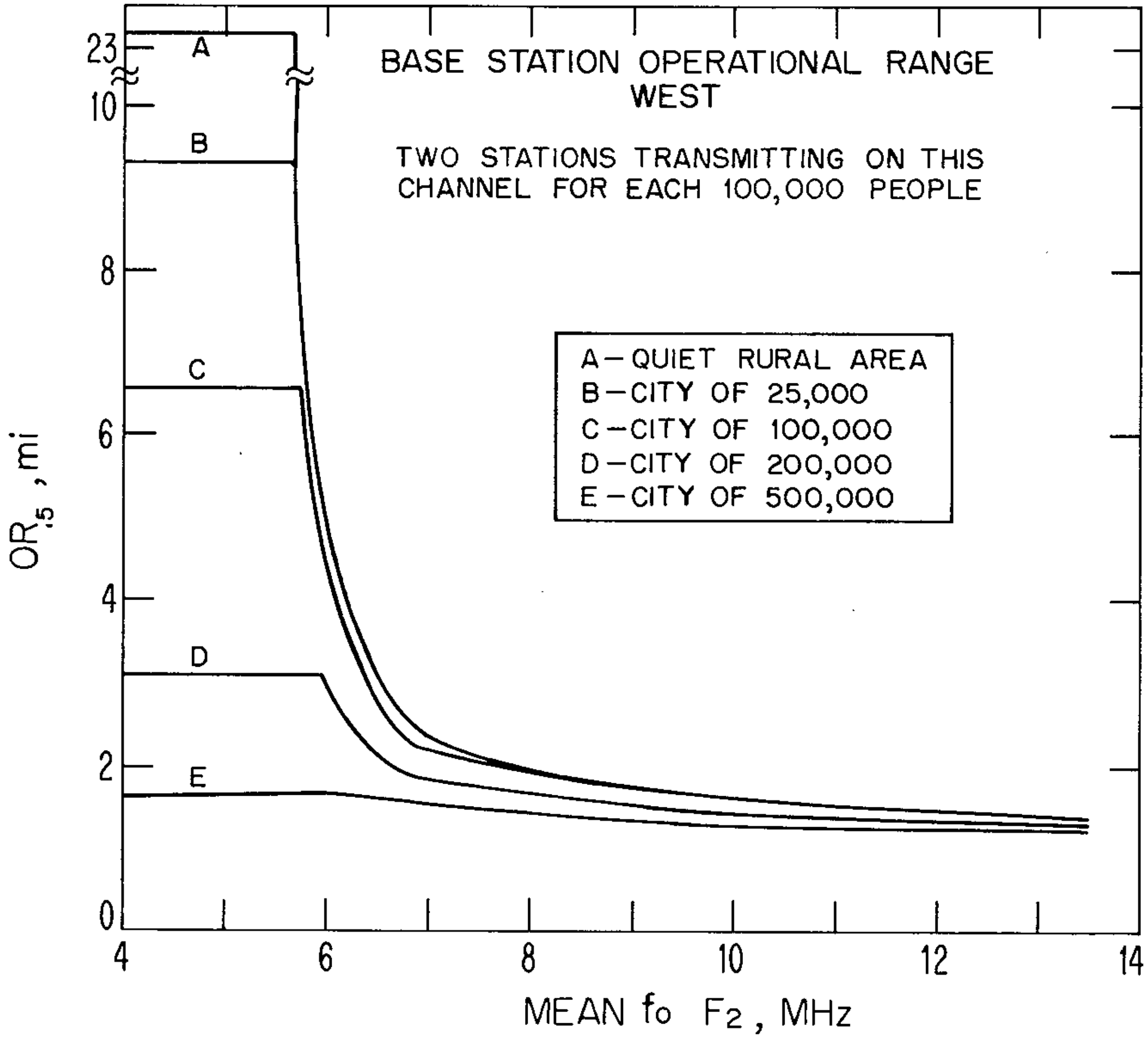

Figure 6. Average operational range of a typical CB base station for the conditions described on the figure. Mobile station operational range is less than half of base station range.

operational range decreases faster with increases in foF2 than for the east because there are so many more potential interferers. If this sounds reversed, remember that skywave interference comes from remote parts of the country, especially for moderate values of foF2. Thus, skip interference in the west is coming from the east where most of the people live, so the west receives more skip interference.

Figure 7 shows average operational range of base stations in the west for a more lightly used channel.

Figures 8-11 are for the same conditions as Figures 3, 5, 6, and 7, but they show the range achieved on at least 75 percent of the attempts, $OR_{.75}$, instead of $OR_{.5}$. This range is, of course, shorter in every case, but the skywave interference has the same relative effects.

Most CB radios are in vehicles, so it is useful to know the operational ranges of mobile CB sets. For the assumptions listed previously, the average range of a mobile CB is slightly less than half the range of a base station. More precisely, for the CB power distributions shown in Appendix B [mobile CB $OR_{.5}$] = [base station $OR_{.5}$] ÷ 2.24.

3.3 Likely Duration of Significant Skip Interference

Figures 3 through 11 and Table 2 can be used together to estimate the duration of significant skywave interference in a solar cycle maximum year. For the case shown in Figure 3, the operational range is cut in half by skywave interference for areas with 100,000 population or less when mean foF2 is 9 MHz or more. The heavy line in Table 2 encloses the time blocks for which this is true--about 8 hours per day for 8 months of the year.

As shown by Figure 2, the mean foF2 is nearly as high during the year before and the year after the peak of the solar cycle, so the conclusion above is probably valid for three consecutive years centered on solar cycle maximum. For 1 year before and 1 year after these 3 years, mean foF2 is about 0.8 of

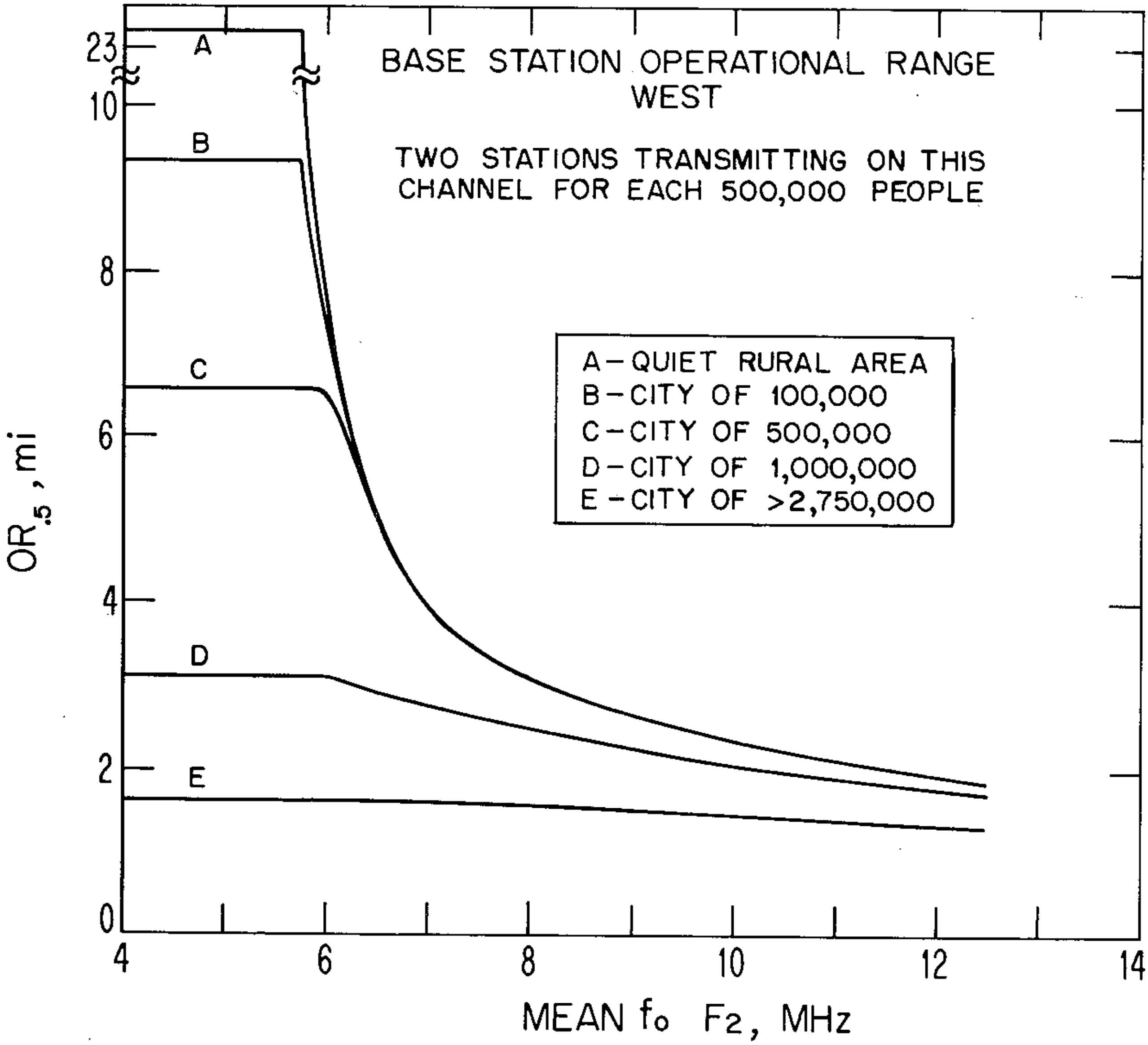

Figure 7. Average operational range of a typical CB base station for the conditions described on the figure. Mobile station operational range is less than half of base station range.

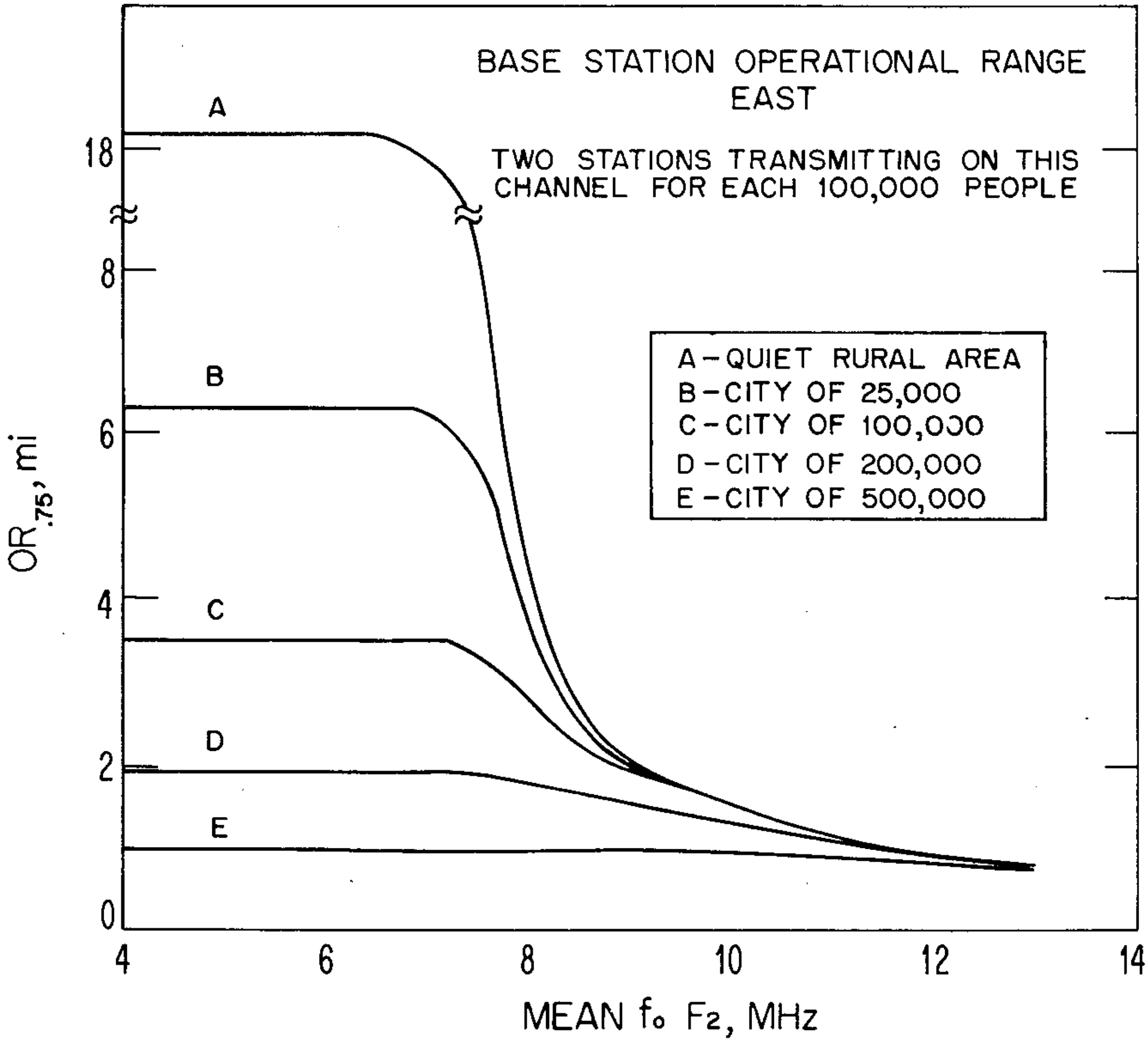

Figure 8. Seventy-five percent operational range of a typical CB base station for the conditions described on the figure. Mobile station operational range is less than half of base station range.

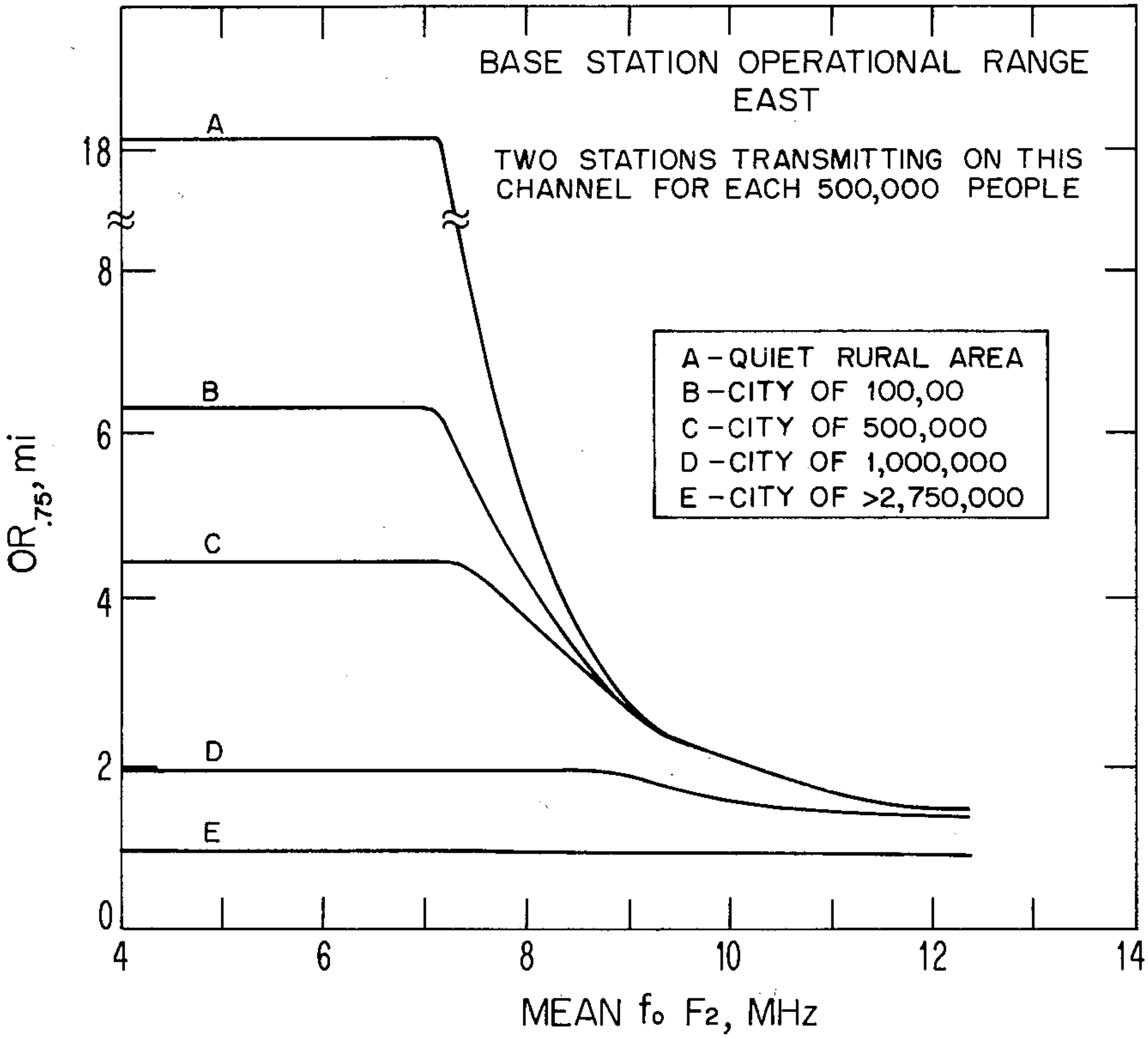

Figure 9. Seventy-five percent operational range of a typical CB base station for the conditions described on the figure. Mobile station operational range is less than half of base station range.

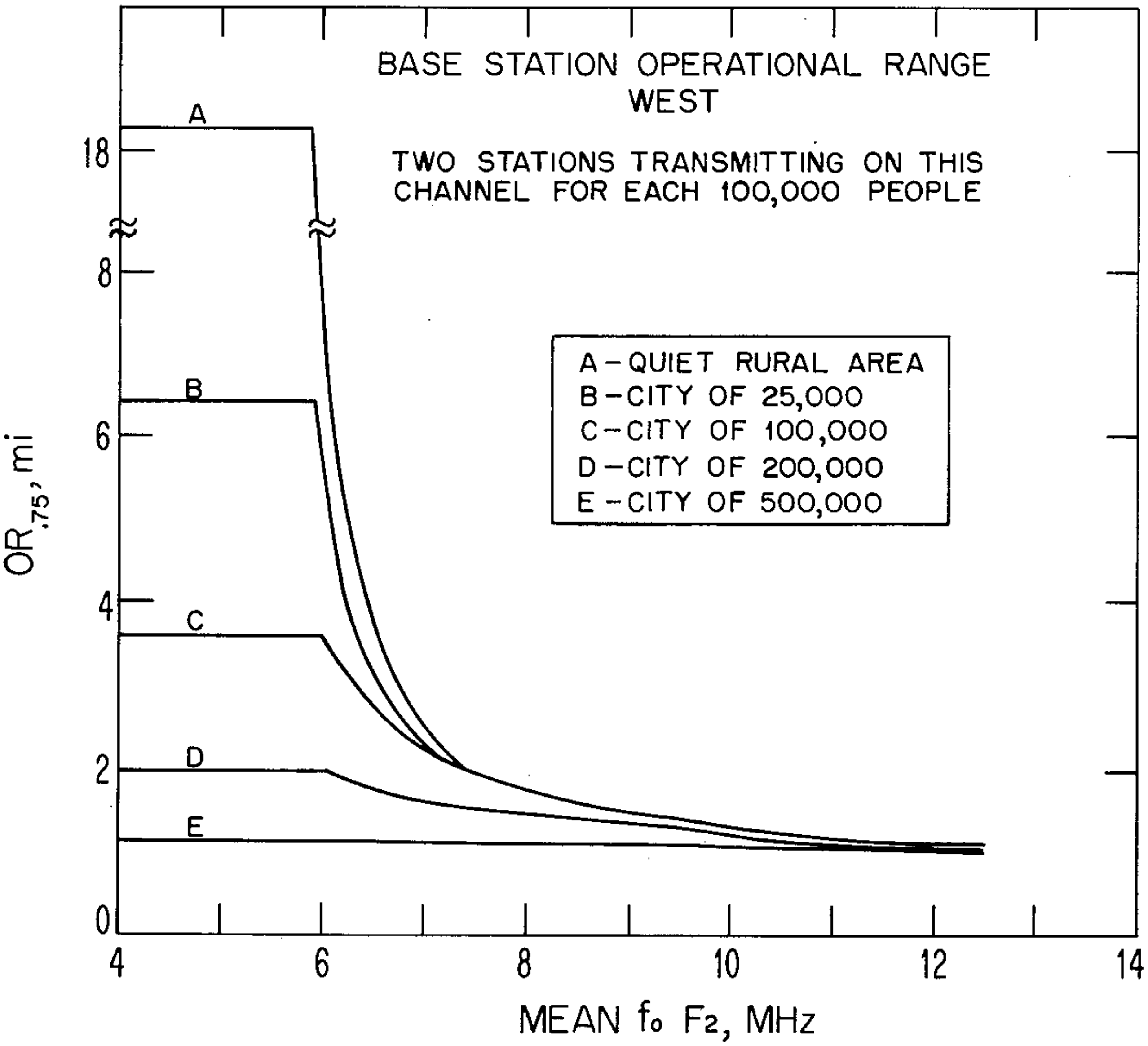

Figure 10. Seventy-five percent operational range of a typical CB base station for the conditions described on the figure. Mobile station operational range is less than half of base station range.

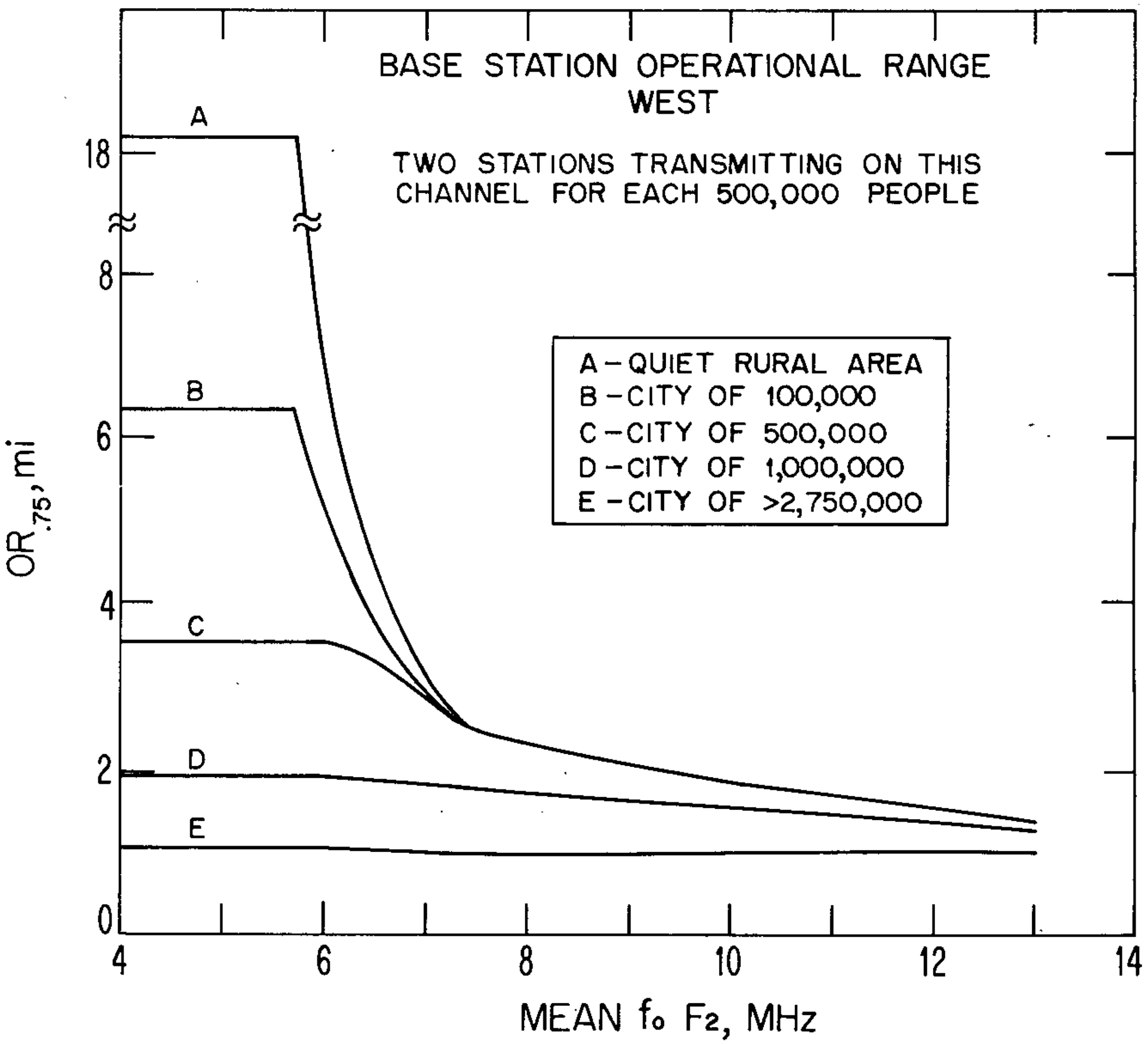

Figure 11. Seventy-five percent operational range of a typical CB base station for the conditions described on the figure. Mobile station operational range is less than half of base station range.

peak foF2. If each entry in Table 2 is multiplied by 0.8, the results are greater than 9 MHz for about 4 hours per day for 6 months of these years.

4. HOW CREDIBLE ARE THE CALCULATED RESULTS?

The curves shown in the previous section are deceptively simple. Their validity depends on the essential correctness of the formulas used, the accuracy and completeness of the data base, and the perfection of the instructions given the computer. In addition, their practical usefulness depends on their relative insensitivity to changes in values that are either poorly known or were held constant during the calculation. This section argues that conclusions based on the results of Section 3 are valid because all these criteria are adequately satisfied.

4.1 Model and Program Correctness

Sections 1 through 5 of this report do not contain detailed lists of formulas and approximation methods used in the computer program because I wanted the main features of the problem and its solution to be understood by nontechnologists. However, the appendices contain a complete description of the mathematics and data used. Engineers and scientists should study the appendices carefully to assure themselves that the model simulates reality.

It is nearly impossible to prove that a complicated computer program is logically correct and that numerical calculations are accurate for all conceivable cases. But, intermediate and final output from the computer model was carefully monitored. It agreed with the few answers we calculated by hand. Probability theory provides a number of tests on internal consistency that were satisfied in all cases. And the results were consistent with the judgment of experienced radio engineers.

4.2 Sensitivity of Answers to Assumptions

The last important question involves the sensitivity of the conclusions to the input parameters that are poorly known, or that were held constant for all calculations. These will now be reviewed.

Although the maximum output power of CB transmitters at the connectors is known, the power actually radiated from the antenna depends on the antenna types, the connections, the antenna height, and its mounting location. This variation is taken into account in the model, but the average value of radiated power is just an educated guess based on personal observation of CB installations. Fortunately, the true average value is irrelevant to computing the operational range against interference. If the average radiated power used in the calculation is too high, both the wanted signal and the interference are stronger by the same amount (on the average) and the signal-to-interference ratio is the same.

For operation against noise alone in small towns and rural areas, the average values of radiated power and noise are both important to the operational range, but for any reasonable assumptions about noise, the conclusions about the effects of skip interference would be qualitatively the same. For example, if the average urban noise were 4 dB greater than assumed, the operational range in a city of 25,000 would be 6.7 mi when there is no skip interference instead of the 9.3 mi shown in Figure 3. But skip interference would still decrease the operational range to less than half that value (2.6 mi) when mean foF2 is 9 MHz. The conclusions about the amount of time that skip interference would be a significant problem are unchanged.

The operational ranges shown in Figures 3 through 11 were computed assuming that 20 percent of all CB's are base stations and 80 percent are mobile. Calculations in Appendix C show that operational range is only about 10 percent different for 10 percent bases or 30 percent bases, so this assumption is not critical.

I assumed that CB radios are distributed randomly within metropolitan areas and that users transmit at random times (without waiting for someone else who might be transmitting).

The effect of nonrandom locations on operational range against local interference is not known, but it is almost certain that skip interference would decrease the operational range about the same amount as is shown in this report. On the other hand, courteous operation (waiting to transmit) was examined in a previous report (Berry, 1977) and found to slightly increase the operational range in the presence of local interference. Skip interference would not change however, because people in remote cities would still transmit at random. Courteous local operation would make the decrease in operational range shown in Figures 3 through 11 even greater.

The assumption that the same fraction of the population is transmitting on the channel all over the country is questionable. Citizen band use probably peaks at certain local times (for example, the morning and evening rush hours), and California is three time zones removed from New York. Examination of detailed results convinced me that it would take a drastic difference in the fraction of people transmitting to change the results significantly because of the "saturation effect." It takes only 20 or 30 skip interferers to cause most of the decrease in operational range in small cities and rural areas; 200 or 300 will do it in cities with local co-channel interference. Yet there are several thousand skip signals contributing interference when mean foF2 is 10 MHz or more in Figure 3. So even if the fraction of people transmitting in other time zones were five times smaller, operational range in cities of 100,000 or less would still be sharply cut by skywave interference. This makes the conclusions relatively insensitive to the assumption of equal use over the whole country.

Figures 3 through 7 are based on calculations made for only two locations--New York and eastern Missouri, and Figures 8 through 11 are based on calculations made for southern California. Naturally, the results would be somewhat different in locations like Florida or North Dakota. However, I looked at the most critical inputs--the probability of skywave propagation times the population density as a function of distance--for many other locations. The operational range for these locations at the peak of a normal solar cycle would not differ from those shown in the report by more than 15 percent--partly because of the similarities of these inputs and partly because of the saturation effect mentioned above.

By far the most important assumption made is that the reflectivity of the ionosphere will be "normal" during the next solar cycle. There is convincing evidence now that there have been periods as long as 70 years when there were very few sunspots (Eddy, 1977). Such periods may occur again, although available evidence suggests that we are not in such a period. Recent predictions for the next solar cycle range from a peak like the one in 1968 (Solar Geophysical Data Bulletin, 1977) to a higher peak like the one in 1948 (Sargent, 1978).

There are two other possibilities: that ionospheric reflectivity will be significantly greater than before, or that it will be significantly less. If it is greater, the effect of skip interference on CB operational range will be about the same as that shown near the right side of Figures 3 through 11, because operational range tends to stabilize as the reflectivity increases--another manifestation of the saturation effect. If the reflectivity is significantly less than normal, Figures 3 through 11 can still be used to estimate the change in operational range because they are shown as a function of reflectivity. However, skip interference would be troublesome for shorter periods than estimated in Section 3.3.

In summary, many of the factors that were input to the computer model are well known and dependable. The conclusions reached are relatively insensitive to others that are uncertain (such as the average level of radiated power from CB radios) or are disregarded (such as the different fraction of the population transmitting in different time zones). The only event likely to invalidate the conclusions that follow is ionospheric reflectivity considerably lower than normal.

5. CONCLUSIONS: AT THE PEAK OF THE SOLAR CYCLE, SKIP INTERFERENCE WILL DISTRIBUTE BIG CITY CB CONGESTION TO EVERYONE

If the ionosphere's reflective power during the next solar cycle is near or above normal, and if Class D Citizens Band radio use does not decrease, then for about 8 hours per day for 8 months of each of the 3 years near the peak of the solar cycle, the operational range of CB'ers in cities with less than 100,000 population will be reduced by more than half by skip interference, and the operational range of rural users will be decreased even more. Operational range in these areas will be reduced by the same amount for 4 hours per day of 6 months of the year immediately before and the year immediately after this 3-year period. About one-third of the population of the United States live in areas with population under 100,000 or in rural areas.

In cities with more than one million population, local interference already limits the operational range of CB so much that increased skywave interference probably will not be troublesome. About half the population of the United States live in such cities.

6. ACKNOWLEDGMENTS

During the study reported here, I had useful discussions with Don Lucas, George Haydon, and Margo PoKempner of the National Telecommunications and Information Administration; and with Carlos Roberts and Ron Stone of the Federal Communications Commission.

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APPENDIX A: MATHEMATICAL FORMULATION

The model used to calculate the results in this report is basically the one described by Berry (1977). The only difference is that the program section used to compute local noncochannel interference (Block III of Figures 2 and 5) in that report is used to compute skywave co-channel interference in this report. However, to make this report independent, the entire model will be explained again; to make the repetition worthwhile, the model is developed in a different way. The description by Berry (1977) was built around logical flow diagrams; a random variable approach is used here.

A.1 The Signal-to-Interference Ratio

The operational range depends on the probability distribution of the random variable,

$$\underline{S/I} = \underline{S} - \underline{I}^{1} \quad , \quad \text{dB}, \tag{A-1}$$

where $\underline{S}$, the wanted signal power, and $\underline{I}$, the interfering signal power, are independent random variables with units dB above a watt (dBW). The probability density function (pdf) of $\underline{S/I}$ is found by convolution (Davenport, 1970):

$$f_{S/I}(x) = \int f_S(y)\ f_I(y - x)\ dy \quad .^{2} \tag{A-2}$$

A.1.1 The Wanted Signal Strength

The wanted signal strength

$$\underline{S} = \underline{P_W} - \underline{L_W} \quad , \text{dBW}, \tag{A-3}$$

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[1] Random variables are underlined in this appendix.

[2] The pdf of random variable Z is denoted $f_Z(x)$.

where $\underline{P_W}$ is the sum of the effective radiated power of the wanted transmitter in dBW and the antenna height gain, and $\underline{L_W}$ is the basic transmission loss (CCIR, 1975).

Propagation studies usually give conditional transmission loss, that is, the distribution of loss at a given distance, $L(x|d)$. To compute the unconditional transmission loss, we need the wanted path length, $\underline{D_W}$ (also a random variable). Then, assuming that $\underline{D}$ and $\underline{L}$ are independent (Davenport, 1970),

$$f_L(x) = \int f_{L_{X|D}}(x|y) \, . \, f_{D_W}(y) \; dy \quad , \qquad \text{(A-4)}$$

where $f_{D_W}(y)$ is the pdf of wanted path lengths. The definition of operational range given later in section A.3 requires the signal strength for a given distance, so the calculation in (A-4) can be skipped, or an impulse-like function can be used for $f_{D_W}(y)$. This latter approach was used to avoid changing the program described by Berry (1977). Then $\underline{S}$ is the signal strength at the desired distance.

A.1.2 The Interference

The total interference, $\underline{I}$, is the sum of the local interference, $\underline{I_u}$, and the skywave (or skip) interference, $\underline{I_s}$. $\underline{I_u}$ and $\underline{I_s}$ are in dBW and cannot be added directly; they must be converted to watts. So let

$$\underline{W_t} = 10^{\underline{I_t}/10} \text{, watts } (t = u \text{ or } s) \quad . \qquad \text{(A-5)}$$

The pdf of $\underline{W_t}$ is found using (Davenport, 1970)

$$f_W(x) = \frac{10 \log_{10} e}{x} \, f_I(10 \log_{10} x) \quad . \qquad \text{(A-6)}$$

Then the pdf of the total interference, $\underline{W}$, is found with a convolution integral for adding random variables assuming $\underline{I_u}$ is independent of $\underline{I_w}$ (Davenport, 1970):

$$f_W(x) = \int f_{W_u}(y) \; f_{W_s}(x - y) \; dy \quad . \qquad \text{(A-7)}$$

Then $\underline{I} = 10 \log_{10} \underline{W}$, and the pdf of $\underline{I}$ is

$$f_I(x) = \frac{\ln 10}{10} \, 10^{\frac{x}{10}} \, f_W\left(10^{\frac{x}{10}}\right) \ . \tag{A-8}$$

A.1.2.1 Local Interference

The interference due to one local interferer is found just like the wanted signal:

$$\underline{I_o} = \underline{P_u} - \underline{L_u}, \quad \text{dBW} \quad , \tag{A-9}$$

where $\underline{P_u}$ is the sum of the effective radiated power and the height gain of interfering stations, and $\underline{L_u}$ is the unconditional transmission loss for local interferers.

The distribution of interfering path lengths, $\underline{D_u}$, is needed to compute the pdf of $\underline{L_u}$, using equation (A-4).

On congested CB channels, there are more than one interferer. If there are N interferers, we must take N samples from the distribution of $\underline{I_o}$ and add them (after converting from dBW to watts).

Convert $\underline{I_o}$ to watts using the transformation shown in (A-5) and (A-6). Denote the power from N interferers as $\underline{\Sigma N}$. Then

$$f_{\Sigma 2}(x) = \int f_{I_o}(y) \ f_{I_o}(x - y) \ dy \quad , \tag{A-10}$$

and for N > 2,

$$f_{\Sigma N}(x) = \int f_{I_o}(y) \ f_{\Sigma (N-1)}(x - y) \ dy. \tag{A-11}$$

The pdf of $\underline{I_u}$ can be found from $f_{\Sigma N}$ using a transformation like (A-8).

A.1.2.2 Skywave Interference

The interference from one skywave interferer is a random variable,

$$\underline{I_s} = \underline{P_s} - \underline{L_s} \quad , \tag{A-12}$$

where $\underline{P_s}$ is the sum of the effective radiated power and height gain of interfering transmitters, and L_s is the skywave basic transmission loss.

The distribution of $\underline{L_s}$ is quite different from that of $\underline{L_u}$, of course. And the number of skywave interferers is usually different from the number of local interferers. When the ionosphere is not reflecting 27 MHz signals, there will be no skywave interference. When the ionosphere is highly reflective, there will be hundreds or thousands of potential skywave interferers. In this case the recursive process given by equations (A-10) and (A-11) is too slow and expensive. So an approximate procedure for adding a large number of samples from a distribution like (A-6) is needed.

First convert $\underline{I_s}$ to watts ($\underline{W_s}$) using (A-6) to get the pdf $f_{W_s}(x)$. Let $\underline{\Sigma N}$ be the sum of N samples from f_{W_s}. The mean, μ_N, of ΣN is (Davenport, 1970)

$$\mu_N = N\mu \quad , \tag{A-13}$$

where μ is the mean of $\underline{W_s}$. The variance of $\underline{\Sigma N}$ is

$$V_N = N\,V \quad , \tag{A-14}$$

where V is the variance of $\underline{W_s}$.

But what is the functional form of $f_{\Sigma N}(x)$? An obvious first approximation is to assume that $f_{\Sigma N}$ is normal because the Central Limit Theorem says that the sum of N independent random variables tends to be normal as N gets large (Davenport, 1970). For many simple distributions, N need not be very large--perhaps no more than 10. But $f_{W_s}(x)$ is an unusual distribution. (Try computing and plotting it for $\underline{I_s}$ normal with mean of 0 dBW and standard deviation of 10 dB.) Calculations with (A-10) and (A-11) showed that the distribution of $\underline{\Sigma N}$ was not at all normal even for large N. However, the dB equivalent of $\underline{\Sigma N}$,

$$\underline{I_N} = 10 \log_{10} \underline{\Sigma N} \quad , \tag{A-15}$$

looks "normal" even for large N.

So I assume $\underline{I}_N$ is normal; that is, that $\underline{\Sigma N}$ is log normal. Then using formulas given by Zehna (1970, p. 106), the variance of $\underline{I}_N$ can be computed:

$$V_{I_N} = \left(\frac{10}{\ln 10}\right)^2 \log_e \left(1 + \frac{V_N}{N\ \mu_N^2}\right) \quad , \tag{A-16}$$

and the mean of $\underline{I}_N$ is

$$\mu_{I_N} = \left(\frac{10}{\ln 10}\right) \left(\log_e (N\mu_N) - \frac{1}{2}\, V_{I_N}\right) \quad . \tag{A-17}$$

The assumption that $\underline{\Sigma N}$ is log normal has not been proven. On the contrary, the Central Limit Theorem proves that $\underline{\Sigma N}$ is normal if N is sufficiently large. However, numerical results for typical interference pdf's show the assumption is a better approximation for moderate N. Furthermore, the mean and variance of $\underline{\Sigma N}$ are correct whatever the shape of the distribution. So (A-16) and (A-17) were used to calculate the sum of large numbers of skywave interferers.

A.2 THE OPERATIONAL RANGE

Because the signal $\underline{S}$ is the value for a wanted communication distance $\underline{D}_w$ (see sect. A.1.1), the signal-to-interference ratio defined by (A-1) is a conditional random variable--the signal-to-interference ratio, given the desired path length D_w. The probability of successful communications is defined to be the probability that $\underline{S/I}$ exceeds a required value R; that is

$$P(\underline{S/I} \geq R | D_w) = \int_R^\infty f_{S/I}(x)\ dx \quad . \tag{A-18}$$

Then the 100q percent operational range, described in section 2.2 of the body of this report, is denoted by OR_q and is defined implicitly by

$$P(\underline{S/I} \geq R | OR_q) = q \quad . \tag{A-19}$$

Notice that OR_q depends on the value of R. Throughout this report, R = 17 dB (CCIR, 1974).

Figure A-1 illustrates a graphical solution of (A-19). The curve shown is $P(S/I \geq R)$ as a function of D_w. For q = 0.75, find the point where the curve crosses 75 percent and read the distance $OR_{0.75}$ from the horizontal scale.

A.3 REFERENCES

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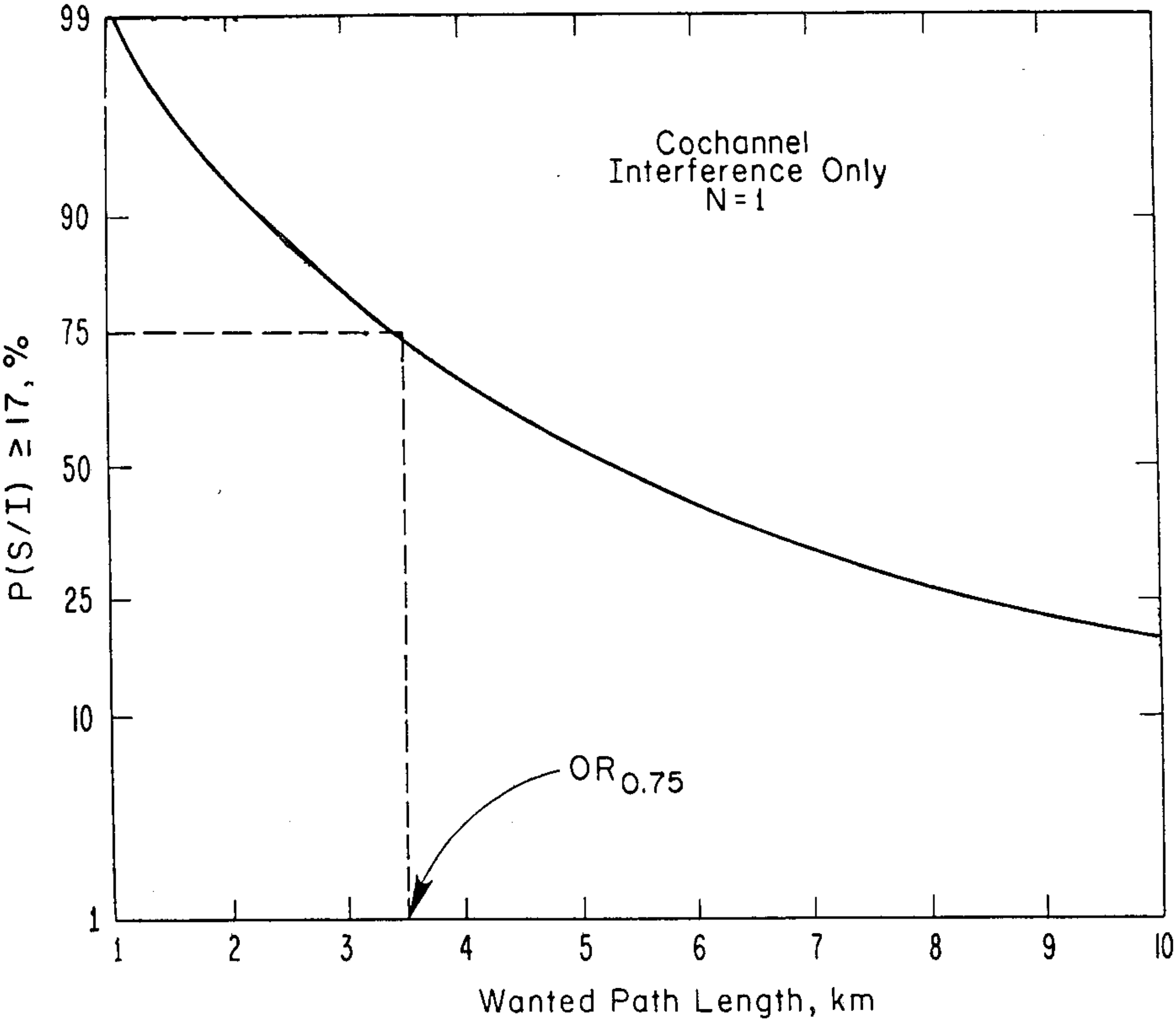

Figure A-1. Determination of the 75 percent operational range using a plot of the probability of achieving a 17 dB signal-to-interference ratio. This is a graphical solution of equation (A-19).

APPENDIX B: MODELING ASSUMPTIONS AND INPUT DATA

The operational range calculation detailed in Appendix A requires as input the statistical distributions of interfering path lengths, transmission loss, effective radiated power of the transmitting stations, and number of stations transmitting on the same channel. The sources of these input data and, where necessary, the assumptions about their distributions are given in this appendix.

One general assumption is that each user transmits randomly in time--whenever he wants to, without waiting for a clear channel.

B.1 INPUT TO COMPUTE WANTED SIGNAL

B.1.1 Wanted Path Length

The wanted path length is a controlled variable. It is varied over the range of interesting path lengths. The easiest way to do this using the general program described by Berry (1977) is to use an impulse-like probability density function (pdf). For the calculations in this report, the pdf of wanted path lengths was assumed to be normal with a mean equal to the desired value and with a very small variation--a standard deviation of 0.1 km.

B.1.2 Effective Radiated Power of Transmitters

There are two classes of CB stations with quite different radiated powers. Most CB radios are installed in vehicles, with short whip antennas mounted fairly close to the ground. Such antennas are not efficient radiators. Assuming that the average antenna is a 40 in (1 m) whip mounted in the center of a car roof 1.5 m above the ground results in an average radiated power of 1 dB above a watt (dBW) for 4 W output from the transmitter. The distribution of radiated power was assumed to be log normal, so that the effective radiated power (ERP) is normally distributed in decibels with a standard deviation of 1.6 dB.

Base stations usually have more efficient antennas mounted higher above the ground. Both these factors increase the radiated power, and their effects can be lumped together. Assuming a 5/8 wavelength antenna mounted 30 ft (9 m) above ground, the average ERP of a base station is 15 dBW, and the assumed standard deviation is 3 dB.

The operational ranges of these two types of stations were calculated separately, and the results are displayed separately in Appendix C and in Table 1.

B.1.3 Transmission Loss

Short-distance groundwave propagation at 27 MHz is fairly simple. The mean value of transmission loss at distance d, computed using standard methods for average ground constants, is

$$M_L = 83 + 40 \log d, \qquad \text{dB} , \qquad \text{(B-1)}$$

where d is in kilometers. Irregular terrain, large buildings with steel girders, or different ground constants cause variations in transmission loss. The transmission loss is assumed to be log normal with a standard deviation of 5 dB (Longley, 1976).

B.2 INPUT TO COMPUTE LOCAL INTERFERENCE

B.2.1 Interfering Path Lengths

The probability distribution of distances that interfering signals have traveled is necessary to evaluate equation (A-4). This distribution depends on the locations of interfering transmitters and of the receiver. It is assumed that CB sets are randomly but uniformly distributed within a metropolitan area which is bounded by a circle with radius 20 km. (This means that the probability that there is a transmitter in a given small area is proportional to the size of the area.) Figure B-1 shows an example of 5000 points distributed randomly but uniformly in a circle. These points were generated with a random number generator.

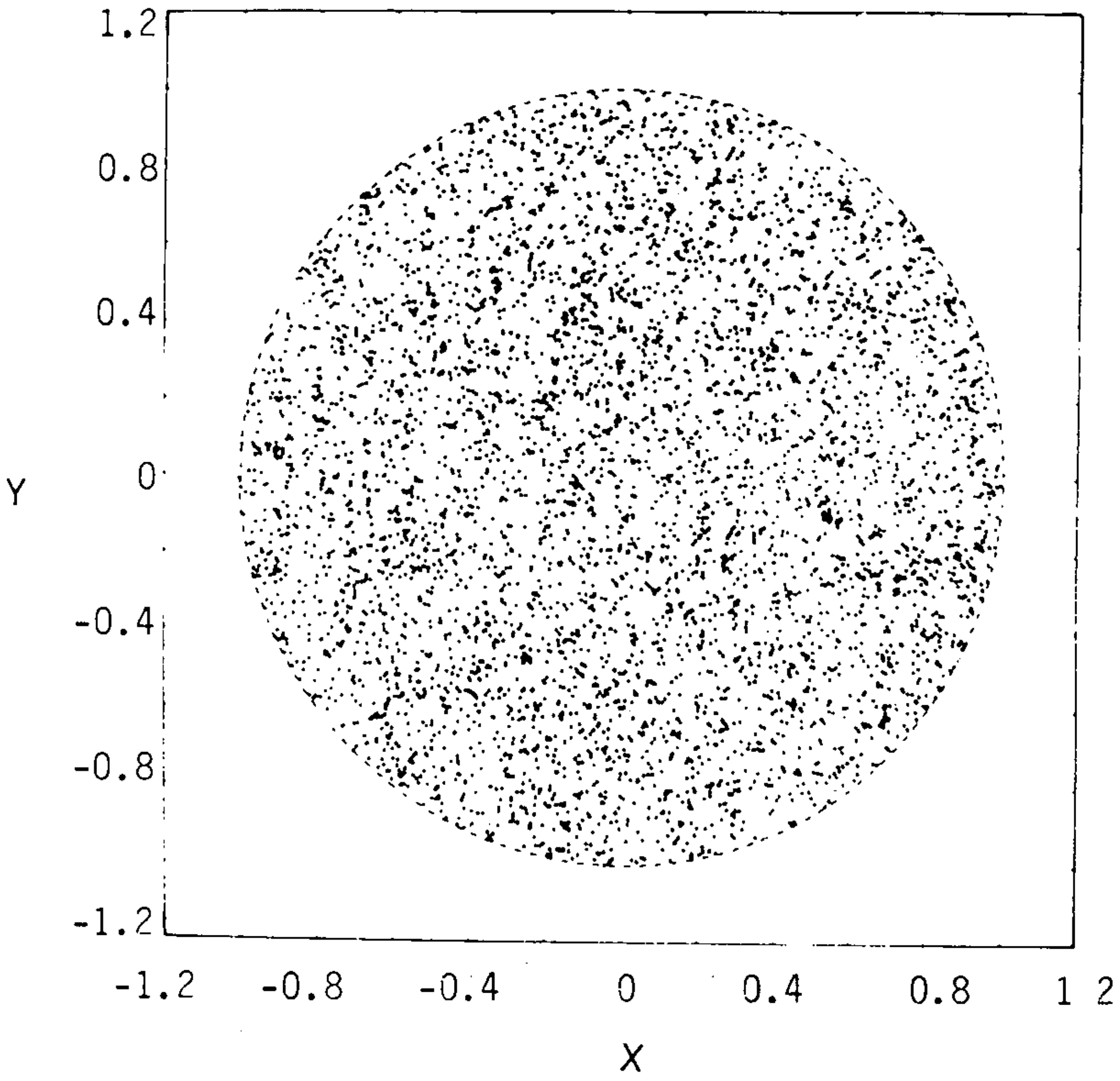

Figure B-1. Illustration of random points in a circle, distributed uniformly with respect to area. The probability that a given sub-area contains n points is proportional to the size of the area and to n. There are 5000 points in this circle.

Figure B-2 shows the geometry necessary to compute the path lengths pdf. The transmitter at T is trying to communicate with a receiver at R. Interference is coming from a transmitter at T_i, so the interfering path length is T_iR. To generate the pdf of path lengths like T_iR, random points were located in the circle with radius R_a with a random number generator. The distance T_iR was computed and tabulated. The process was repeated 10,000 times, and the resulting table of relative fre-frequency of path lengths was input to the computer program as the pdf of interfering path lengths. Figure B-3 shows plots of these pdf's for three different wanted path lengths. Notice that the pdf of interfering path lengths does not depend on the wanted path lengths for interfering path lengths less than about 10 km. The differences beyond 10 km are caused by the bounding of the metropolitan area with a circle, as shown in Figure B-2. This bounding does not affect the final results much because the path lengths of interest in cities are mostly less than 10 km.

B.2.2 Effective Radiated Power of Interfering Transmitters

Interfering transmitters are, of course, from the same set as the wanted transmitter. A difference is that interfering transmitters come from the set of all CB stations, while separate calculations were made for the wanted transmitter being a base station or a mobile station. Combining bases and mobiles into a single set of interfering stations yields the pdf of effective power shown in Figure B-4. The peak on the left is the ERP of the mobiles. The area under the peak is the fraction of stations that are mobile. The peak on the right is average ERP of the base stations.

Operational ranges were computed assuming that 70, 80, or 90 percent of the CB sets are mobile, and the rest are base stations. The different percentages made only a small difference in the operational range, as shown later in Table C-2. Survey

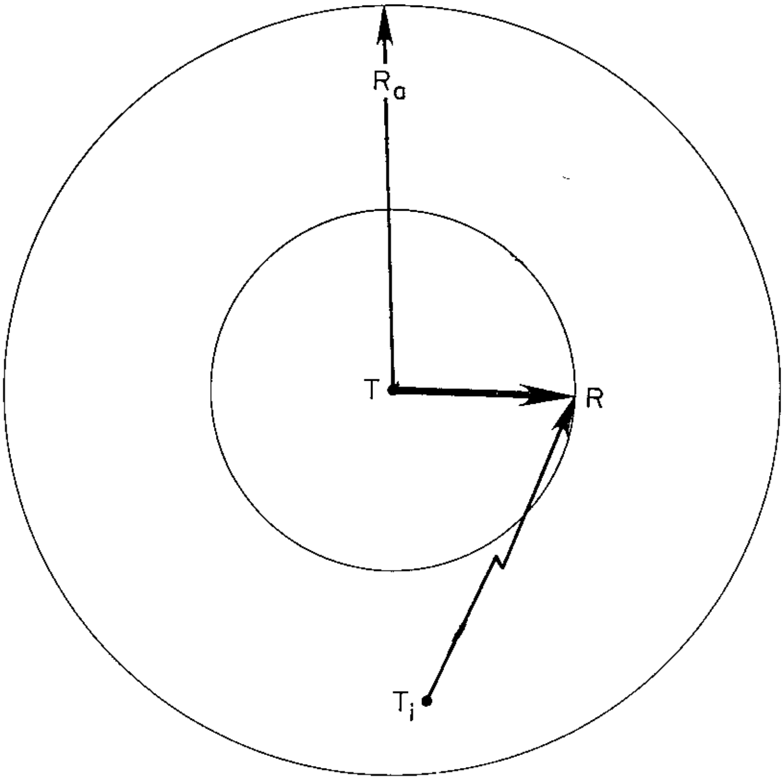

Figure B-2. Geometry for computing pdf of interfering path lengths. Receiver is located at random position on circle with radius TR, and interfering transmitter is located anywhere within the circle with radius R_a.

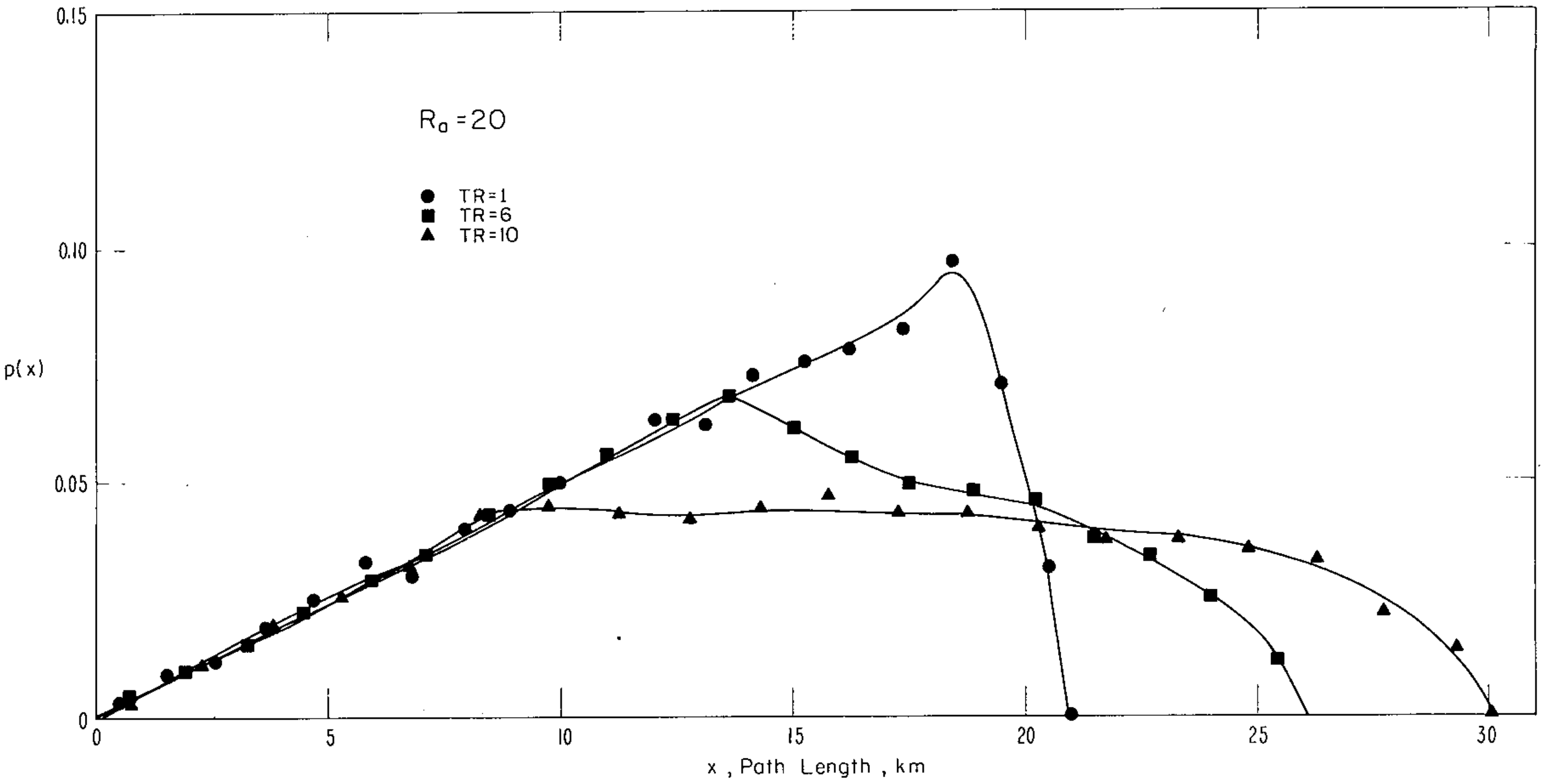

Figure B-3. Probability density functions for interfering path lengths, for three different wanted path lengths. The geometry is shown in Figure B-2.

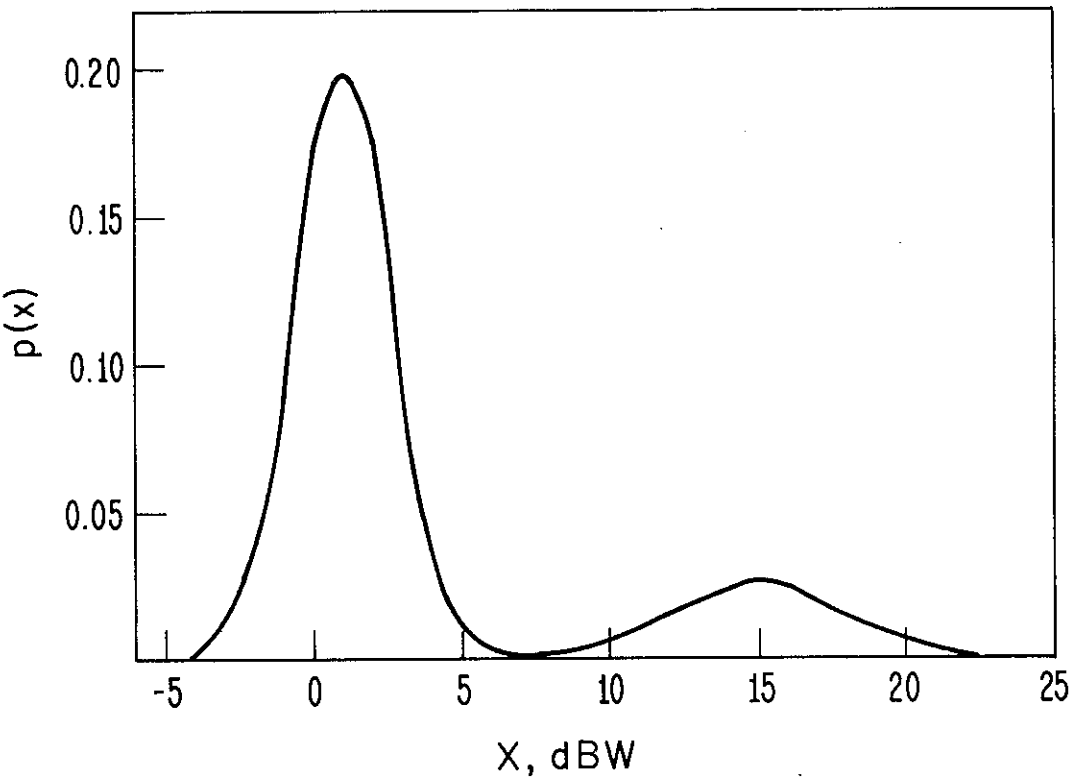

Figure B-4. Probability density function assumed for effective radiated power of all CB transmitters in an area. The bump on the left is the distribution for mobile transmitters, and the bump on the right is the distribution for base stations. The area under a bump is the percentage of stations of that type. In this case, 80 percent of the stations are mobile.

data indicate that about 82 percent of CB's are mobile (Private Communication, Ronald N. Stone), so the results shown in this report are for 80 percent mobiles.

B.2.3 Transmission Loss for Interference

Transmission loss for local interference is identical to transmission loss for local wanted signals and is given in B.1.3.

B.2.4 Number of Interfering Transmitters

Effects of various levels of CB congestion were studied by varying the number of simultaneous interferers. Operational range was calculated for 0, 1, 3, 6, and 10 local interferers.

B.3 MODELING OF SKYWAVE INTERFERENCE

B.3.1 Interfering Path Lengths

Modeling of the skywave interference is complicated by the fact that not all transmitted signals will propagate to the receiver. When solar activity is low, 27 MHz waves usually penetrate the ionosphere, and there is no skywave transmission of CB signals. At the peak of solar activity, the probability that the ionosphere will reflect 27 MHz signals back to earth is greater. The probability of reflection is greatest at noon on winter days at the maximum of the sunspot cycle.

More important to determining the pdf of interfering path lengths, the probability of transmission depends on the path length itself. To a first approximation, the ionosphere will reflect waves of frequency (Davies, 1965)

$$f \leq fo \sec \phi \quad , \tag{B-2}$$

where ϕ is the angle of incidence of the radio ray on the ionosphere, as shown in Figure B-5, and fo is the highest frequency wave that the ionosphere will reflect when $\phi = 0$. For CB radio, f = 27 MHz, so CB waves reflect only when

$$\sec \phi \geq 27/fo \quad . \tag{B-3}$$

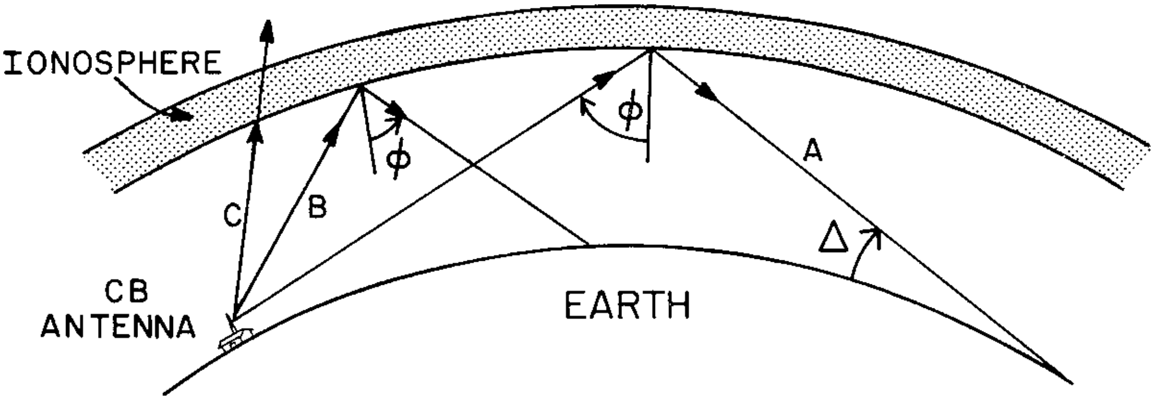

Figure B-5. Geometry of skywave transmission ray paths, showing the angle of incidence on the ionosphere, ϕ, and the elevation angle, Δ.

Figure B-5 shows that ϕ (and hence, sec ϕ) increases as the distance between transmitter and receiver increases. The distance for which sec ϕ = 27/fo is called the skip distance--skywaves will not arrive from shorter distances. As the distance increases, the probability that skywaves will arrive from that distance increases, as the inequality (B-3) becomes stronger and stronger.

The probability that a signal arrives from a given distance also depends on the number of transmitters operating at that distance. It is assumed that the number of transmitters is proportional to the population at that distance. Making the plausible assumption that the probability of ionospheric propagation is independent of the population results in

$$f_d(d) = B\ t(d)\ N^*(d) \quad , \qquad \text{(B-4)}$$

where $f_d(d)$ is the pdf of skywave interference path lengths, t(d) is the probability that CB signals will propagate from distance d, and N*(d) is the population at distance d.

The constant B is determined by the requirement that the integral of $f_d(d)$ over all possible d must be unity. The minimum distance, d_{min}, is the skip distance where $t(d) = 0$. The maximun distance, d_{max}, is either the maximum one-hop range (where the arriving ray is tangent to the earth) or the distance beyond which $N^*(d) = 0$. For the assumptions made in the next section, the maximum one-hop range is about 3800 km.

The final result is

$$f_d(d) = \frac{t(d)\ N^*(d)}{\int_{d_{min}}^{d_{max}} t(d)\ N^*(d)\ dd} \quad . \qquad \text{(B-5)}$$

The probability of skywave transmission from distance d, t(d) was computed with the computer program HFMUFES 4 (Haydon, et al., 1976).

To determine $N^*(d)$, the 1970 census population of each state was entered on a map. The population of CB users was assumed to be zero on the oceans and in Canada and Mexico. Then for each receiving location analyzed, the population within 500 km was counted, the population between 500 and 1000 km was counted, the population between 1000 and 1500 km was counted, and so forth. When the radius of a ring divided a state, the population of major metropolitan centers and the relative areas in the two rings were used to approximately divide the state's population. These tabular values for population were plotted and a smooth curve drawn through them. The smooth curve is $N^*(d)$.

Figure B-6 shows $N^*(d)$ for New York City. Also shown is t(d), the probability that 27 MHz waves will propagate from distance d at winter noon at the peak of an average sunspot cycle. The product, $t(d)\ N^*(d)$, appears in equations (B-5) and (B-14), so it is also shown in Figure B-6.

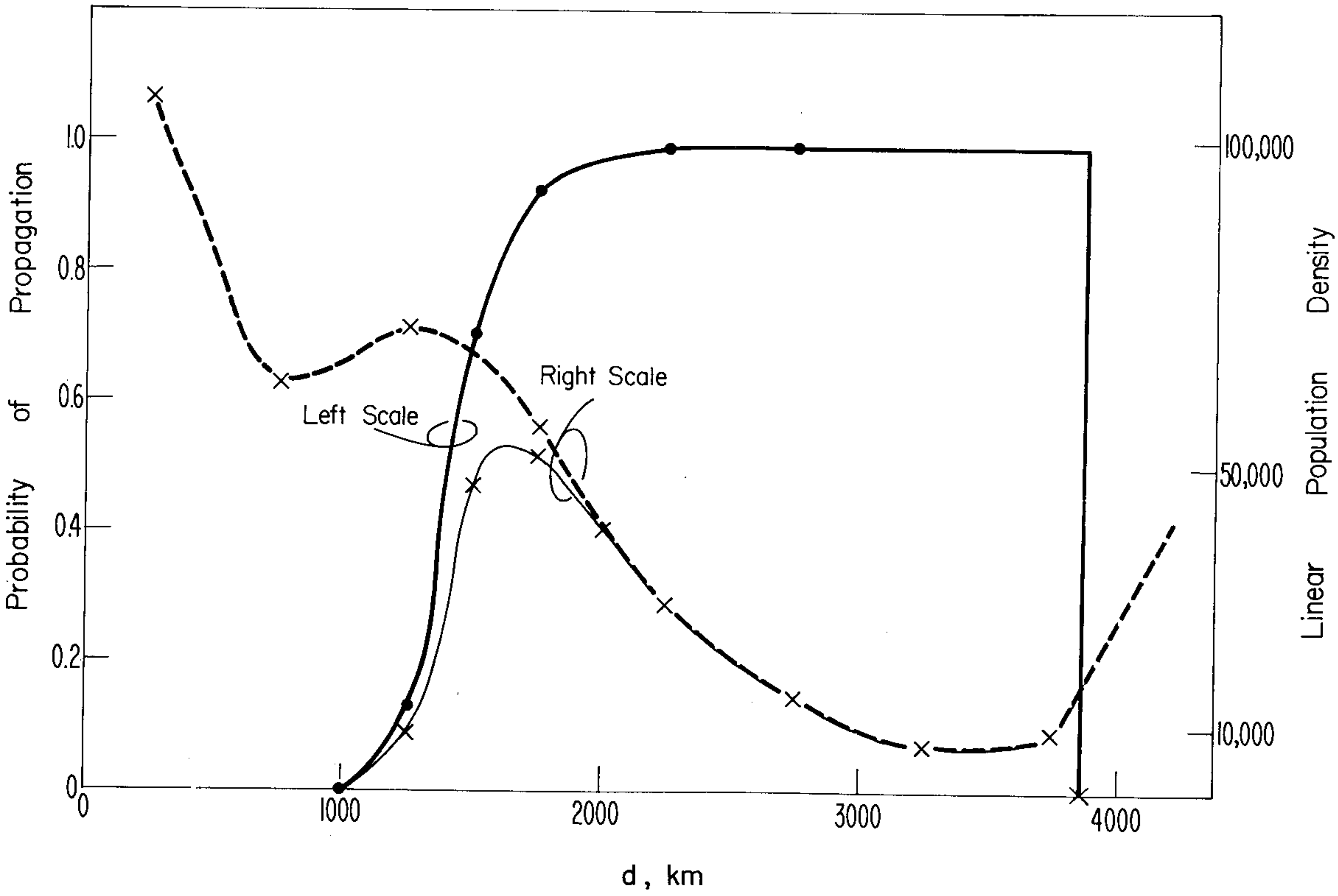

Figure B-6. Skywave propagation probability (heavy solid line) and population density (dashed line) as a function of distance from New York City. Propagation is for winter noon for sunspot number of 110. The lighter solid line is the product of the other two functions.

B.3.2 Effective Radiated Power of Skywave Interference Transmitters

It was assumed that transmitter characteristics were the same all over the U.S. So the pdf of ERP for transmitters of skywave interference is that shown in Figure B-4.

B.3.3 Skywave Transmission Loss Model

The mean skywave transmission loss for transmission over great circle distance d is

$$L_b = 139.4 + 20 \log_{10} f - 20 \log_{10}|E| + L_{es} \quad , \quad \text{dB} \qquad \text{(B-6)}$$

where f is the radio frequency, 27 MHz; E is the quasi-maximum one-hop skywave field strength in µV/m for 1 kW ERP; and L_{es} is the average "excess system loss" (Barghausen, et al., 1969), assumed to be 9.5 dB.

The first three terms on the left are Norton's (1959) relation between transmission loss and field strength; L_{es} is an empirical correction for skywave transmission added by Lucas and Haydon (1966).

$$|E| = \frac{3(10^5)}{D} \sqrt{\frac{\pi}{12}} \cos^2\Delta \left| (1 + e^{-i\phi_R})^2 \right| |T| \quad . \qquad \text{(B-7)}$$

In (B-7),

$$D = 2\sqrt{2a^2\left(1 - \cos \frac{d}{2a}\right) + h^2} \qquad \text{(B-8)}$$

is the skywave path length in kilometers where a is the earth's radius (in kilometers), and h is the virtual height of reflection, assumed to be 320 km.

$$\cos \Delta = \frac{2a}{D} \sin \frac{d}{2a} \quad , \qquad \text{(B-9)}$$

where Δ is the elevation angle and cos Δ is the vertical radiation pattern of a short vertical antenna (see Figure B-6).

$$(1 + e^{-i\phi_R})$$

is the foreground reflection factor for an antenna over imperfectly conducting ground.

$$\phi = 4\pi \frac{f}{300} h_1 \sin \Delta \tag{B-10}$$

is the difference in phase between the direct and ground-reflected wave (Jordan, 1950), where f is in megahertz and h_1 is the antenna height in meters.

$$R = \frac{\eta \sin \Delta - \sqrt{\eta - \cos^2 \Delta}}{\eta \sin \Delta + \sqrt{\eta - \cos^2 \Delta}} \tag{B-11}$$

is the ground reflection coefficient for vertically polarized waves. In (B-11),

$$\eta = \varepsilon - i \frac{18.10^3 \sigma}{f} , \tag{B-12}$$

where $\varepsilon = 10$ is the relative dielectric constant and $\sigma = 0.003$ S/m is the conductivity of average soil (Jordan, 1950). T is the ionospheric reflection coefficient. It is approximated by (Lucas and Haydon, 1966)

$$20 \log_{10} |T| = - \frac{615(1 + 0.0037.SSN)(\cos 0.881\chi)^{1.3}}{(f_{MHz} + f_H)^{1.98}} \sec \alpha, \text{ db} \tag{B-13}$$

where SSN is the 12-month average sunspot number, χ is the sun's zenith angle, α is the angle of incidence on the E-region at a height of 100 km, and $f_H = 1.4$ MHz is the gyro-frequency.

The probability distribution of signal strength from a single transmitter is assumed to be log normal with a standard deviation of 5 dB. This accounts for variations in ionospheric absorption, ground conductivity, virtual reflection height, etc.

B.3.4 Number of Interfering Skywave Signals

The basic assumption here is that the same fraction of the population is transmitting on each channel nationwide. This makes the number of interfering skywave signals proportional to the number of local interferers. Although this assumption is not strictly true (because of the 3 hours difference in time between the east and west coasts), the percentage difference is probably not too great during the middle of the day when skywave interference is most important. The results in Appendix C will show that relatively small fractional changes in the number of interfering skywave signals do not affect the major conclusions of this study.

With this assumption, the number of interfering skywave signals, N2, is

$$N2 = \int_{d_{min}}^{d_{max}} N^*(d)\ F\ t(d)\ dd \quad , \qquad \text{(B-14)}$$

where, as before, N*(d) is the population at d and t(d) is the probability of skywave transmission from d. The factor F is the fraction of the population transmitting on the channel under investigation.

B.4 RADIO NOISE

Even in the absence of interference from other CB transmitters, operational range is limited by radio noise. In quiet rural areas the predominant radio noise is galactic noise. The median galactic noise at 27 MHz is -148 dBW in a 6 kHz bandwidth, with a standard deviation of 2 dB (CCIR, 1964).

In populated areas, electrical noise from automobile ignitions and other electrical equipment is the main competition to CB signals in the absence of interference. For a 6 kHz receiver bandwidth, measured values range from -100 dBW to -140 dBW (Skomal, 1973). A plausible median is -132 dBW, with a standard deviation of 8 dB (Spaulding, et al., 1971).

B.5 REFERENCES

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APPENDIX C: DETAILED OUTPUT AND GENERALIZATION

This appendix contains tables of the operational range computed for specific cases using the input described in Appendix B. Figures showing how these specific results scale as functions of area population for fixed mean foF2 allow the generalizations shown in the body of the report.

C.1 EFFECTS OF LOCAL CONGESTION ON CB OPERATIONAL RANGE

Table C-1 contains the operational range of CB radios when there is no skywave interference. Table 1 in the main body of the report was derived from Table C-1 by changing the units from kilometers to miles. For any particular circumstance, the mean operational range ($OR_{.5}$) for a base station is about 2 1/4 times the mean operational range for a mobile station. The ratio of the two is also roughly a factor of two for $OR_{.25}$ and $OR_{.75}$.

Operational range in typical urban noise is less than half the range in quiet rural areas. Adding just one simultaneous local interferer lowers the mean operational range by one-third. The operational range decreases as the number of interferers increases, but OR is not inversely proportional to N. In fact, Berry (1977) shows that $OR_{.5}$ is approximately inversely proportional to the square root of N. This relationship, which is true for local interference, is primarily a function of the distance to the nearest interferer, rather than the result of adding the power of all interferers.

The calculations which led to Table C-1 were made assuming that 80 percent of the CB transmitters were mobile and 20 percent were base stations. To test the sensitivity of the computed operational range to this assumption, operational range was computed assuming that 10 percent and 30 percent of the transmitters were base stations. The results are shown in Table C-2 for 1 and 3 interferers. When 30 percent of the transmitters are base stations, the operational range is about

Table C-1. Operational Range in Kilometers of CB Radios in Different Radio Environments

(Eighty percent of the radios are mobile units. ERP of mobiles and bases is given by Figure B-4.)

	Base OR, km			Mobile OR, km		
	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
Natural Noise	29.5	37.5	48.0	13.6	17.0	21.0
Urban Noise	10.2	15.0	22.0	4.6	6.6	9.7
1 Local Interferer	5.7	10.6	16.4	2.6	4.3	7.2
3 Local Interferers	3.2	5.0	7.9	1.3	2.3	3.4
6 Local Interferers	2.1	3.4	5.1	1.0	1.5	2.3
10 Local Interferers	1.6	2.6	3.8	*	1.1	1.7

*Operational ranges less than 1 km were not calculated accurately.

Table C-2. Operational Range in Kilometers for Different Relative Numbers of Base Stations and Mobile Stations

	Percent Base Stations	Base OR, km			Mobile OR, km		
		$OR_{.75}$	$OR_{.5}$	$OR_{.25}$	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
1 Interferer	10	6.4	11.2	18.2	2.9	4.7	7.6
	20	5.7	10.6	16.4	2.6	4.3	7.2
	30	5.2	9.7	14.7	2.4	4.0	6.6
3 Interferers	10	3.5	5.6	8.7	1.6	2.5	3.7
	20	3.2	5.0	7.9	1.3	2.3	3.4
	30	2.8	4.5	7.1	1.2	2.0	3.1

20 percent smaller than when 10 percent of the interferers are base stations. This change is small compared to the changes caused by more interferers, or the addition of skywave interference, so it can be ignored in what follows. In addition, a survey showed that about 20 percent of the stations are base stations (R. N. Stone, private communication). All other calculations in this report assume that 20 percent of the transmitters are base stations.

C.2 EFFECTS OF SKYWAVE INTERFERENCE ON OPERATIONAL RANGE

The first calculations which included skywave interference were made for specific cities (New York, St. Louis, and Los Angeles) for the time when ionospheric reflectivity is highest (winter noon, near sunspot cycle maximum). These calculations for New York City are shown in the top four lines of Table C-3.

The New York metropolitan area has a population of about 9.9 million (U.S. Bureau of the Census, 1976). "One local interferer" implies that two persons in 10 million are transmitting on this channel (the wanted transmitter and the interfering transmitter). It is assumed that the same fraction of the population is transmitting on this channel all across the United States, so that 40 people are transmitting on this channel out of the 200 million in the U.S. They cause enough skywave interference to decrease significantly the operational range (compare Table C-3 with Table C-1).

One purpose of the study was to determine how the effects of skywave interference depend on the population in the area. So the calculations were repeated for smaller cities in the same general area as New York. Table C-3 shows calculations of operational range for cities of population 3.3 million, 1.1 million, and 220 thousand in the general vicinity of New York. The same number of local interferers results in a different number of skywave interferers for cities of different sizes. For example, one local interferer in a city of 3.3 million means that two transmitters are on for each 3.3 million people in the

Table C-3. Operational Range in Kilometers for Cities of Different Population in the Northeast U.S. (Near New York City)

(The time is winter noon for the peak year of an average sunspot cycle (sunspot number = 110). Mean fof2 is 10.8 MHz.)

Metropolitan Population	Number of Local Interferers	Bases			Mobiles		
		$OR_{.75}$	$OR_{.5}$	$OR_{.25}$	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
9.9 M	1	4.6	6.5	8.8	2.1	3.0	3.9
	3	2.9	4.2	6.0	1.3	1.9	2.6
	6	2.1	3.2	4.4	0.9	1.4	1.9
	10	1.6	2.5	3.5	*	1.1	1.5
3.3 M	1	3.8	5.1	6.7	1.7	2.3	3.1
	3	2.5	3.7	5.0	1.1	1.6	2.2
	6	2.0	2.9	3.9	0.9	1.2	1.7
	10	1.6	2.3	3.2	*	1.0	1.4
1.1 M	1	3.1	3.9	5.0	1.3	1.7	2.2
	3	2.3	3.1	4.0	1.0	1.3	1.7
	6	1.8	2.5	3.2	0.8	1.1	1.4
	10	1.5	2.1	2.8	*	0.9	1.1
0.22 M	1	2.1	2.8	3.5	*	*	*
	3	1.7	2.2	2.7	*	*	*

*Operational ranges less than 1 km were not calculated accurately.

United States--a total of about 120. So even though the local interference is the same for the first and fifth lines of Table C-3, there is more skywave interference in the second case, and the operational range is smaller.

There is even more skywave interference when there is one local interferer in a city of population 1.1 million, and the operational range is accordingly smaller. Inspection of Table C-3 shows that the decrease is not linearly related to the number of interferers. Later results will show that when the operational range is strongly affected by skywave interference, it is almost linearly related to the logarithm of the number of skywave interferers.

Table C-4 shows operational range for cities of different size near St. Louis. The top four lines represent St. Louis itself. As in the previous case, skywave interference decreases the operational range.

Unfortunately, Tables C-3 and C-4 cannot be directly compared because they have no common metropolitan area size. Our original efforts were directed at computing effects for "typical" cities. It was late in the study before we realized that the results fit a general scaling rule that allowed us to reach overall conclusions. This generalization is described in section C.3.

Table C-5 shows the operational range for various size cities near Los Angeles for winter noon near the peak of an average solar cycle. Again, skywave interference has a significant affect on operational range, as shown by comparison of Table C-5 with Table C-1.

Skywave transmission of 27 MHz signals is most probable at winter noon near the peak of the solar cycle. To explore the significance of skywave interference at other times, operational range near New York was calculated for a winter evening at the peak of the solar cycle (Table C-6), for winter morning on the west coast (Table C-7), for fall noon (Tables C-8 and C-9), and for summer noon (Table C-10). These times and locations were

Table C-4. Operational Range in Kilometers for Cities of Different Population in the Midwest U.S. (Near St. Louis)

(The time is winter noon for the peak year of an average sunspot cycle (SSN = 110). Mean foF2 is 11.7 MHz.)

Metropolitan Population	Number of Local Interferers	Bases			Mobiles		
		$OR_{.75}$	$OR_{.5}$	$OR_{.25}$	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
7.6 M	1	4.3	6.0	8.2	1.9	2.7	3.7
	3	2.8	4.1	5.7	1.2	1.8	2.6
	6	2.1	3.1	4.3	0.9	1.3	1.9
	10	1.6	2.4	3.4	*	1.1	1.5
2.4 M	1	3.5	4.6	6.0	1.5	2.1	2.7
	3	2.5	3.5	4.6	1.1	1.5	2.0
	6	1.9	2.7	3.6	0.9	1.2	1.6
	10	1.5	2.2	3.1	*	1.0	1.3
0.8 M	1	2.8	3.6	4.7	1.2	1.5	2.0
	3	2.1	2.9	3.7	1.0	1.2	1.6
	6	1.9	2.3	3.1	*	1.0	1.3
	10	1.4	2.1	2.7	*	0.8	1.1

*Operational ranges under 1 km were not computed accurately.

Table C-5. Operational Range in Kilometers for Cities of Different Population on the West Coast of the U.S. (Near Los Angeles)

(The time is winter noon for the peak year of an average sunspot cycle (SSN = 110). Mean foF2 = 11.5 MHz.

Metropolitan Population	Number of Local Interferers	Bases			Mobiles		
		$OR_{.75}$	$OR_{.5}$	$OR_{.25}$	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
7.0 M	1	4.3	6.1	8.2	2.0	2.7	3.6
	3	2.9	4.2	5.7	1.3	1.9	2.6
	6	2.1	3.1	4.3	0.9	1.4	1.9
	10	1.6	2.4	3.5	*	1.1	1.5
2.3 M	1	3.6	4.8	6.2	1.6	2.2	2.8
	3	2.6	3.6	4.7	1.1	1.5	2.0
	6	2.0	2.8	3.8	0.8	1.2	1.6
	10	1.6	2.3	3.1	*	1.0	1.3
0.8 M	1	2.9	3.8	4.7	1.2	1.6	2.1
	3	2.2	2.9	3.7	1.0	1.3	1.6
	6	1.8	2.4	3.2	*	1.0	1.4
	10	1.4	2.0	2.6	*	0.8	1.1

*Operational ranges under 1 km were not computed accurately.

Table C-6. Operational Range in Kilometers for Cities of Different Population in the Northeast U.S.

(The time is 6 p.m. EST in winter for a peak year of an average sunspot cycle (SSN = 110). Mean foF2 = 9.3 MHz.)

Metropolitan Population	Number of Local Interferers	Bases			Mobiles		
		$OR_{.75}$	$OR_{.5}$	$OR_{.25}$	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
9.9 M	1	5.4	8.6	12.7	2.4	3.8	5.4
	3	3.1	4.8	7.1	1.3	2.1	3.1
	6	2.1	3.4	4.9	0.9	1.5	2.2
	10	1.6	2.6	3.8	*	1.1	1.7
3.3 M	1	4.9	7.3	10.3	2.2	3.2	4.4
	3	3.0	4.6	6.5	1.3	2.0	2.9
	6	2.1	3.2	4.6	0.9	1.4	2.1
	10	1.6	2.6	3.7	*	1.1	1.6
1.1 M	1	4.3	5.9	7.9	2.0	2.7	3.5
	3	2.8	4.1	5.6	1.2	1.8	2.5
	6	2.1	3.1	4.3	0.9	1.4	1.9
	10	1.6	2.4	3.4	*	1.0	1.5
0.22 M	1	3.5	4.5	5.5	Not Calculated		
	3	2.6	3.5	4.6			
	6	2.0	2.8	3.7			
	10	1.6	2.3	3.1			

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* Operational ranges less than 1 km were not calculated accurately.

Table C-7. Operational Range in Kilometers for Cities of Different Population on the West Coast

(The time is 6 a.m. in winter for the peak year of an average sunspot cycle (SSN = 110). Mean foF2 is 6.8 MHz.)

Metropolitan Population	Number of Local Interferers	Bases $OR_{.75}$	Bases $OR_{.5}$	Bases $OR_{.25}$	Mobiles $OR_{.75}$	Mobiles $OR_{.5}$	Mobiles $OR_{.25}$
5 M	1	5.6	9.4	14.6	2.6	4.0	6.0
	3	3.1	4.9	7.6	1.4	2.2	3.3
	6	2.1	3.4	5.0	0.9	1.5	2.2
	10	1.6	2.6	3.8	*	1.1	1.7
1.7 M	1	5.3	8.5	12.8	2.1	3.7	5.2
	3	3.1	4.8	7.2	1.2	2.1	3.1
	6	2.1	3.3	4.9	0.8	1.5	2.2
	10	1.6	2.6	3.8	*	1.1	1.6
0.55 M	1	5.0	7.2	10.2	2.2	3.1	4.2
	3	3.0	4.5	6.4	1.3	2.1	2.8
	6	2.1	3.2	4.7	0.9	1.4	2.0
	10	1.6	2.5	3.6	*	1.1	1.6
0.2 M	1	3.6	4.7	6.0	Not Calculated		
	3	2.5	3.5	4.6			
	6	2.0	2.8	3.7			
	10	1.6	2.3	3.1			

* Operational ranges less than 1 km were not calculated accurately.

Table C-8. Base Station Operational Range in Kilometers for Cities in Indicated Regions

(The time is fall noon for the peak year of an average solar cycle (SSN = 110).)

Metropolitan Population	Number of Local Interferers	Northeast Mean fof2 = 9.0 MHz			Midwest Mean foF2 = 9.2 MHz		
		$OR_{.75}$	$OR_{.5}$	$OR_{.25}$	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
1.0 M	1	4.5	6.4	8.9	Not Calculated		
	3	2.9	4.3	6.0			
	6	2.1	3.1	4.5			
	10	1.7	2.5	3.5			
0.5 M	1	Not Calculated			4.1	5.7	7.6
	3				2.8	4.0	5.4
	6				2.1	3.0	4.2
	10				1.7	2.5	3.4
0.1 M	1	3.1	3.9	5.0	3.1	4.0	5.1
	3	2.3	3.1	3.9	2.3	3.1	4.0
	6	1.8	2.6	3.4	1.8	2.5	3.4
	10	1.4	2.0	2.6	1.4	2.0	2.5

Table C-9. Base Station Operational Range in Kilometers for Cities on the West Coast

(The time is fall noon for the peak year of an average solar cycle (SSN = 110). Mean foF2 = 9.5 MHz.)

Metropolitan Population	Number of Local Interferers	$OR_{.75}$	$OR_{.5}$	$OR_{.25}$
5.0 M	1	4.6	6.5	9.0
	3	2.9	4.4	6.1
	6	2.1	3.2	4.5
	10	1.7	2.5	3.5
1.0 M	1	3.5	4.7	6.0
	3	2.6	3.5	4.6
	6	1.9	2.8	3.7
	10	1.6	2.3	3.2
0.5 M	1	3.1	4.0	5.1
	3	2.3	3.2	4.1
	6	1.8	2.6	3.4
	10	1.4	2.0	2.7
0.2 M	1	2.5	3.0	4.1
	3	2.0	2.7	-
	6	1.6	2.1	-
	10	1.4	1.9	-

Table C-10. Operational Range in Kilometers for Cities of Different Population on the West Coast

(The time is noon PST in summer for the peak year of an average sunspot cycle (SSN = 110). Mean foF2 = 7.3 MHz.)

Metropolitan Population	Number of Local Interferers	Bases			Mobiles		
		OR$_{.75}$	OR$_{.5}$	OR$_{.25}$	OR$_{.75}$	OR$_{.5}$	OR$_{.25}$
7.0 M	1	5.5	8.9	>>10	2.5	3.8	5.5
	3	3.1	4.8	7.4	1.4	2.2	3.2
	6	2.2	3.4	5.0	1.0	1.5	2.2
	10	1.7	2.6	3.8	*	1.2	1.7
2.3 M	1	5.1	7.6	10.7	2.3	3.3	4.6
	3	3.0	4.6	6.7	1.3	2.1	3.0
	6	2.2	3.3	4.8	1.0	1.4	2.1
	10	1.7	2.6	3.7	*	1.1	1.6
0.8 M	1	4.4	6.2	8.3	2.0	2.8	3.7
	3	2.9	4.3	5.8	1.2	1.8	2.6
	6	2.1	3.1	4.4	0.9	1.3	1.9
	10	1.7	2.5	3.5	*	1.1	1.5
0.2 M	1	3.5	4.7	6.0	Not Computed		
	3	2.4	3.5	4.6			
	6	2.0	2.8	3.7			
	10	1.6	2.3	3.1			

*Operational ranges less than 1 km were not calculated accurately.

chosen to cover a range of probability of propagation. (Calculations of the probability of propagation were available for every 6 hours of the day for a year when the sunspot number is 110, which is the value for an average solar cycle maximum. The probability of ionospheric propagation of CB signals was very low for nighttime and for summer morning and evening.)

C.3 GENERALIZATION OF RESULTS

Tables C-3 through C-10 show that skywave interference decreases operational range for a considerable time during the peak year of a solar cycle. The size of the decrease depends on the population of the area being studied and the fraction of the population transmitting on a given channel. Two observations about factors significantly influencing the calculations make it possible to generalize these calculations for specific typical cases.

First, the distribution of interference from the large number of skywave interferers was computed using the approximate transformation described in section A.1.2.2. This approximation shows that the mean sky wave interference level is proportional to the logarithm of the number of interfering signals, which is in turn proportional to the number of people transmitting on this channel. For a fixed number of local interferers, the number transmitting depends on the population of the area. This sequence of relations suggests plotting operational range as a function of the logarithm of metropolitan area population. Such a plot is shown in Figure C-1(a).

The points in Figure C-1(a) are taken from Tables C-3, C-4, and C-5. (It turned out that there is so little difference between the results for New York and St. Louis that they can be lumped together.) For example, in Figure C-1(a), the first, third, fifth, and seventh points from the left on the line for one local interferer are from Table C-3 (New York). The second, fourth, and sixth points from the left are from Table C-5 (Los Angeles). The line is an empirical fit to the points. The

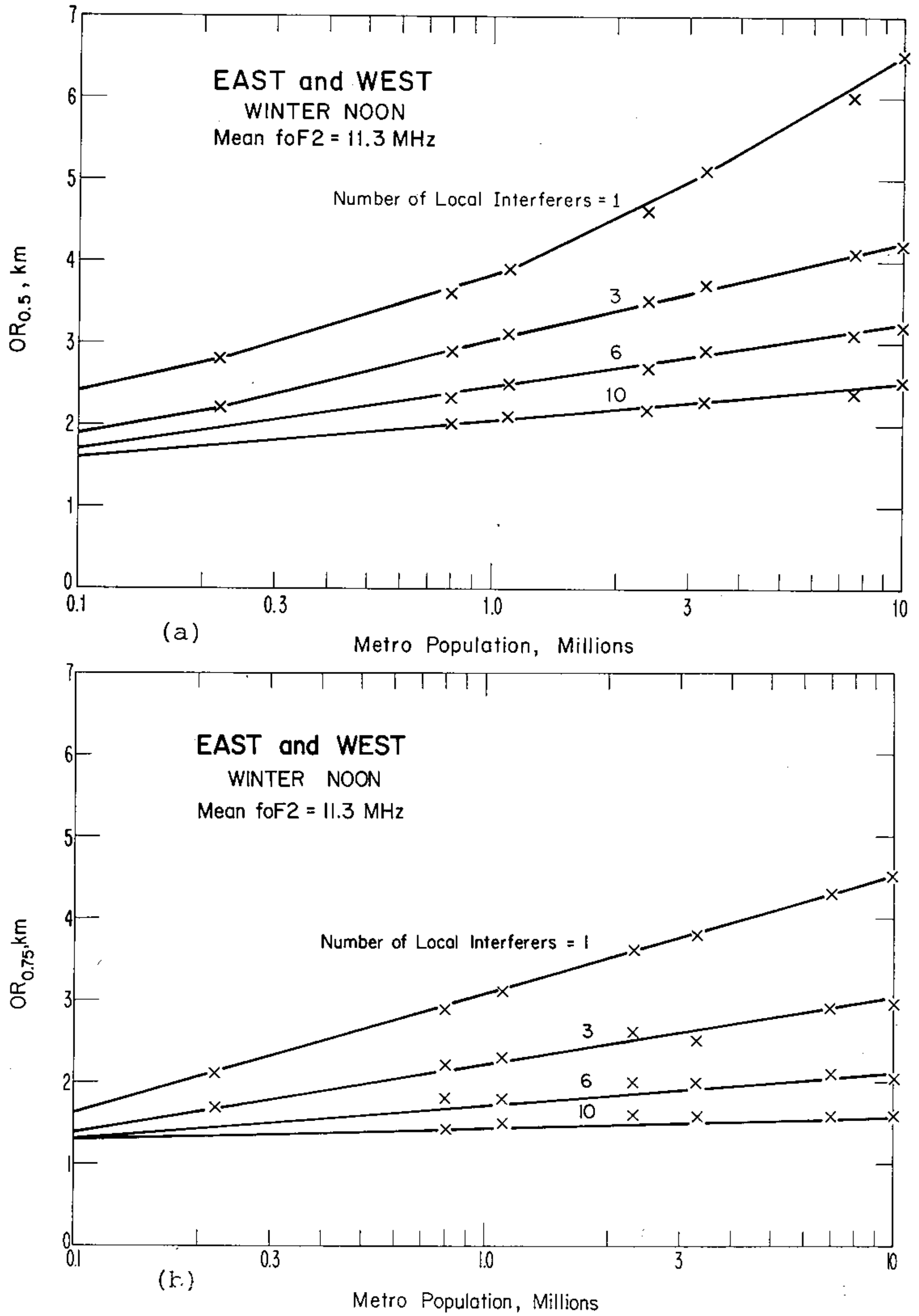

Figure C-1. Operational range as a function of population in the metropolitan area for various numbers of simultaneous local interferers. Skywave interference is included for the conditions shown on the figure.

operational range is clearly a well-behaved function of log (metro population) that is nearly linear over an order of magnitude of range in population. It seems reasonable to use Figure C-1 to estimate operational range in metropolitan areas with any population between 100 thousand and 10 million.

Figure C-1(b) is a plot of $OR_{.75}$ for the same conditions as Figure C-1(a). The points come even closer to falling on straight lines than those in Figure C-1(a). Figure C-2 is plotted using points from Table C-6. Figure C-3 is from Table C-7, Figure C-4 is from Table C-8, Figure C-5 is from Table C-9, and Figure C-6 is from Table C-10. In each case the behavior is nearly linear when there are many interferers. For a small number of local interferers, the curves do not always fall on a straight line. This is probably because the dominant interference changes from local to skywave as the metropolitan area population decreases.

The second major factor influencing the calculated operational range is the probability of skywave transmission. This is proportional to the ionospheric critical frequency, foF2 (Davies, 1965). So it is likely that the operational range will be a fairly consistent function of foF2.

There is one difficulty--this foF2 is the foF2 at the location where the wave reflects from the ionosphere. For the assumptions made in Appendix B, reflection occurs at a point midway between the transmitter and the receiver. But CB skywave interference is coming from all over the country, and foF2 varies over the country. The solution to this problem is to average the values of foF2 over the country. Roberts and Rosich (1971) show maps with contours of foF2 for different levels of solar activity. Rather than average over the whole country, the foF2 values at New York, St. Louis, and Los Angeles were averaged for each time that operational range had been computed. These average values are shown on the tables and figures in this appendix.

To show the dependence of operational range on foF2, data from Figures C-1 to C-6 can be replotted to produce figures like

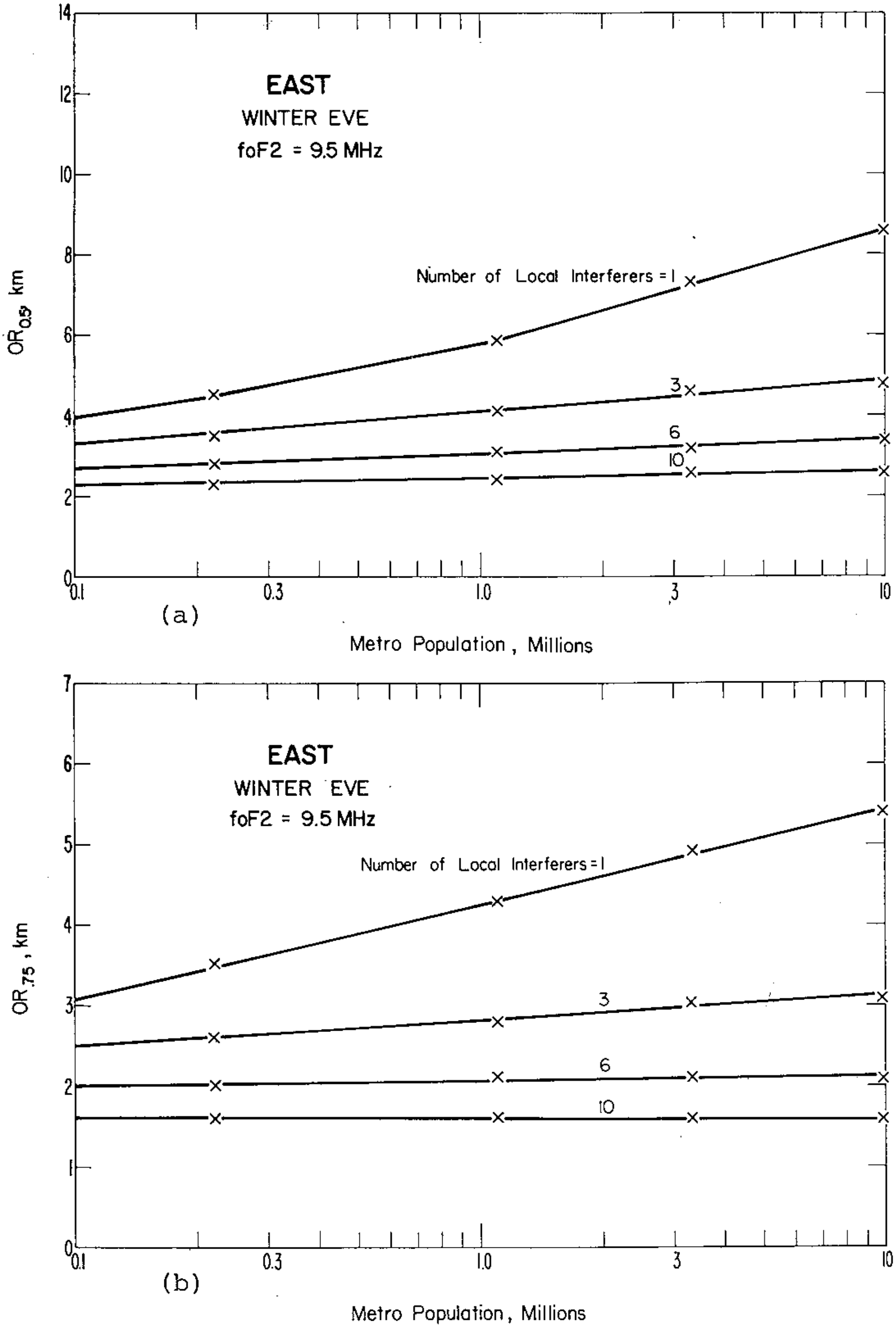

Figure C-2. Operational range as a function of population in the metropolitan area for various numbers of simultaneous local interferers. Skywave interference is included for the conditions shown on the figure.

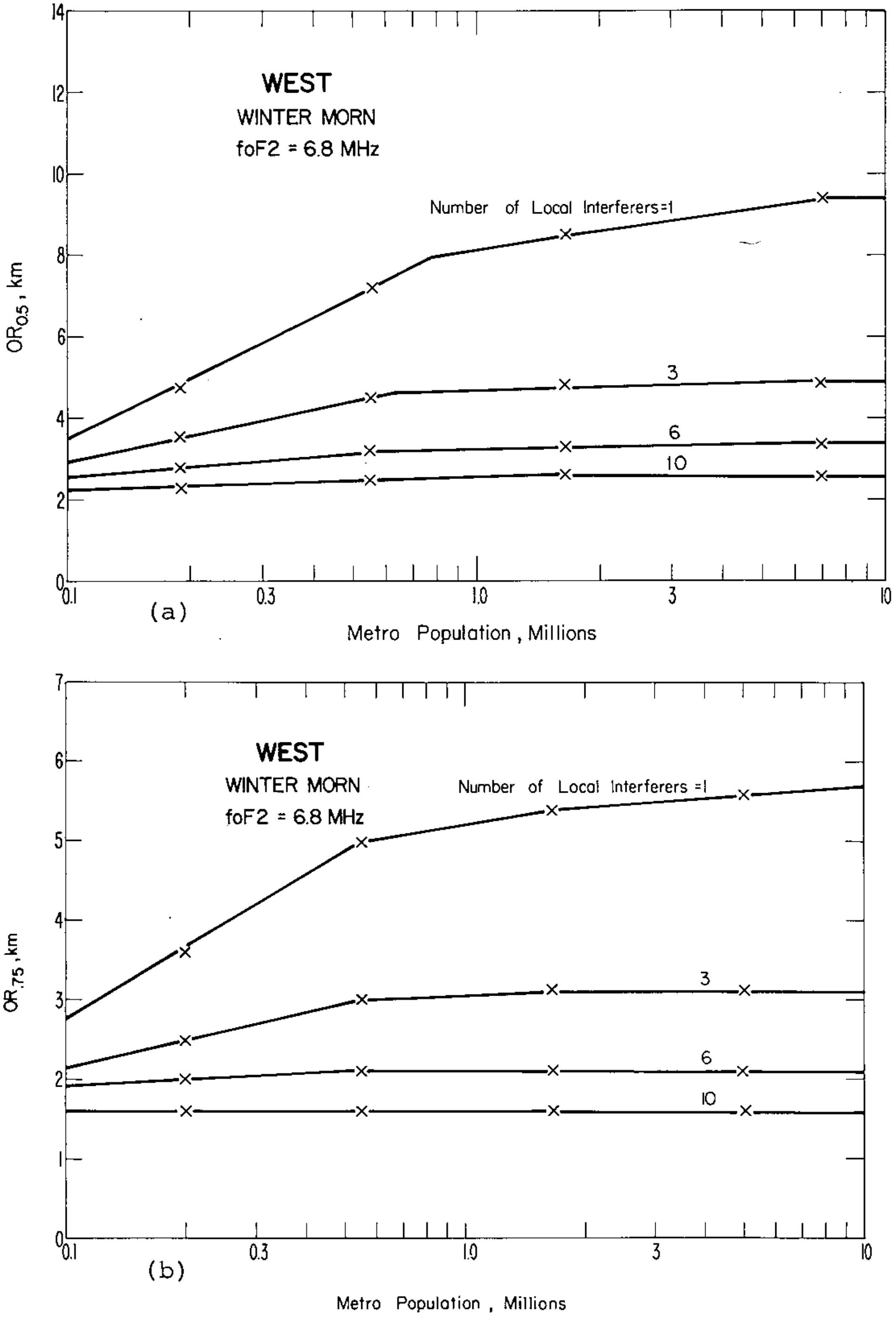

Figure C-3. Operational range as a function of population in the metropolitan area for various numbers of simultaneous local interferers. Skywave interference is included for the conditions shown on the figure.

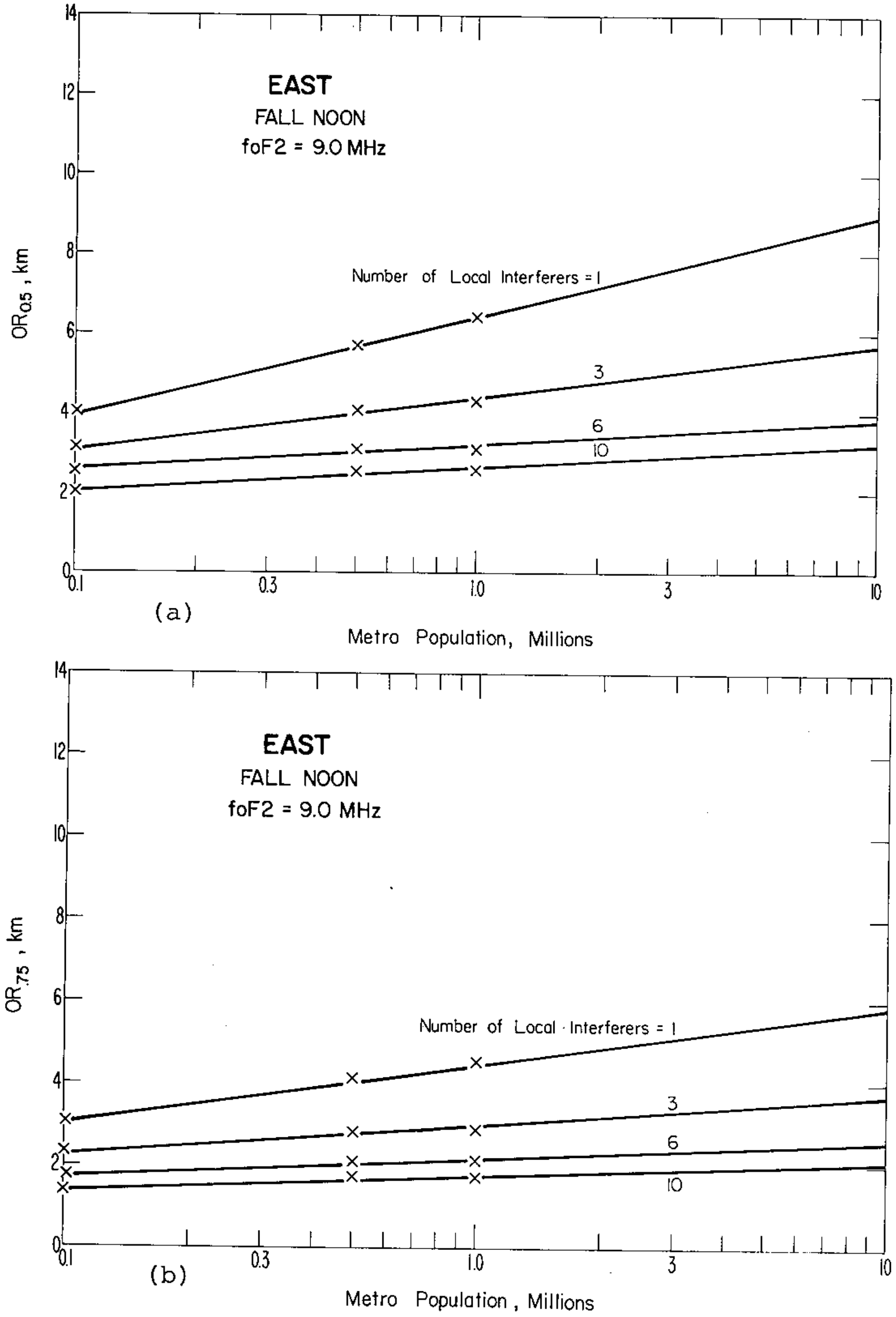

Figure C-4. Operational range as a function of population in the metropolitan area for various numbers of simultaneous local interferers. Skywave interference is included for the conditions shown on the figure.

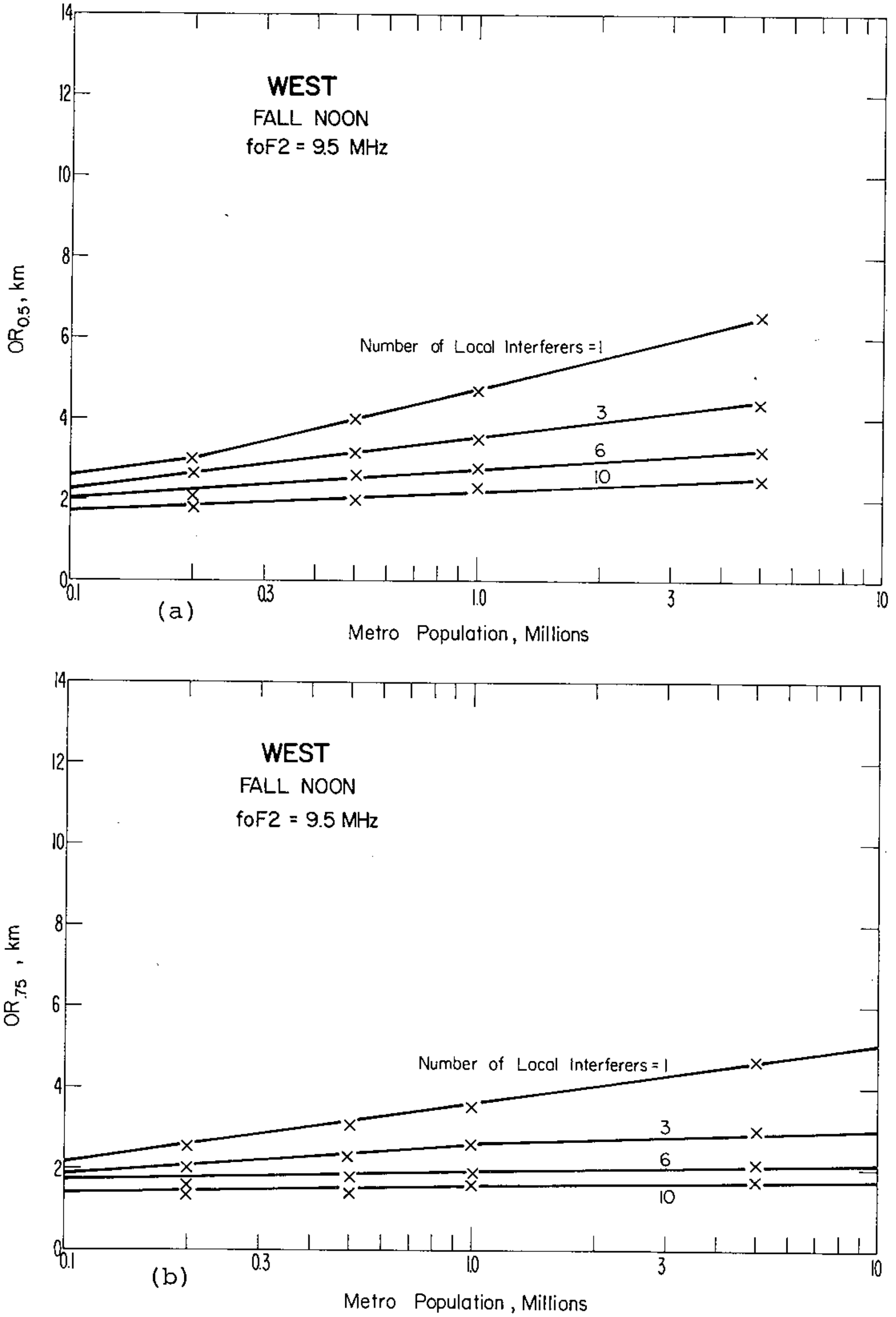

Figure C-5. Operational range as a function of population in the metropolitan area for various numbers of simultaneous local interferers. Skywave interference is included for the conditions shown on the figure.

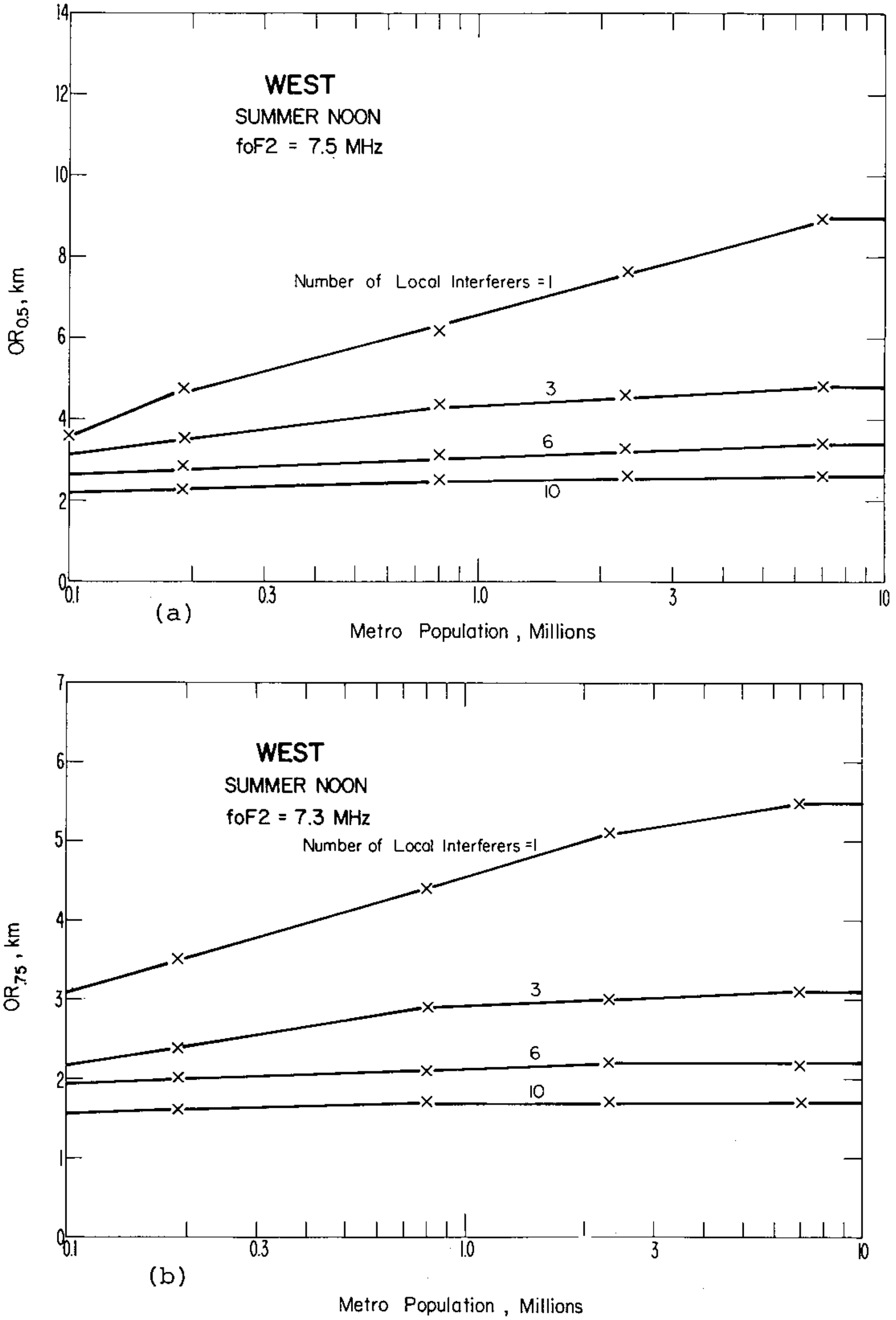

Figure C-6. Operational range as a function of population in the metropolitan area for various numbers of simultaneous local interferers. Skywave interference is included for the conditions shown on the figure.

C-7, which is Figure 3 of the main body of the report. For example, Figure C-1(a) shows that the median operational range in a city of 100,000 population is 2.4 km when there is one local interferer. This value (converted to miles) is plotted on Figure C-7 at mean foF2 = 11.3 MHz. "One interferer" implies that there are two stations transmitting--the wanted transmitter and the interferer. Because there are two stations transmitting for each 100,000 population, there are four stations transmitting in a metropolitan area with 200,000 population. One of them is the wanted transmitter, and the other three are interferers. So the operational range for a city of 200,000 can be read from the curve for three interferers in Figure C-1(a). Its value will help determine curve D of Figure C-7. Similarly, the values for ten interferers on Figure C-1(a) correspond to a metropolitan area with 500,000 population, and help determine curve E of Figure C-7.

Because there is only one interferer in an area with population 100,000, there are no local interferers in an area with a population of 25,000. (Recall that it is assumed that the same fraction of the population is transmitting everywhere.) But there is still the same amount of skywave interference. Examination of the intermediate computer output showed that skywave interference is much greater than local noise for this case, so the operational range for areas with 25,000 or less population is the same as for an area with 100,000 population for foF2 = 11.3 MHz.

Continuing, the operational range for various size cities can be read from Figure C-2 for mean foF2 = 9.5 MHz and for other values of foF2 from Figures C-3 to C-6. For values of foF2 small enough that the probability of skywave propagation is approximately zero, the operational range is given by Table C-1. Drawing a smooth curve through the points obtained completes Figure C-7, which shows how large mean foF2 must be to decrease operational range. The predictions of Roberts and Rosich (1971) provide the data for a table of mean foF2 for each

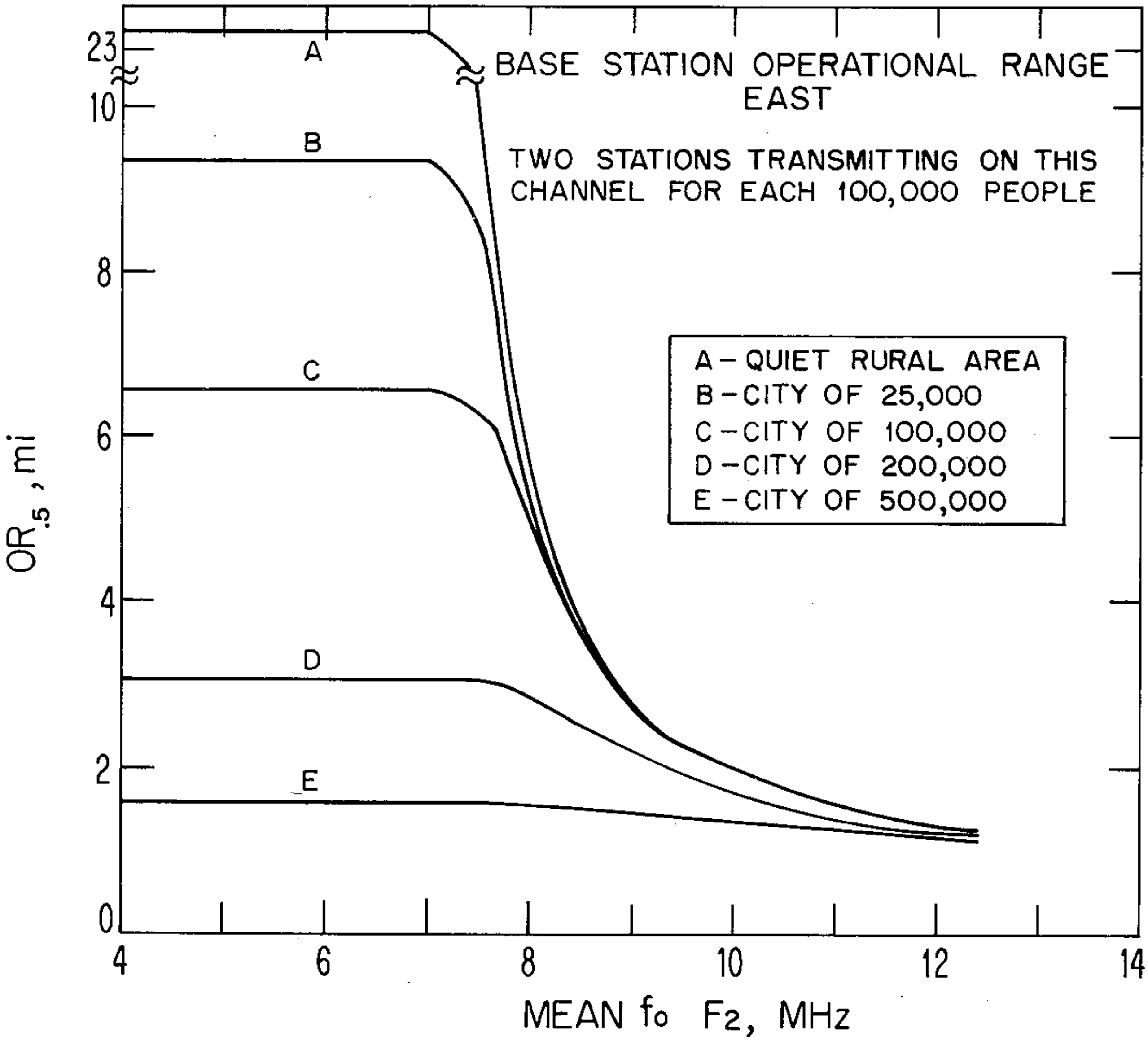

Figure C-7. Average operational range of a typical CB base station for the conditions described on figure, as a function of the ionospheric reflectivity parameter, mean foF2. The left side of the figure corresponds to low solar activity; the right side is representative of winter daytime conditions near the peak of a solar cycle. Mobile station operational range is less than half base station range.

2-hour time block of each month of a sunspot maximum year (see Table 2 of the body of the report). The operational range for each time block in the table can be found by comparing its mean foF2 with a figure like C-7.

Looking back, you see that interpolation and smoothing have been used to extrapolate from specific "typical" cases to general estimates of operational range everywhere in the U.S. during an average solar cycle. The inaccuracies introduced by this process are probably no larger than those in the modeling assumptions described in Appendix B. They are certainly much smaller than the effects observed--namely that skywave interference at solar cycle maximum can decrease the operational range of CB radios in small cities and rural areas to less than half its value without skywave interference.

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The combined effects of local interference, skywave ("skip") interference, and radio noise on Citizens Band radio range are calculated. If the ionospheric reflectivity is normal or above normal during the next solar cycle, and CB use does not decrease, the operational range of CB users in cities of under 100,000 will be less than half its present value during daylight hours of nonsummer days for 3 years at the peak of the cycle. CB'ers in metropolitan areas with more than a million residents will probably not be bothered much by skip interference.

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