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FREQUENCY SHARING BY FIXED AND MOBILE USERS IN THE 4-28 MHZ RAN--ETC(U)

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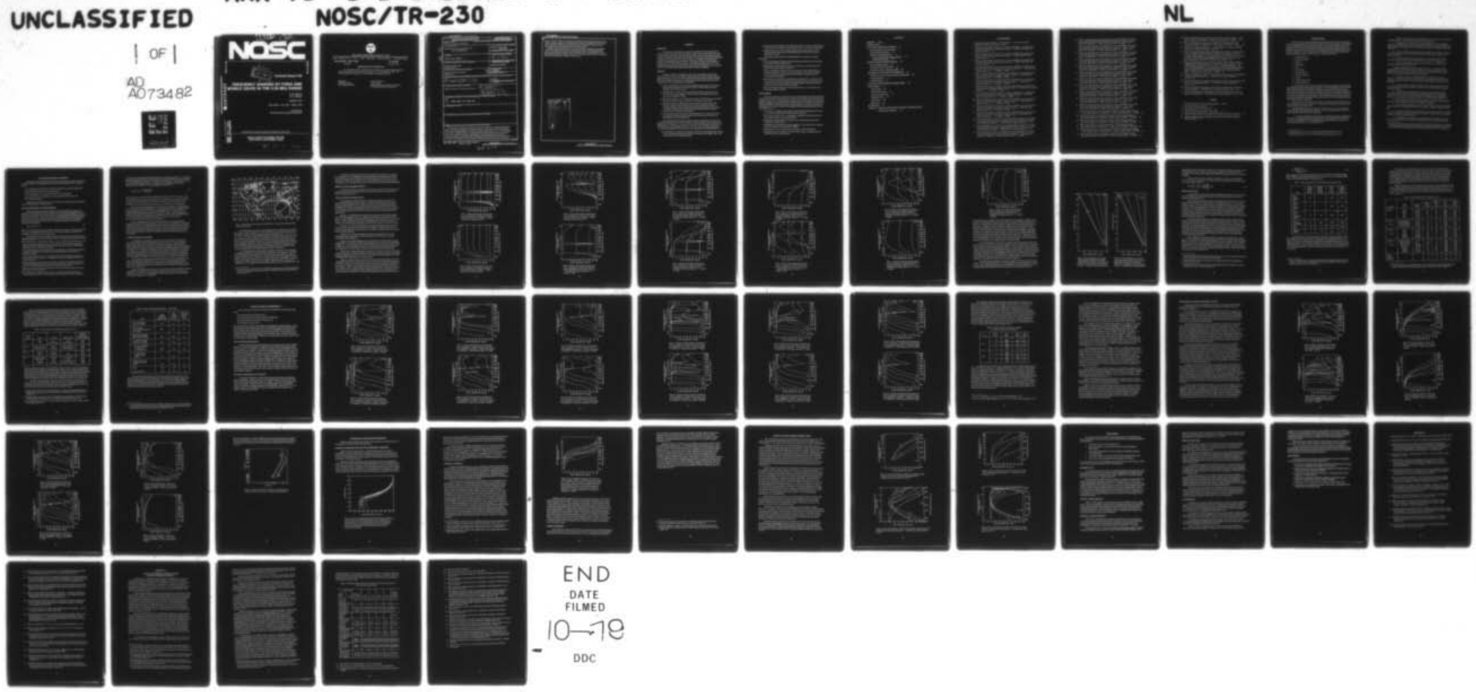

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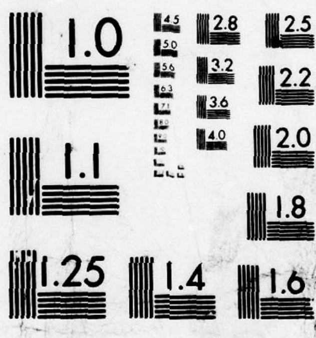

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FREQUENCY SHARING BY FIXED AND MOBILE USERS IN THE 4-28 MHz RANGE

D. B. Sailors
R. P. Brown

28 March 1978

Final Report: July 1976 — March 1978

Prepared for
Naval Electronic Systems Command

NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

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NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CA 92152

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Technical Director

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The work reported here was performed by members of the EM Propagation Division, Naval Ocean Systems Center, during the period July, 1976 through March, 1978. The authors appreciate the assistance of John Sanfilipo in preparing the figures.

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The feasibility of hf fixed and mobile services to share the hf fixed service frequency bands has been assessed. The circuit compatibility of the fixed service with the mobile service on co-channel assignments is dependent on the channel usage U of the interferer and has a minimum value of 1-U. For communication circuits, such as mobile circuits which are operated sporadically, channel usage is low and circuit compatibility is, hence, high. The uniformity in channel usage of a particular mobile system is important in determining opportunities for sharing. When channel usage of the mobile service is high, interference may be reduced to the fixed service by employing space diversity and directive antennas, and by using single → next page

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sideband modulation (SSB) for radio telephony. Interference increases in the mobile service when its receiver is within the mainbeam of the interfering fixed transmitter. The difference in maximum fixed service and minimum mobile service transmission power can be minimized by having the mobile service employ narrow band telegraph modulation wherever practical.

For specific sunspot activity, month of year, time of day, paths of propagation, the frequencies of concern for interference increase with increasing sunspot number, with increasing path length desired, and for transition from night to day. This is primarily due to increasing path MUF. As the desired path length decreases during the daytime, its lowest usable frequency (LUF) decreases causing lower and lower frequencies to be subject to interference.

SUMMARY

OBJECTIVE

The objective of this study was to assess the feasibility of hf fixed and mobile services to share common fixed service frequency bands. Due to recent advances in radio communication technology, bands allocated to mobile hf services have become especially crowded. An analysis of the theoretical feasibility of hf frequency sharing and identification of related issues is essential to the search for alternative solutions to the problems of frequency congestion and radio interference. This study is directed to the feasibility of sharing, in the 4–28 MHz frequency range, by the fixed and mobile services. It is also intended to provide necessary information in developing the United States policy position for the 1979 General World Administrative Radio Conference (GWARC).

RESULTS

Computer models for estimating the theoretical compatibility between high frequency skywave systems are available. Such models may be used to simulate sharing where interference occurs and to develop specific plans and technical criteria for sharing. When these methods were applied to a sample sharing situation between the fixed and mobile services, the following results were obtained:

- *Circuit compatibility* of the fixed service with the mobile service on co-channel assignments is dependent on the channel usage U of the interferer and has a minimum value of 100-U percent.
- *Channel usage* for circuits which are operated sporadically during any hour of the month, such as the majority of mobile circuits, is generally low and hence, the circuit compatibility is high.
- *High channel usage* (i.e., $U > 50$ percent) can only occur when the average waiting time for the channel is greater or equal to the average message length.
- *Trunking techniques,* employed by some mobile users to improve the traffic efficiency, require that each mobile unit carry radio equipment capable of switching among n channels and that spectrum space be allowed for each of the n channels. Trunking is used when the average waiting time for a channel is much less than the average message length.
- *Traffic characteristics* vary widely among different users in a single service; thus, the uniformity in channel usage of a particular mobile system is important in determining its sharing opportunities.

The frequency spectrum and locations of concern for interference, as well as the strength of this interference, vary for (1) different relative lengths of the desired and interfering paths, (2) solar activity, (3) time of day, (4) day-to-day atmospheric conditions, (5) season of the year, (6) geomagnetic latitude, and (7) the particular operating frequency. The following propagation characteristics are very dependent on environmental factors:

- The frequencies of concern for interference increase with increasing sunspot number, with increasing path length desired, and for the transition from night to day. This is primarily due to increasing path MUF.

- As the desired path length decreases during the daytime, its lowest usable frequency (LUF) decreases; causing lower and lower frequencies to be subject to interference.
- A higher frequency, or lower sunspot number, causes a larger skip zone at the desired receiver, within which no interfering signal can be received by regular ionospheric refraction.

When channel usage is high, the following methods are effective in reducing interference:

- For a radiotelephony fixed system, single sideband suppressed carrier modulation is preferable to double sideband AM.
- When double sideband AM is the interfering emission, space diversity provides additional protection against interference.
- Circuit compatibility is increased for the fixed service when a highly directive antenna is employed. However, circuit compatibility is reduced for the mobile service whenever the desired mobile receiver is within the main beam of the interfering fixed transmitter.
- The effects of the difference in maximum power transmitted by the fixed service and the minimum power transmitted by the mobile service can be reduced for the mobile service by having it employ narrowband telegraph modulation whatever practical, instead of double sideband telephony.
- Other less traditional methods of decreasing interference, such as adaptive array technology, appear promising.

CONCLUSIONS

If circuit requirements of mobile circuits are only moderate, then frequency sharing with the fixed services is possible. However, because of the complex nature of the sharing problem and the fact that a comprehensive model has yet to be developed, that resolves the loading, propagation, and electromagnetic environmental factors involved, a measured and systematic approach to sharing applications seems necessary. As a result of this study, the following issues emerged as central to the feasibility of hf band sharing between the fixed and mobile services.

- The need for a sharing procedure which would divide the shared bands according to the relative propagation path lengths of the two services.
- Within this procedure, the use of ionospheric variability of the MUF and LUF in determining frequency sharing opportunities.
- Desirability of single sideband modulation with a supressed carrier for radio telephony in the fixed services.
- Desirability of employing narrowband telegraphy in the mobile services whenever practical, instead of double sideband telephony.
- Subdivision of the new shared bands according to mobile channel usage.
- Consideration of the uniformity of mobile channel usage in assigning particular mobile systems to the shared bands.

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INTRODUCTION

Advances in radio communication over the last decade have resulted in an increased use of telecommunication services and heavy demands on the radio spectrum. These demands have been traditionally met by simple administrative solutions, since engineers were able to increase operable system frequencies almost as fast as the demand for spectrum space. The resulting congestion of the radio frequency (rf) spectrum has required sharing of frequencies between a number of services. However, in the 4-28 MHz range, frequency bands are still allocated exclusively to each of the user services. These services include:

1. aeronautical fixed,
2. aeronautical mobile,
3. amateur,
4. broadcasting,
5. fixed,
6. land mobile,
7. maritime mobile,
8. meteorological aids,
9. mobile,
10. radio astronomy, and
11. standard frequency.

At high frequency (hf), many of the bands have become congested to a point where operations are not afforded the requisite reliability. This is particularly true in the hf mobile bands. With the growth of communication satellite systems, which handle fixed service needs and have decreased the need for conventional hf fixed circuits, it has been suggested that hf fixed and mobile services share the hf fixed service bands. The purpose of this report is to present an assessment of the feasibility of such a sharing situation and to provide data useful in developing the United States policy position for the 1979 General World Administrative Radio Conference (GWARC).

Certain features of the operations of fixed and mobile services have a direct impact on their shared use of the same hf bands. It is important to bring these to mind before outlining the analysis used in this study.

The Radio Regulations (ref 1) define the fixed service to be, "A service of radiocommunication between specified fixed points." Hf circuits operating in the fixed service may be generally characterized by the following:

1. Frequency assignments are limited (e.g., 2–8 frequencies) and are usually fixed for each circuit by international agreement, although certain users with large communication sets (e.g., INTERPOL) may be authorized to use a given frequency on several of its own links simultaneously or on a shared basis (ref 2).

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1. Radio Regulations, 1976 ed., Article 2, International Telecommunications Union, 1976.
2. International Frequency List, Vol. 1–4, International Telecommunications Union, 1975.

2. Major point-to-point circuits are normally operated on a more or less full-time, continuous basis (i.e., channel usage greater than 83 percent) (ref 3).

3. Communication systems used are usually wideband (3-12 kHz) multiplex emission and use high power (5–80 kw) transmitters and directive antennas; diversity operation at the receiver is commonly used. Emission types include 0.1A1, 6A9B, 1.24F1, and 6A3 (ref 2).

4. Circuit controllers are usually experienced, well trained, and tend to remain on a particular circuit for a considerable length of time developing useful experience on a given circuit (ref 3).

5. Circuit quality requirements are high because of both the type of traffic handled and the need for adequate transmission rate to avoid costly backlogs (ref 3).

6. Fixed circuits generally range in length from 400 km to 10 000 km and include both land and oceanic paths (ref 2).

The Radio Regulations defines the mobile service to be: "A service of radiocommunication between mobile and land stations, or between mobile stations" (ref 1). Semi-mobile circuits are circuits in which one terminal is mobile and the other is fixed. Such circuits are generally characterized (ref 3) as follows:

1. Frequency resources are relatively flexible; special frequency bands are allocated for aeronautical, marine, and land mobile circuits. Major users frequently have considerable clearance within each band which may be authorized for use by any one of their units.

2. Circuit operation is usually very sporadic, since traffic requirements are low and personnel limited; notable exceptions do exist, however, where full-time terminated circuits are required.

3. Communication systems are not usually very complex, ranging from low power CW operation to single channel teletype, radiotelephony, and a few multiplex circuits (i.e., 0.5A1, 3A3J, 6A3, and 3A7J emission); transmitter power is usually low (0.1–5 kw) and antennas are essentially non-directive (vertical, monopole, dipole, etc.).

4. Operating personnel frequently lack experience and have little training; meaningful experience is difficult to obtain due to mobility of operations.

5. Circuit quality requirements are only moderate, owing to the type of messages and the possibility of using simple repetition for redundancy without creating traffic backlogs.

6. Circuit time availability is very important due to possible emergency conditions and lack of alternative or backing communications capability; the probability of not having to wait for a channel is high (70 percent).

7. The capability for handling, maintaining and operating complex communication or analysis equipment is severely limited, by available space and available personnel.

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3. Environmental Sciences Services Administration IERTM-ITSA 28, Monitoring Techniques for Evaluating Useful Frequencies for HF Telecommunication Circuits (U), by JC Blair with Appendix: Recommended Link/Frequency Evaluation Techniques, by WR Hinchman and RD Jennings, p 72–83, March 1967.

ANALYSIS OF FREQUENCY SHARING

The assessment of band sharing between hf systems required detailed consideration of statistical factors. The probability of interference depends upon the following major factors:

- the propagation characteristics of both the interference and desired signal paths,
- the radiation patterns of the antennas involved,
- the susceptibility of the desired receiver to the undesired signal,
- the utilization factors resulting from communication traffic volume, and
- the transmitted power.

Ideally, each of these parameters in the interference prediction process should take on a statistical distribution of values (ref 4).

CIRCUIT RELIABILITY AND COMPATIBILITY

Many reasonably good computer models exist that are designed to predict the properties of radio signals received via skywave modes of inospheric propagation (ref 5–9). In general, the prime objective of these models is to optimize communication performance in the presence of noise. A common measure of expected performance available from prediction models is the percentage of days within a given month that the circuit quality is expected to be satisfactory at a given hour. This measure is termed *circuit reliability*. Expressed mathematically,

$$q_{a_1 a_2} = q_{S-N} \cdot q_f \qquad (1)$$

Where q_f is the percentage of days within the month that the sky-wave path $a_1 a_2$ will exist and q_{S-N} is the likelihood that, if the signal is reflected, the strength of this signal will adequately exceed the noise level at the receiver.

The prediction of circuit reliability, based on the operation of a skywave system in an interference-free environment and subject only to radio noise, has been extended (ref 10)

[4] Beckmann P, Elements of Applied Probability Theory, 1st Ed., p 3, Harcourt, Brace & World, Inc., 1968.

[5] Environmental Sciences Services Administration Tech. Rep. ERL 110-ITS 78, Predicting Long-term Operational Parameters of High-frequency Sky-wave Telecommunication Systems, by AF Barghausen, JW Finney, LL Proctor, and LD Schultz, May 1969.

[6] Environmental Sciences Services Administration Tech. Rep. IER-ITSA 1, Predicting Statistical Performance Indexes for High Frequency Ionospheric Telecommunications Systems, by DL Lucas and GW Haydon, Aug. 1966

[7] Office of Telecommunications Rep. 76-102, Predicting the Performance of High Frequency Sky-wave Telecommunications Systems (the Use of the HFMUFES 4 Program), by GW Haydon, M Leftin, and R Rosich, Sept. 1976.

[8] International Radio Consultative Committee, New Delhi, 1970, Rep. 252-2; CCIR Interim Method for Estimating Skywave Field Strength and Transmission Loss at Frequencies Between the Approximate Limits of 2 and 30 MHz, International Telecommunications Union, Geneva, 1970.

[9] Bradley PA, "Long-term HF Propagation Predictions for Radio-circuit Planning," Radio and Electron. Eng., Vol 45, p 31–41, Jan/Feb. 1975.

[10] Sailors DB, Kugel CP, and Haydon GW, Predicting the Compatibility of High Frequency Skywave Communication Systems, IEEE Trans. Electromagn. Compat., Vol EMC-19, p 332-343, August 1977.

to estimate the expected performance in the presence of skywave interference. In this technique, the effect of interference is characterized by a parameter called *circuit compatibility.* Circuit compatibility is the ratio of the estimated circuit reliability, considering the operation of one interfering transmitter, to estimated circuit reliability under otherwise interference-free conditions. Circuit compatibility is expressed as,

$$q'_{a_1a_2 \mid b_1b_2} = \frac{q_{a_1a_2 \mid b_1b_2}}{q_{a_1a_2}} \qquad (2)$$

where, $q'_{a_1a_2 \mid b_1b_2}$ is the circuit compatibility of circuit a_1a_2 with b_1b_2, $q_{a_1a_2 \mid b_1b_2}$ is the probability of successful communications from transmitter a_1 to receiver a_2 when transmitter b_1 is transmitting to a receiver at b_2, and $q_{a_1a_2}$ (circuit reliability) is the probability of successful communications from a_1 to a_2 when b_1 is not transmitting.

Notice, that if communications over circuit a_1a_2 are unaffected by transmissions from b_1, then the circuit compatibility is one. If transmissions from b_1 completely block communications from a_1 to a_2, the circuit compatibility is zero. If the circuit a_1a_2 operates satisfactorily 80 percent of the time when b_1 is silent, and only operates satisfactorily 40 percent of the time when b_1 is transmitting, then circuit compatibility is 0.5. It is not only possible, but indeed likely, that $q'_{a_1a_2 \mid b_1b_2} \neq q'_{b_1b_2 \mid a_1a_2}$. Thus, the level of interference may be nonreciprocal.

Circuit compatibility is a function of the probability of simultaneous transmission of the desired and undesired signals (the duty cycle of the interferer), of the joint probability that the received signal power-to-noise density ratio and signal-to-interference ratio is above that required for the desired grade of service, and (for hf skywave systems) of the joint probability of ionospheric layer support on both the desired and undesired paths. Signal acceptability criteria for hf skywave frequency sharing analysis is given in the appendix.

A SAMPLE SHARING SITUATION

The assessment of interference to the fixed service was made by choosing one fixed service path from the International Frequency List (ref 2). This was Monrovia, LBR to Beirut, LBN: a 5651 km path and served as the baseline to compare further analysis. Mobile transmitters on great circle radials in the Atlantic Ocean (36.63 degrees N, 6.32 degrees W to 32 degrees N, 67 degrees W) and in the Mediterranean Sea (34.0 degrees N, 25 degrees E to 32 degrees N, 30 degrees E) were chosen as interfererers. In addition, three other mobile paths were chosen to fill the gap between the two sets of potential interferers (mobile transmitters at 36 degrees N, 0 degrees E; 35 degrees N, 4 degrees W; and 36.84 degrees N, 8 degrees W to the mobile receiver at 32 degrees N, 30 degrees E).

To determine the effect of the desired path length on circuit compatibility, fixed service transmitters were selected for 1/8, 1/4, 1/2, and 3/4 path-length points from Beirut, on the Monrovia to Beirut path. This produced respective path lengths of 705, 1413, 2826, and 4239 km which are identified in later data as Egypt, Libya, Nigeria, and Upper Volta, respectively.

Figure 1 illustrates this environment, with the fixed base line and mobile interferers as solid lines. The extremes of the interference paths to the fixed service receiver are identified as broken lines. The geomagnetic latitudes encountered by these paths range from about 12 degrees N to 51 degrees N.

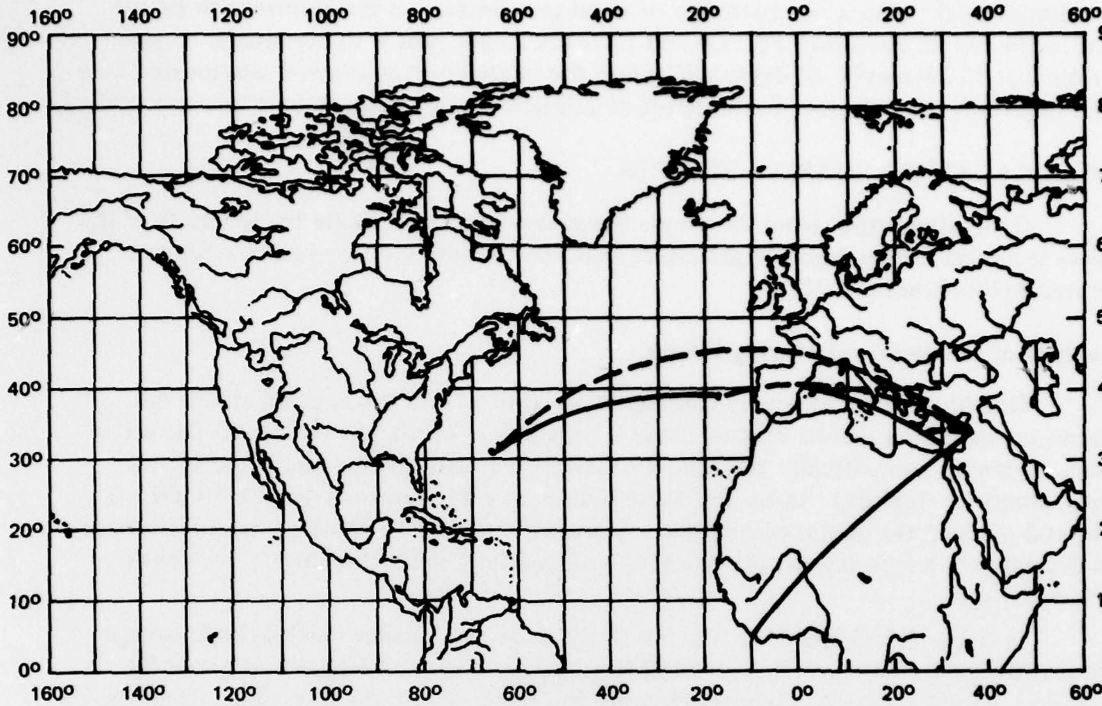

Figure 1. Sample sharing situation paths ((–) desired paths; (– –) extremes of mobile transmitter to fixed receiver paths).

The initial analysis was done for both night and day, for July, and for a mid-solar cycle value of sunspot number (50). Further analysis was done for Winter and for sunspot numbers 10 and 110. The frequencies used in the analysis were 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, and 27 MHz. Both correlations of the MUFs on the two paths ρ' and the correlation between the signal S and interference I, ρ were assumed to be weak (25 percent). The mean transmitted power used for the fixed services and mobile services were a respective 2.5 kW and 1.5 kW. It was also assumed that all fixed service antennas met the minimum standard antenna directivity given in CCIR Recommendation 162.2 (ref 11). For the fixed and mobile paths, the emissions chosen were double sideband (6A3) and single sideband with suppressed carrier (3A3J), respectively.

For the initial analysis, good commercial quality was assumed. The two signal-acceptability thresholds were obtained from the table given in the appendix. The usage on the fixed path was assumed at 83.3 percent and on the mobile paths the usage was allowed to vary from 10 to 100 percent. A value midway between urban and rural was used for the radio noise environment of the fixed service sites (–148.6 dBW at a receiving frequency of 3 MHz). Rural noise (–165.6 dBW at 3 MHz) was used to represent the mobile services. The variations in the transmitter emission power were assumed to be 2 dB.

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[11] International Radio Consultative Committee 13th Plenary Assembly, Geneva, 1974, Recommendation 162-2; The use of directional antennas in the bands 4 to 28 MHz, International Telecommunications Union, Geneva, 1975.

The effects of interference by fixed service on the mobile service were examined by computing the circuit compatibility of fixed transmitters on the Monrovia to Beirut path, with mobile circuits of 502 km and 1702 km length, and with the mobile receive terminal at 32 degrees N, 30 degrees E. Since the intended fixed receiver was located at 33.5 degrees N, 35.5 degrees E, the effect of a directive antenna on sharing was also studied.

MOBILE CHANNEL SHARING EFFECTS

Computer output from the program was examined to evaluate the tradeoffs of the many technical factors which might affect satisfactory radio service in an interference limited environment (ref 10).

Analysis of Mobile/Fixed Sharing Effects

One of the most extensive parametric variations examined was the affects on circuit compatibility due to channel usage U. Figures 2–4 show the effects of channel usage on circuit compatibility for a mobile service path with the baseline fixed service path, Monrovia to Beirut. In each of these figures, at usage values of 10, 20, 40, 60, 80, and 100 percent, the circuit compatibility is shown both as a function of the interference to desired path length ratio (b_1a_2 to a_1a_2), and as a function of the interference path length (b_1a_2).

In figure 2, at 1200 GMT, the interferer range dependence exhibits little change from 1300 km to 6000 km; this is at 15 MHz, July, and with a sunspot number of 50. However, within 1000 km, the interfering transmitter is within the skip zone of the desired receiver. At about 2500 km, an increase in compatibility occurs, which is caused by a change in the dominant interfering mode (from a one hop E mode to a two hop F mode).

In figure 3, at 9 MHz and 2400 GMT, the circuit compatibility can be seen to be insensitive to the interferer range variation beyond 2000 km. It also exhibits the same skip zone dependence that was seen in figure 2, for interferer separations from the desired receiver less than 1000 km.

In figure 4, at 15 MHz, the nighttime interferer range dependence of circuit compatibility again shows a region of high compatibility in the skip zone, for range separations less than 2000 km.

Figures 5–12, along with figures 2–4, show the effects of channel usage on circuit compatibility for mobile service paths with progressively shorter fixed service path lengths. In figures 5–12, at usage values U of 20, 60, and 100 percent, and at the frequencies 9 and 15 MHz, the circuit compatibility is shown as a function of the interference-to-desired path length ratio $b_1a_2 \mid a_1a_2$ and as a function of the interference path length b_1a_2.

Figures 2 and 5–8 represent daytime conditions, and figures 3, 4, and 9–12 represent nighttime conditions. These figures show the importance of channel usage in determining frequency sharing opportunities. In all of the curves illustrated in these figures, the circuit compatibility has a minimum value of 100-U percent.

Beyond a certain value of the interference-to-desired path length ratio, the circuit compatibility increases at all usage levels. The value of the ratio determining this effect is dependent on the time of day and upon the ratio of operational frequency to the MUFs on the two paths. Figures 5–7 show the same skip zone features on the higher frequency as seen in figure 2; that is, within 1000 km the interfering transmitter is within the skip zone of the desired receiver and again at about 2500 km an increase in compatibility occurs, which is caused by a change in the dominant interfering mode (from a one hop E mode to

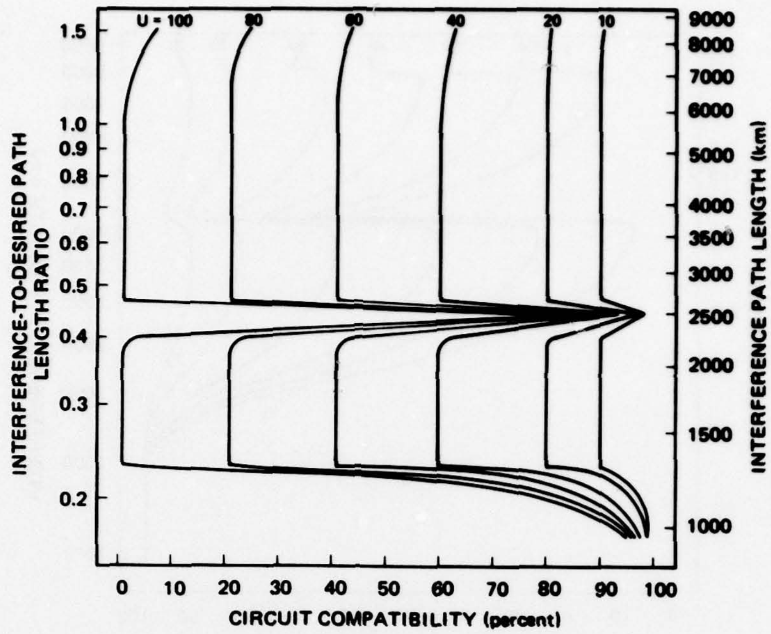

Figure 2. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - 15 MHz, 1200 GMT, July, sunspot number 50.

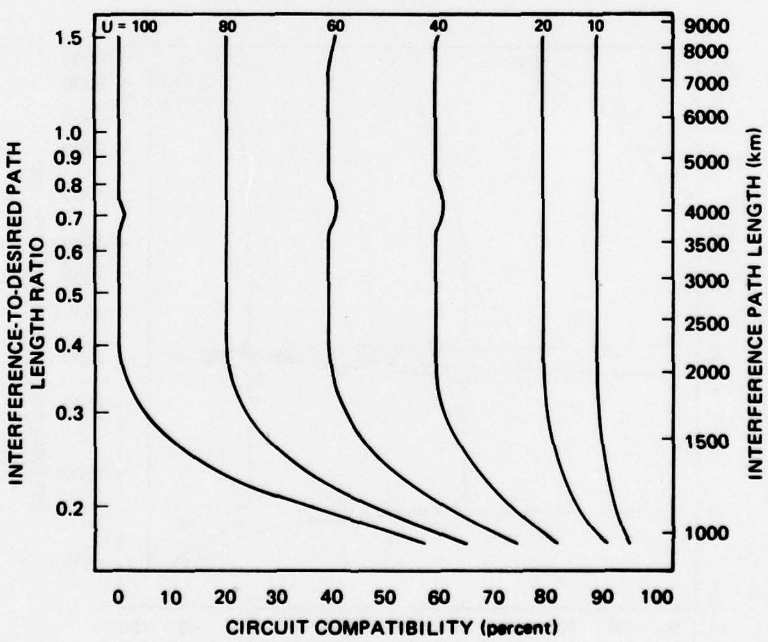

Figure 3. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - 9 MHz, 2400 GMT, July, sunspot number 50.

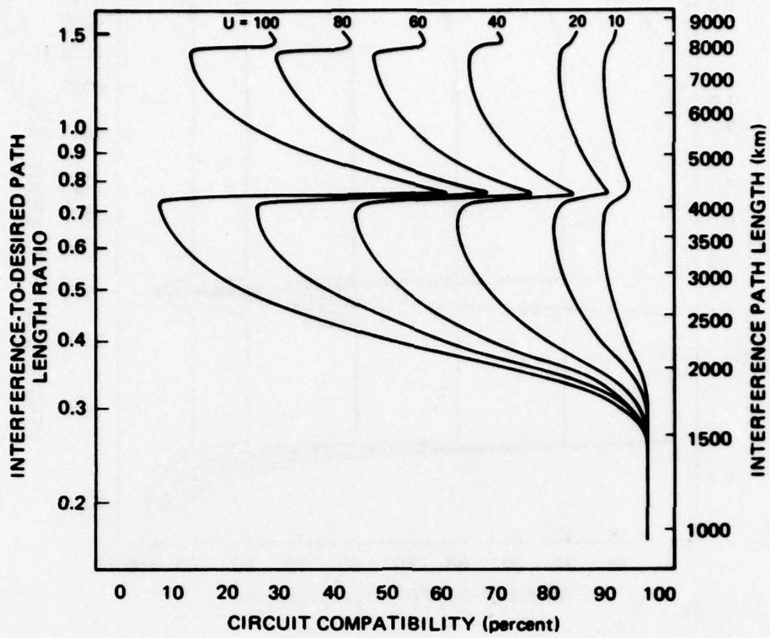

Figure 4. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - 15 MHz, 2400 GMT, July, sunspot number 50.

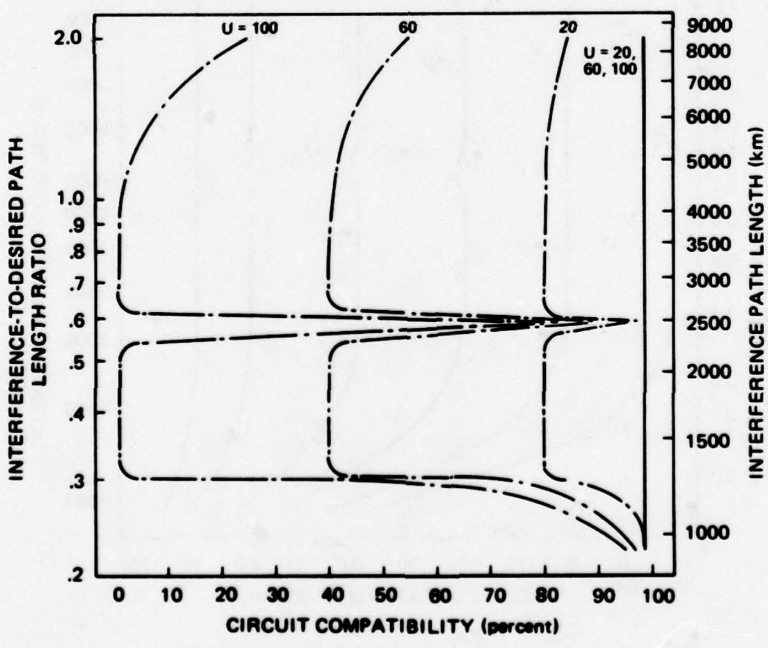

Figure 5. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Upper Volta to Beirut, 4239 km) - - 1200 GMT, July, sunspot number 50, (– · –) 15 MHz, (–) 9 MHz.

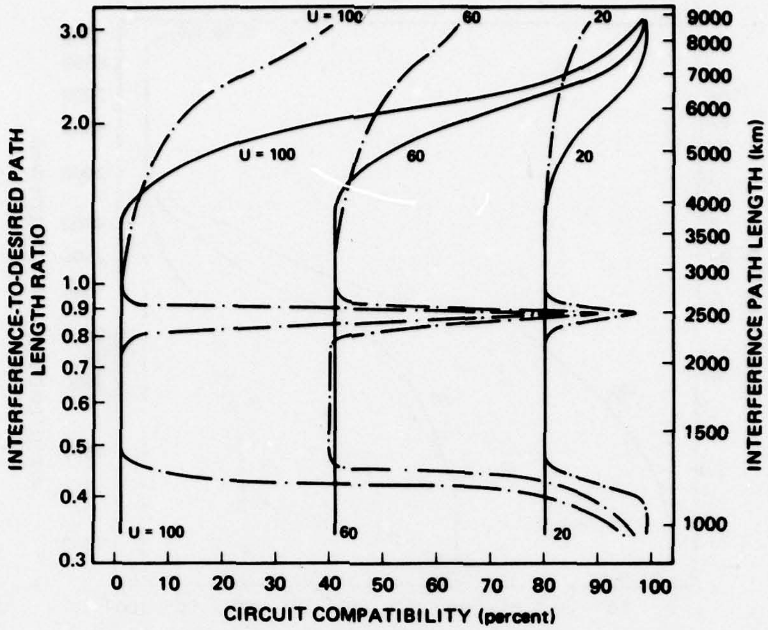

Figure 6. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Nigeria to Beirut, 2826 km) - - 1200 GMT, July, sunspot number 50, (– - –) 15 MHz, (–) 9 MHz.

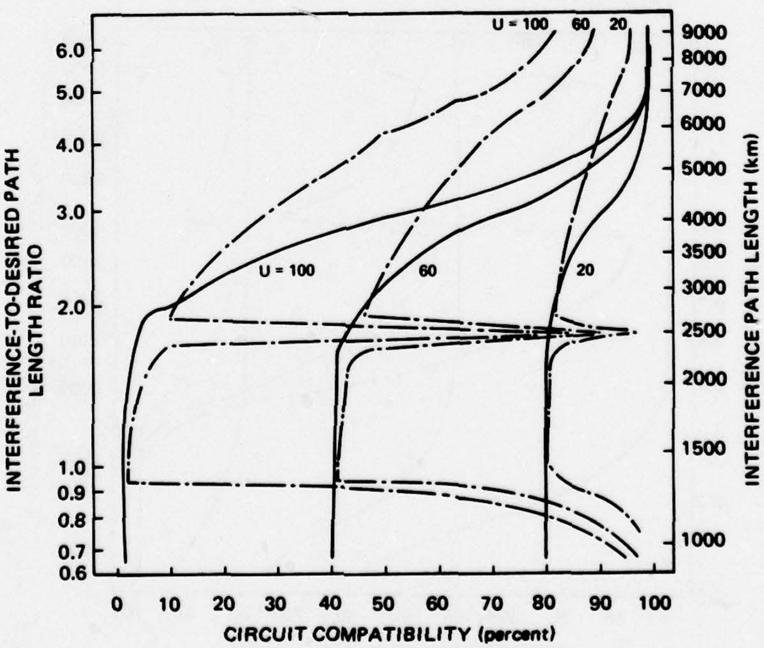

Figure 7. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Libya to Beirut, 1413 km) - - 1200 GMT, July, sunspot number 50, (– - –) 15 MHz, (–) 9 MHz.

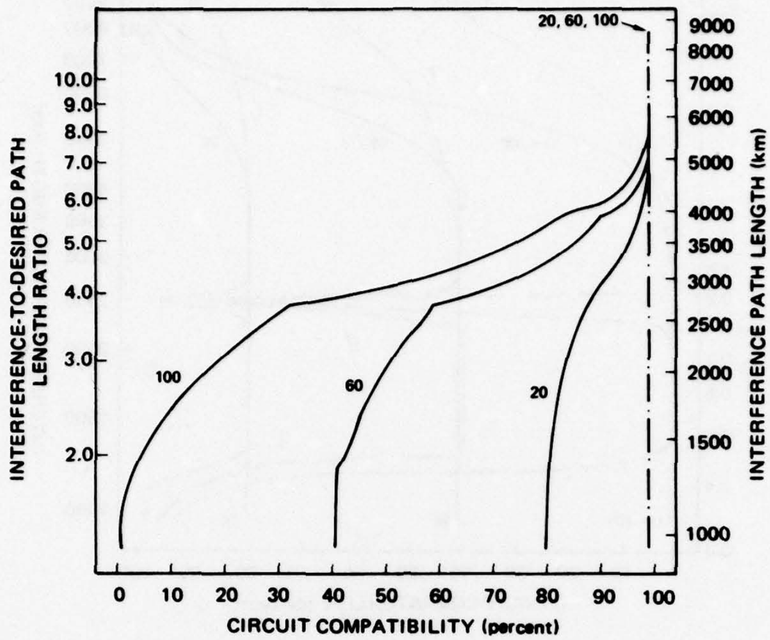

Figure 8. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Egypt to Beirut, 705 km) - - 1200 GMT, July, sunspot number 50, (– · –) 15 MHz, (–) 9 MHz.

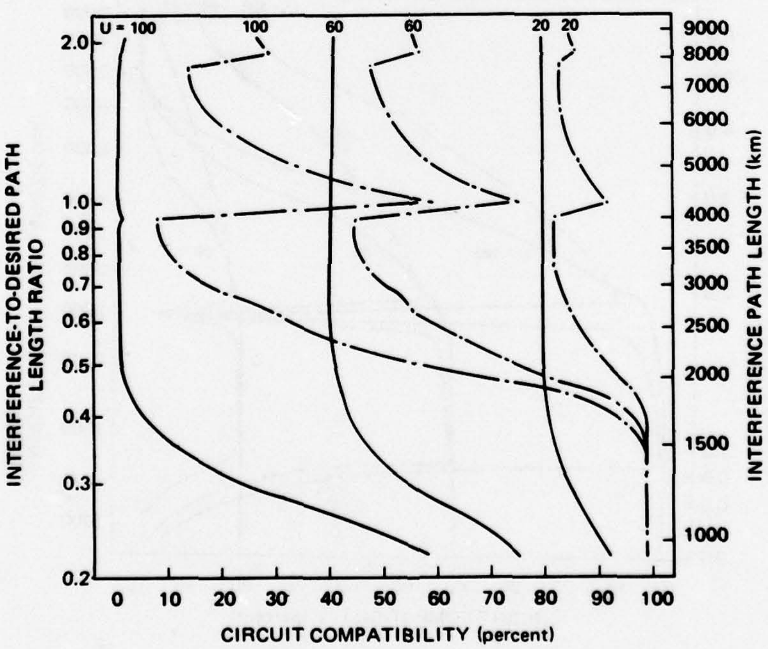

Figure 9. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Upper Volta to Beirut, 4239 km) - - 2400 GMT, July, sunspot number 50, (– · –) 15 MHz, (–) 9 MHz.

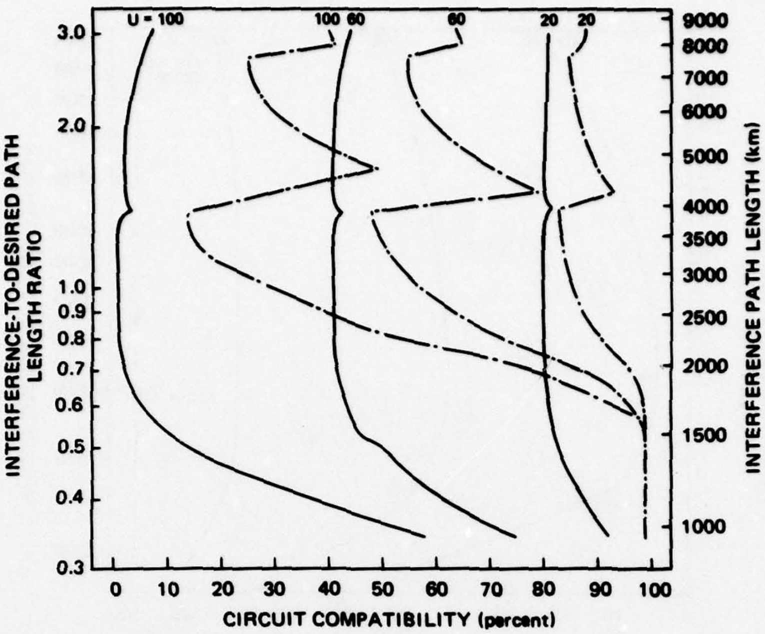

Figure 10. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Nigeria to Beirut, 2826 km) - - 2400 GMT, July, sunspot number 50, (– · –) 15 MHz, (–) 9 MHz.

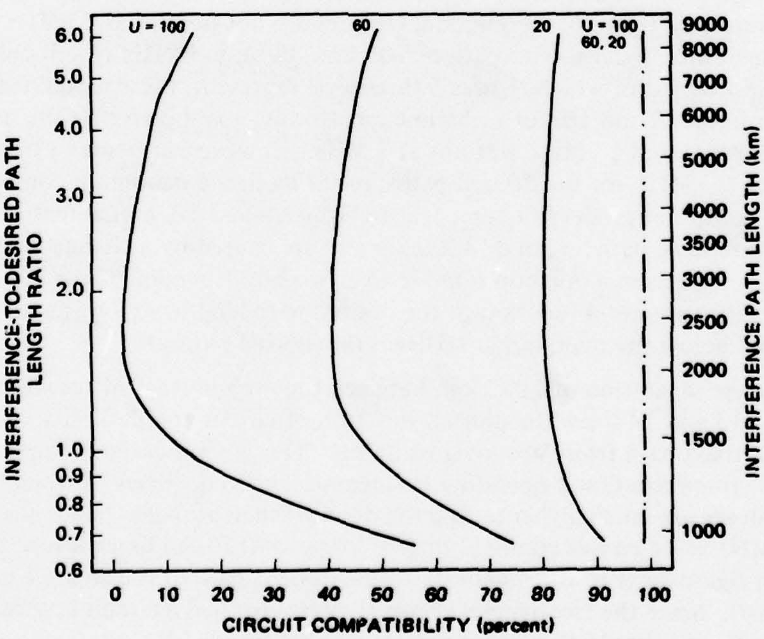

Figure 11. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Libya to Beirut, 1413 km) - - 2400 GMT, July, sunspot number 50, (– · –) 15 MHz, (–) 9 MHz.

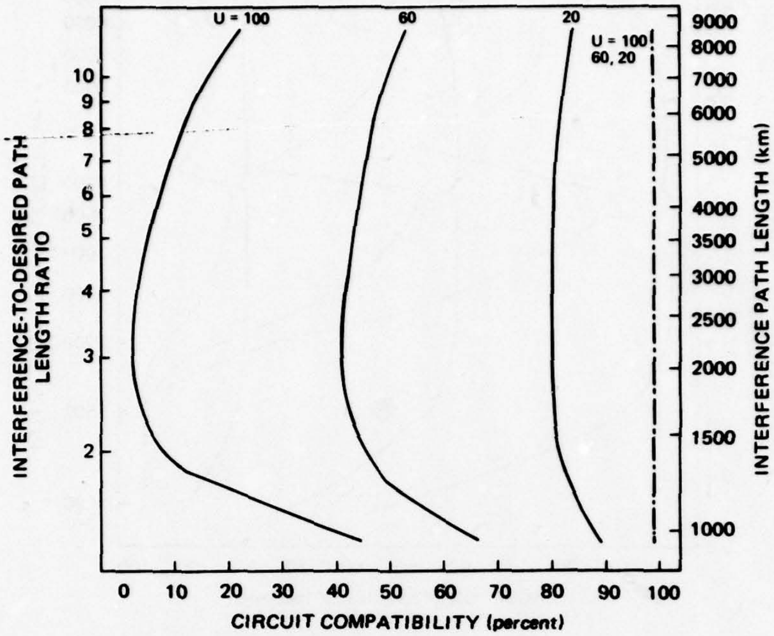

Figure 12. Effects of channel usage U (in percent) on circuit compatibility for a mobile service path with a fixed service path (Egypt to Beirut, 705 km) – – 2400 GMT, July, sunspot number 50, (– - –) 15 MHz, (–) 9 MHz.

a two hop F mode). In figure 8, these modal features are not present as 15 MHz is above the MUF on the desired fixed service path of 705 km. Because 9 MHz is well below the MUFs for the desired paths, which figures 5 through 8 represent, these modal features are not present. In figures 9 and 10, for nighttime conditions, it is shown that the modal features are still present at 15 MHz, but not at 9 MHz. However, in figures 11 and 12, 15 MHz is above the MUF for the desired paths, resulting in the maximum compatibility allowed by the computer model (99 percent). In figures 9 and 10, modal features begin at about an interference path length of 4200 km and are caused by a change in the dominant interfering mode from a one hop F mode to a two hop F mode. These increases in circuit compatibility are not a function of the desired path length, so long as the operating frequency is well below the operational MUF on the desired path.

For a range separation of 2092 km, between the mobile transmitter and the fixed receiver, figures 13 and 14 show the diurnal variation of circuit compatibility of the mobile service with the fixed path from Monrovia to Beirut. This is a function of the interfering channel usage U (in percent) and operating frequency. The frequencies of which interference could be of concern are much higher during the daytime than at night. Since the frequencies 5 through 13 MHz had a circuit compatibility of 99 percent for all usage levels, they were not included in figure 13 (i.e., the reliability of the desired path in the absence of interference was zero). Since the frequencies above 17 MHz also had a circuit compatibility of 99 percent for all usage levels, they were not included in figure 14.

At a fixed usage level, figures 12-14 show the higher frequencies to be most compatible. The two lowest frequencies on both figures have a circuit compatibility of 100-U percent. Above these frequencies, the ratio of probability that the operating frequency on the desired path will be below the MUF on both paths, to the probability that the

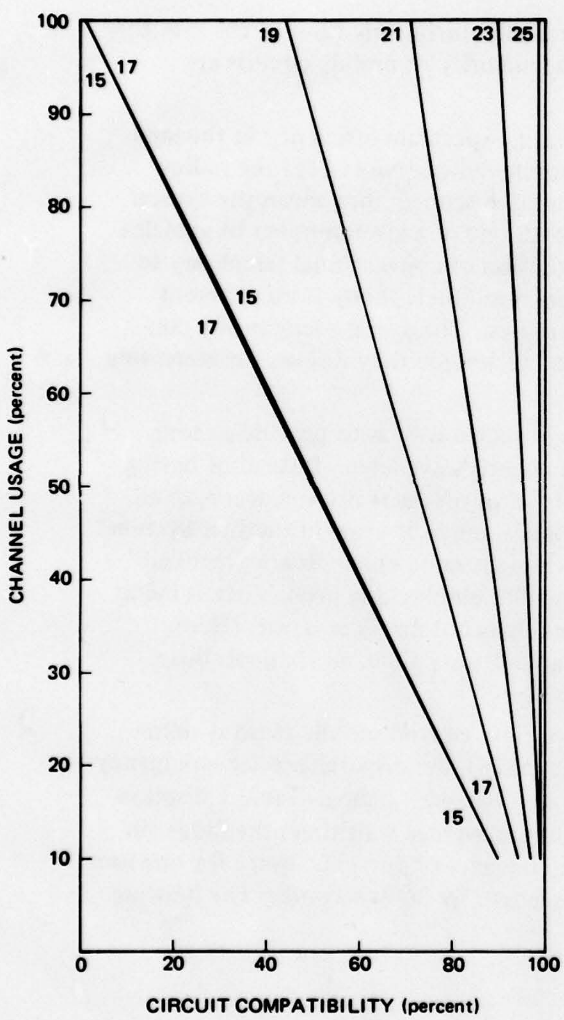

Figure 13. Circuit compatibility as a function of channel usage and of frequency for a mobile service path with its transmitter at a fixed distance (2092 km) from a fixed service receiver (Monrovia to Beirut) - - 1200 GMT, July sunspot number 50.

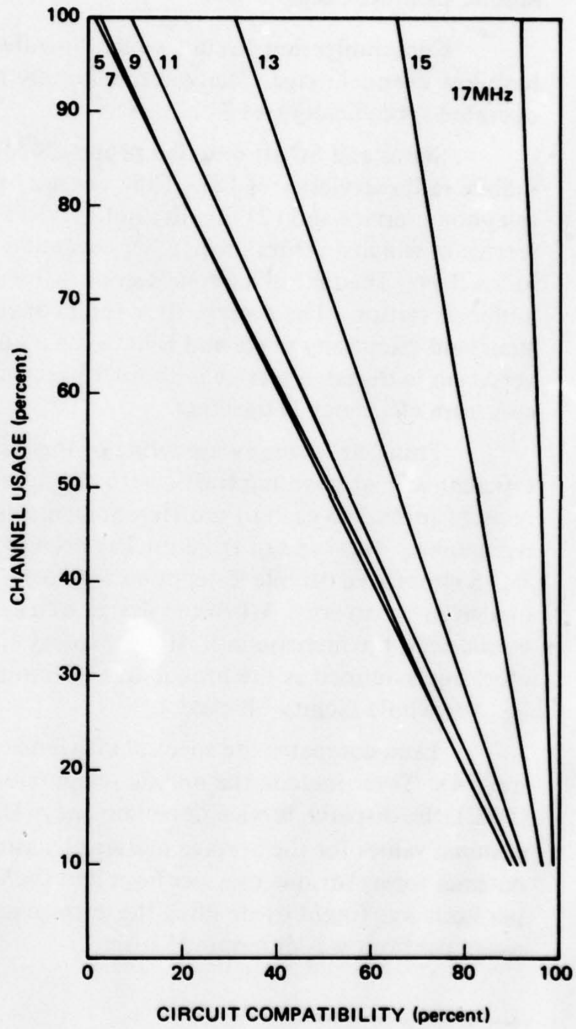

Figure 14. Circuit compatibility as a function of channel usage and of frequency for a mobile service path with its transmitter at a fixed distance (2092 km) from a fixed service receiver (Monrovia to Beirut) – – 2400 GMT, July, sunspot number 50.

operating frequency will be below the MUF on the desired path, begins to approach zero as the frequency is raised. In figure 13, for instance, the MUF on the desired path was 20.8 MHz. Here, the curves for 23 MHz and 25 MHz show little interference, as would be expected.

These two figures provide a valuable relationship. If the circuit compatibility q′ (U′) is known for a usage level of U′, then the circuit compatibility for any other usage level U (in percent) is given by,

$$q'(U) = \left\{ 1 - \frac{U}{U'} \left[1 - \frac{q'(U')}{100} \right] \right\} \times 100 \qquad (3)$$

Mobile Channel Usage

Communication circuits which operate sporadically during any hour of the month have low channel usage. Many authors imply that the majority of mobile circuits are operated sporadically (ref 3, 12).

Staras and Schiff describe proposals for increasing spectrum efficiency in the land mobile radio services (ref 13). They consider two mobile radio services: (1) the radiotelephone service and (2) the dispatch service. By dispatch service, they mean the typical service in which a central dispatcher communicates with one of a given number of vehicles in his fleet. The radiotelephone service is just an extension of conventional telephony to a mobile station. The average time for a conversation in radiotelephony is no different than land telephony usage and is between 3 and 4 minutes. The average length of a conversation in dispatch service is about 15 seconds. One technique they discuss for increasing spectrum efficiency is trunking.

Trunking is simply a pooling of the facilities in such a way as to provide a more efficient way of handling traffic with the number of channels available. Instead of having N users applied to each of n different channels, the total of nN users is given access to all n channels. This type of trunking has been in use for a number of years in the Bell System IMTS (Improved Mobile Telephone Service), in which eight radio channels are "trunked" in a given urban area. When the design of a system with high blocking probability is being considered, the increase in traffic capability for trunking is not nearly so great. (Here, blocking is defined as the probability of finding, at an arbitrary time, all channels busy, i.e., the whole facility blocked.)

Lane compares the spectral efficiencies of a variety of land mobile radio systems (ref 14). These include the mobile telephone service (MTS), the dispatch service-emergency (DSE), the dispatch service nonemergency (DSNE), and one-way paging. Table 1 displays nominal values for the average message length, maximum average wait time, the usage (in decimal form) for one user per hour and the limiting usage per hour. The usage for one user per hour was found by dividing the average message length by 3600 seconds. The limiting usage per hour was determined from,

[12] Utlaut WF, Spread-spectrum Principles and Possible Application to Spectrum Utilization and Allocation, Telecommunications Journal, Vol 45, p 20-32, January 1978.

[13] Staras H and Schiff L, Spectrum Conservation in the Land Mobile Radio Services, IEEE Spectrum, Vol 8, p 28-36, July 1971.

[14] Lane RN, Spectral and Economic Efficiencies of Land Mobile Radio Systems, IEEE Trans. Vehicular Technology, Vol VT-22, p 93-103, November 1973.

$$U = \frac{W_{AQ}(\infty) / \ell}{1 + (W_{AQ}(\infty) / \ell)} \qquad (4)$$

where, $\overline{w}_{AQ}(\infty)$ is the average waiting time for $N \rightarrow \infty$ users and $\bar{\ell}$ is the average message length. Equation (3) is based on equation (19) of Crow (ref 15). The table also includes the mean and standard deviation of these parameters.

Table 1. Service parameters for land mobile radio systems (ref 14).

Service	Average message length (seconds)	Maximum average wait time (seconds)	Usage (N = 1 users per hour)	Usage (limiting usage per hour)
Mobile telephone (MTS)	140	3	0.039	0.021
Dispatch service emergency (DSE)	30	5	0.009	0.143
Dispatch service nonemergency (DSNE)	30	20	0.009	0.40
One-way paging (OWP)	30	300	0.009	0.909
Mean	57.5	82	0.017	0.368
Standard deviation	55	145.5	0.015	0.116

It is evident upon examination of table 1, that there is relative inefficiency of the MTS compared to the other services. This is precisely why trunking is utilized. Using figure 4 of reference 13 and a blocking probability of 0.02, eight channels will carry an approximate load of 0.44 Erlangs per frequency (ref 14). There is an economic cost to be considered for such a system; namely, each mobile unit must carry radio equipment that can be switched among the n channels. Moreover, spectrum space must be allowed for each channel.

[15] Office of Telecommunications Telecommunications Research and Engineering Report 40, Effect of Variability in Received Power on Probabilities of Communication and Delay in Land Mobile Communication Systems, by EL Crow, December 1972.

The inefficiency of the MTS occurs for two major reasons. First, the users are untrained in the use of the system. Because of this, they cannot be expected to cooperate in making a more efficient system (i.e., shorter messages, longer wait time). Second, the average length of a conversation is due partly to the first reason and partly to the nature of the conversations. Whereas, the operation of the dispatch service in a given local is a kind of organized anarchy. Each potential user does not try to get on the air until the conversation in progress at the time is terminated, and they keep their conversations as short as possible.

Hagn and Dayharsh (ref 16) have presented land mobile spectrum utilization data for several catagories of land mobile users. (These categories were prescribed by the FCC in one of its notices of inquiry.) This data, along with estimates of usage (in decimal form), are given in table 2. The mean usage is 0.303; the maximum and minimum usage are 0.781 and 0.107, respectively.

Table 2. Land mobile spectrum utilization (ref 15).

Categories	Radio service	Frequency (MHz)	Message duration (seconds)	Message waiting time (seconds)	Usage (N = 1 users per hour)	Usage (limiting usage per hour)
Category I	Police	154.950	10.3	17.0	0.003	0.622
	Police	155.490	8.2	2.9	0.002	0.259
	Police	156.210	10.2	6.9	0.003	0.408
	Fire	154.130	6.7	1.3	0.002	0.160
	Fire	154.340	6.3	0.77	0.002	0.107
Category II	Special Emergency	155.220	9.2	5.4	0.003	0.371
	Special Emergency	155.220	7.8	2.2	0.002	0.218
Group A	Local Government	155.085	6.8	0.63	0.002	0.130
	Local Government	158.760	11.2	1.3	0.003	0.107
Category II	Power	153.410	9.3	6.0	0.003	0.394
	Power	153.410	9.7	6.0	0.003	0.382
Group B	Power	153.575	19.8	13.5	0.006	0.405
	Railroad	160.650	11.8	2.5	0.003	0.174
	Railroad	160.890	10.0	2.2	0.003	0.180
Category II	Special Industrial	151.535	8.9	3.2	0.002	0.265
	Special Industrial	452.	10.0	3.9	0.003	0.285
Group C	Motor Carrier	159.585	15.7	4.3	0.004	0.213
	Motor Carrier	159.900	11.1	3.7	0.003	0.248
	Business	461.325	27.2	30.8	0.008	0.538
	Business	461.375	27.6	98.2	0.008	0.781
	Petroleum	153.350	8.7	1.1	0.002	0.115
Mean			11.7	10.2	0.003	0.303
Standard deviation			6.0	21.4	0.002	0.179

16. Hagn GH and Dayharsh TI, Land-Mobile Radio Communication Channel Occupancy, Waiting Time, and Spectrum Saturation, IEEE Trans. Electromagn. Compat., Vol EMC-19, p 281-284, August 1977.

Thus far, it has been assumed that all users of a service have more or less similar characteristics (are homogeneous) and that the traffic generated by a user is independent of both the number and the characteristics of other users sharing the channel. In practice, the traffic generated by a user will decrease as more users are added. In addition, there is a wide variation in traffic characteristics among different users in a single service. Felperin, et al. (ref 17), and Hagn and Dayharsh (ref 18) have examined the uniformity of mobile land users. Felperin only considered the correlation in average channel occupancy; whereas, Hagn and Dayharsh also considered the correlation in general waiting time. These results are summarized in table 3 for the same services as were given in table 2. Based on

Table 3. Characteristics of the different services (ref 16, 17).

Category/ Group	Service	Uniformity	Characteristics	Correlation Coefficient of average occupancy
I	Police	Poor	mixed	0.002
	Fire	Poor (very high)	below average use	-0.322
II-A	Special emergency	Good	below average use	0.606
	Local government	Poor (high)	below average use	0.051
II-B	Power	Power	–	-0.09
	Railroad	Fair (good)	mixed	0.245
II-C	Special industrial	Fair (high)	above average use	0.312
	Motor carrier	Poor	mixed	-0.236
	Business	Good	well above average use	0.644
	Petroleum	Good (high)	below average use	0.848

Felperin, a subjective estimate of the uniformity is given in table 3. A value in parentheses is given if the estimate in Hagn and Dayharsh differs. Also given, are the characteristics of the service and the correlation of the average occupancy. Those services ranking high are probably characterized by users having fairly homogeneous operational characteristics. This homogeneity may be due to a fairly tightly defined communications mission, or to the very large number of assignments per channel, effectively smoothing out mission related differences.

The Joint Technical Advisory Committee (JTAC) of the IEEE was presented case histories of urban area radio spectrum usage (ref 19). Table 4 summarizes the results (in decimal form) for the hour of peak usage. The mean usage of the mobile units is 0.54. The JTAC also shows that there is considerable diurnal variation in usage.

17. Stanford Research Institute Project 8652, Final Report – Volume II, National and Regional Spectrum Management Planning Assistance, by KD Felperin, PD Shaft, TL Humphrey, OS Yu, and TJ Yung, February 1971.

18. Stanford Research Institute Project 8652-1, Final Report, Technical Assistance for the FCC National and Regional Spectrum Management Program, by GH Hagn and TI Dayharsh, January 1973.

19. Joint Technical Advisory Committee of the IEEE, Spectrum Engineering – the Key to Progress, Supplement 5, IEEE, March 1968.

Table 4. Urban area radio spectrum usage – case histories.

Service	Average transmission length (seconds)	Peak average wait time (seconds)	Peak usage (limiting usage per hour
FAA - Local Control Channel (118.9 MHz	14.8	22.5	.60
US Coast Guard Search and Rescue Operations (157.1 MHz)	32.0	39.4	.45
Special Industrial Radio Mobile-to-Base (450 MHz)	38.0	68.0	.64
Los Angeles City Police Mobile Units (150 MHz)	25.0	22.0	.47
Fire Services (150 MHz)			
Los Angeles City	14.4	6.2	.3
Los Angeles County	16.6	6.6	.286
Los Angeles County Sheriff (40 MHz) Mobiles	15.0	60.0	.8
Orange County Law Enforcement (45 MHz) Mobiles	10.0	40.0	.8
Mean	20.73	29.33	.54
Standard Deviation	9.88	24.21	.20

So far as hf frequency sharing is concerned, the operational conditions for the mobile services are as important as frequency in determining the average message length and peak waiting times (i.e., the channel usage). In the case of the mobile telephone service, since the CCIR recommends maintaining the quality of the landline service, the usage factors will still hold at hf (ref 20). In addition, the uniformity and the diurnal variation of the average hourly usage are important.

20. International Radio Consultative Committee 13th Plenary Assembly, Geneva, 1974, Recommendation 77-2; Conditions Necessary for Interconnection of Mobile Radiotelephone Stations and International Telephone Lines, International Telecommunications Union, Geneva, 1975.

MAJOR FACTORS OF INTERFERENCE

The hf spectrum of concern for interference is dependent on the following major factors:

- channel usage of the interfering service,
- the relative lengths of the desired and interfering paths,
- solar activity and environmental conditions, and
- the assigned frequency itself.

The minimum value of circuit compatibility is determined by the channel usage U. In the previous section, the minimum value of circuit compatibility (in percent) was found to be given by 100–U. Here, the maximum value of circuit compatibility is a function of the desired path length, the interference path length, the time of day, season and solar cycle variations, and the operational frequency as well as channel usage. In this section, figures presented are for a channel usage of 100 percent. Equation (3) can be used to obtain effects for other values of channel usage.

PATH ATTENUATION EFFECTS

Several additional features, less dependent on channel usage, are evident in figures 5 through 12. These relate primarily to attenuation on the desired and interference paths. First, in figures 5–7, as in figure 2 at 15 MHz, an increase in circuit compatibility is shown at a range ratio greater than one. In this case, the attenuation is greater on the interference path than on the desired path. In figure 5, the circuit compatibility of 9 MHz is shown to be 99 percent for all usage values; the attenuation on the desired path was so great that the potential interference was of no concern. In figures 6 through 8, the circuit compatibility is shown to increase at 9 MHz at a range ratio greater than two. Beyond this range, the circuit compatibility increases much faster at 9 MHz than at 15 MHz, due to the increased D-region absorption at 9 MHz. In figures 9 through 12, it is shown that at 9 MHz a large value of the interference-to-desired path range ratio is required to cause the circuit compatibility to increase significantly. This occurs, because at night the only important source of attenuation is free space loss which is not as sensitive to distance changes as is the daytime D-region absorption.

SEASONAL AND SOLAR CYCLE EFFECTS

The data were evaluated to determine the seasonal and solar cycle variations on circuit compatibility. Figures 15 and 21 are for sunspot number 10 and for 1200 GMT. Figures 16 and 22 are for sunspot number 50. Figures 17 and 23 are for sunspot number 110 and 1200 GMT. Figures 18 and 24 are for sunspot number 10 and 2400 GMT. Figures 19 and 25 are for sunspot number 50 and 2400 GMT. Figures 20 and 25 are for sunspot number 110 and 2400 GMT. Figures 15 through 20 are for January, while figures 21 through 26 are for July.

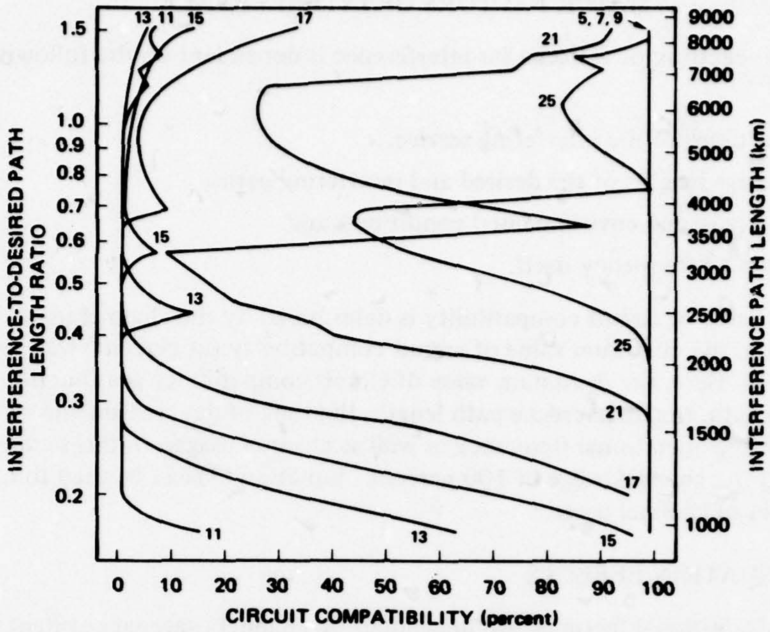

Figure 15. Effects of seasonal and solar cycle variations or circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - January, sunspot number 10, 1200 GMT, U = 100%, fixed service MUF = 24.3 MHz.

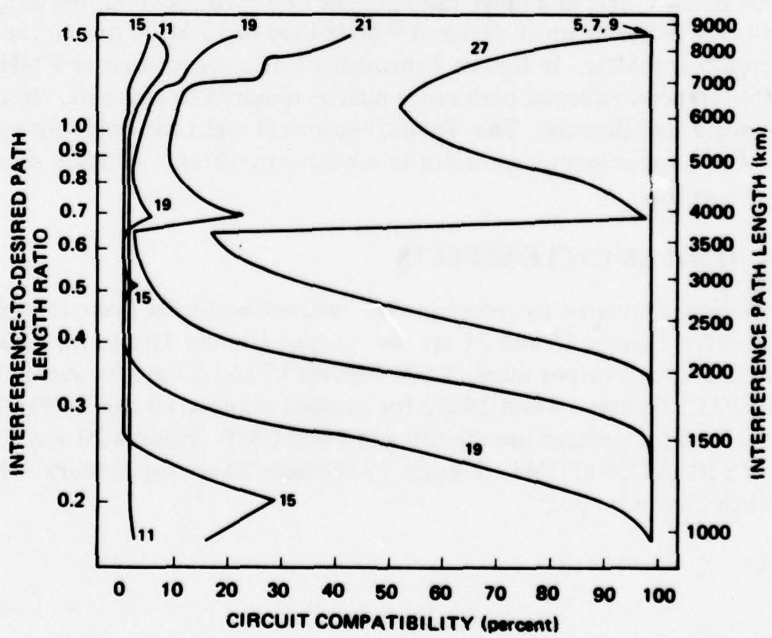

Figure 16. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - January, sunspot number 50, 1200 GMT, U = 100%, fixed service MUF = 28.1 MHz.

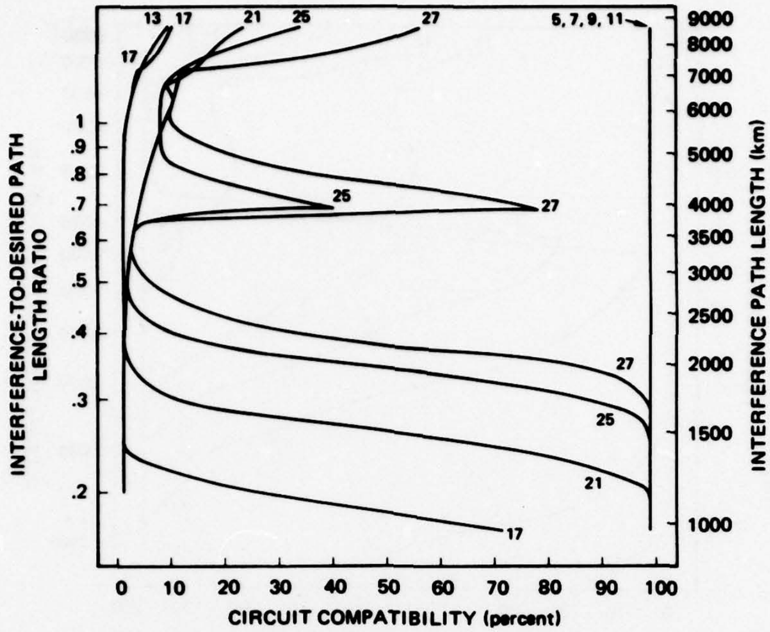

Figure 17. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - January, sunspot number 110, 1200 GMT, U = 100%, fixed service MUF = 31.1 MHz.

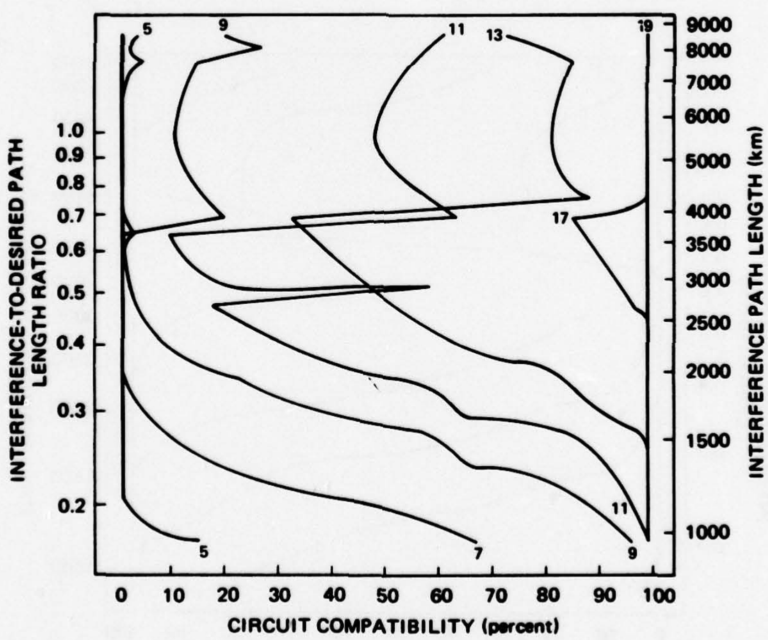

Figure 18. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - January, sunspot number 10, 2400 GMT, U = 100%, fixed service MUF = 12.3 MHz.

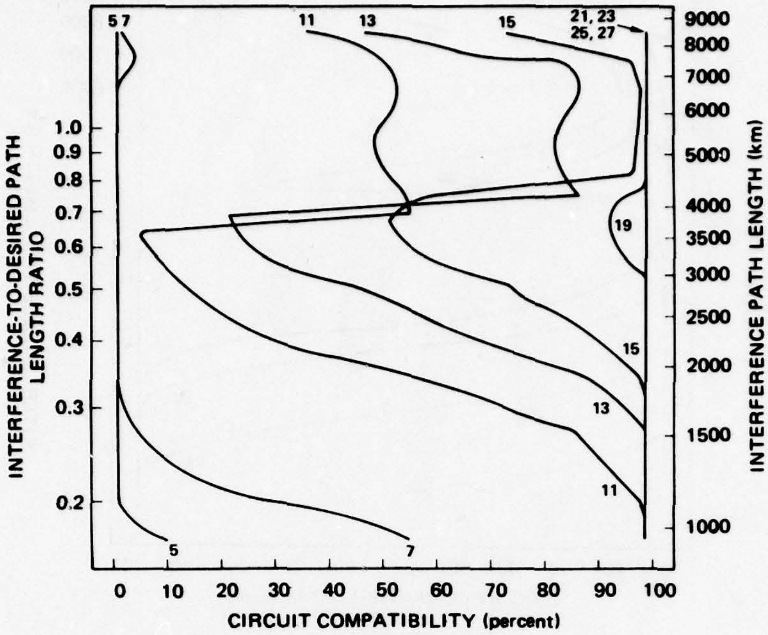

Figure 19. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - January, sunspot number 50, 2400 GMT, U = 100%, fixed service MUF = 14.3 MHz.

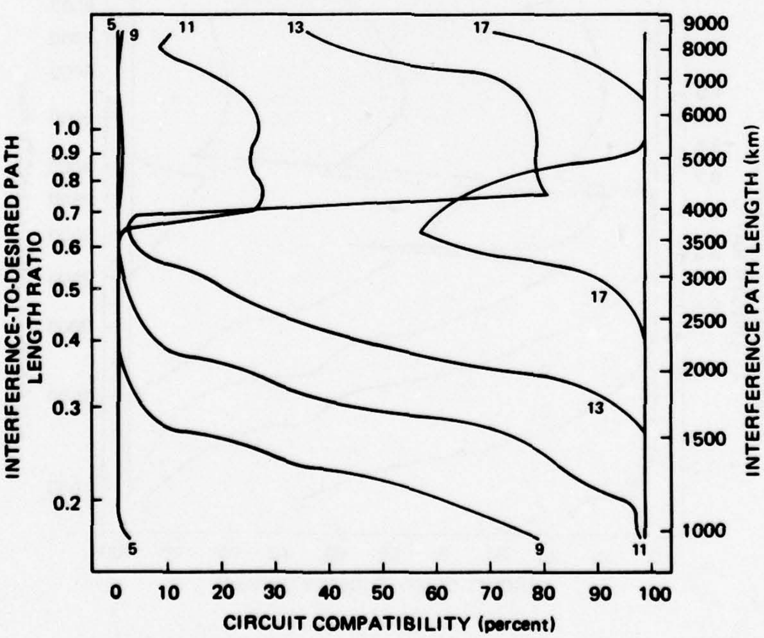

Figure 20. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - January, sunspot number 110, 2400 GMT, U = 100%, fixed service MUF = 18.3 MHz.

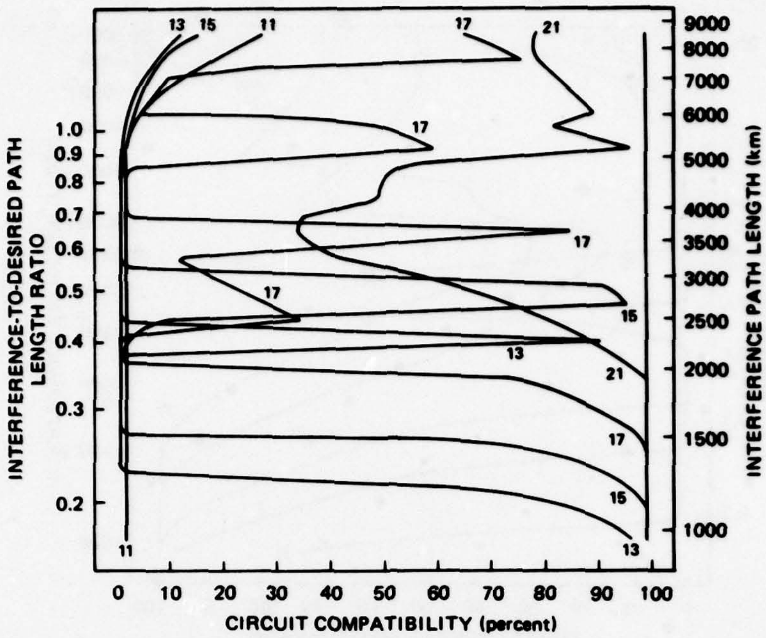

Figure 21. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - July, sunspot number 10, 1200 GMT, U = 100%, fixed service MUF = 17.4 MHz.

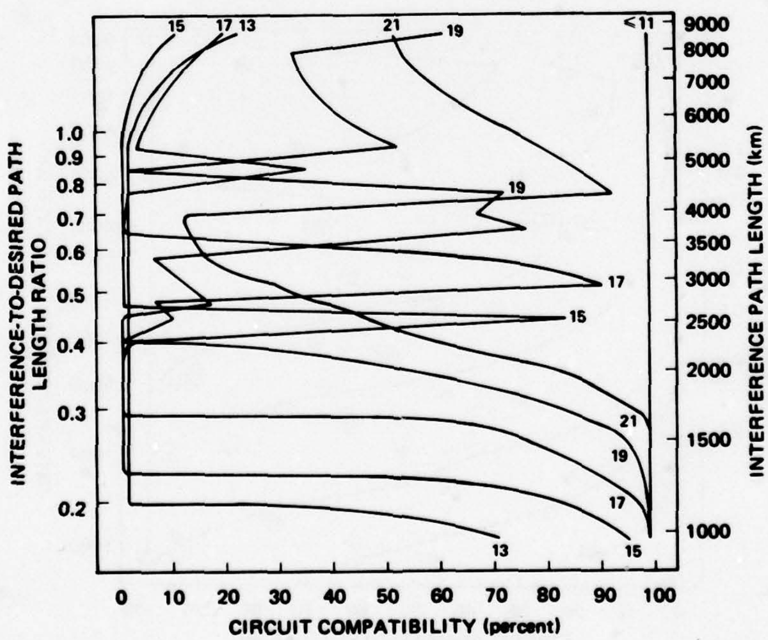

Figure 22. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - July, sunspot number 50, 1200 GMT, U = 100%, fixed service MUF = 20.8 MHz.

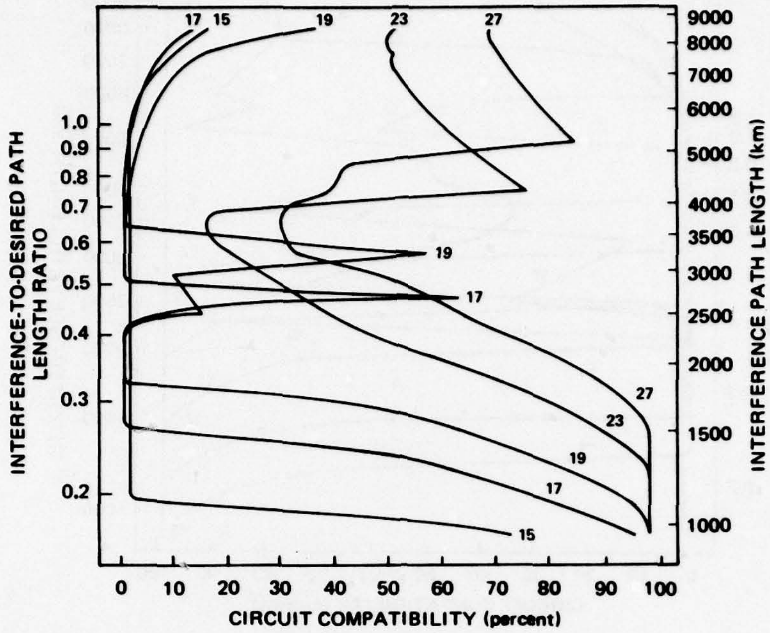

Figure 23. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - July, sunspot number 110, 1200 GMT, U = 100%, fixed service MUF = 25.2 MHz.

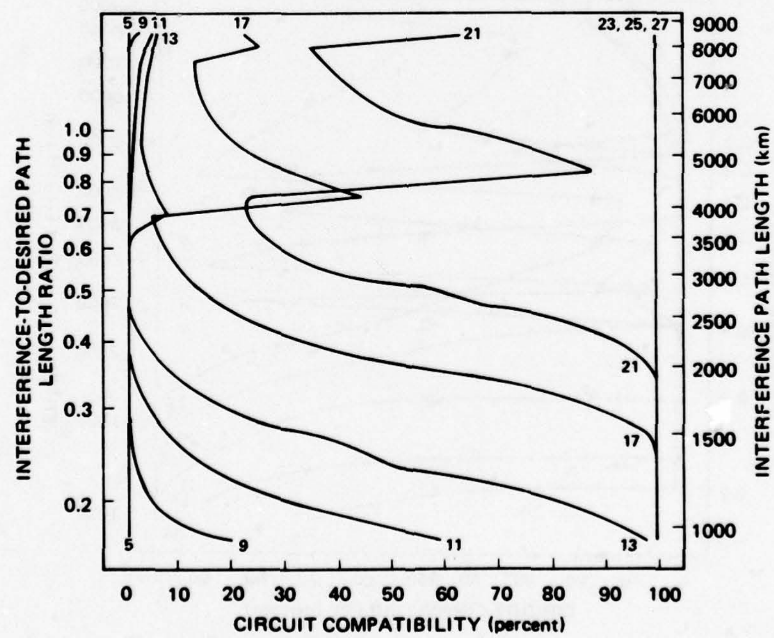

Figure 24. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - July, sunspot number 10, 2400 GMT, U = 100%, fixed service MUF = 11.1 MHz.

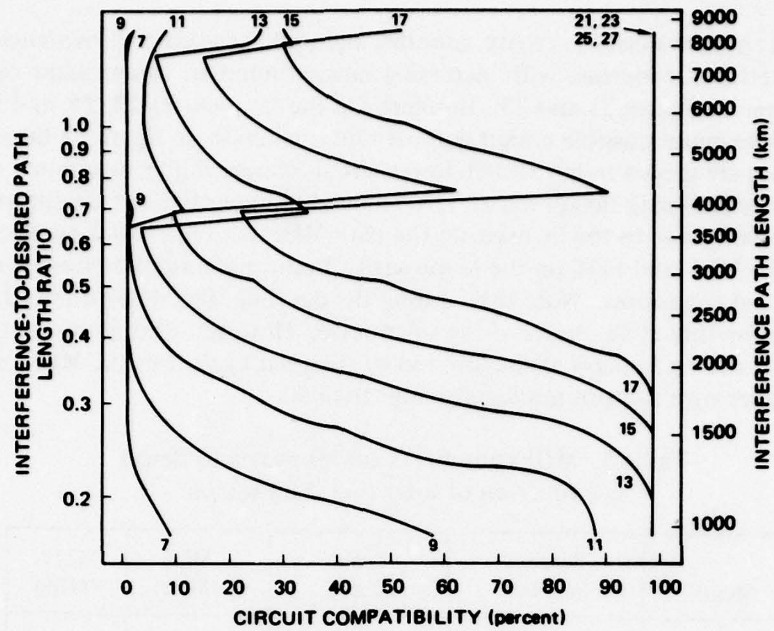

Figure 25. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - July, sunspot number 50, 2400 GMT, U = 100%, fixed service MUF = 16.0 MHz.

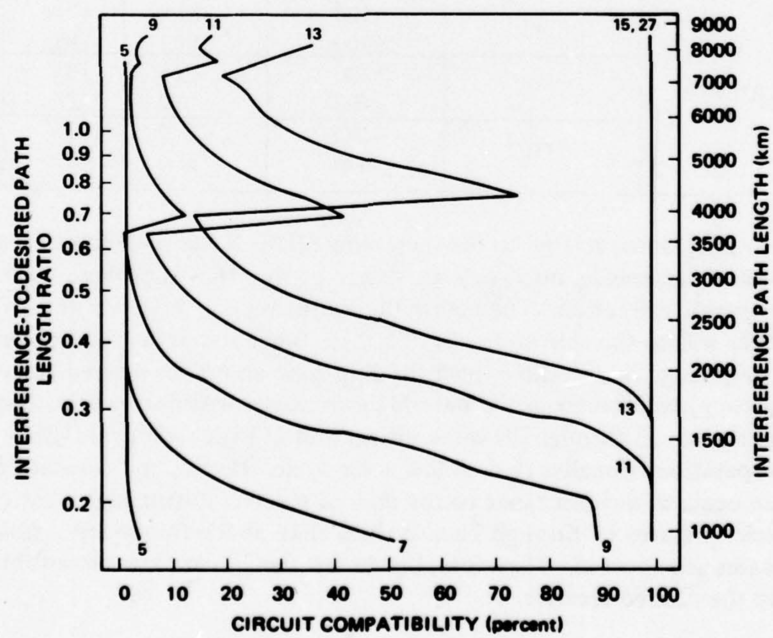

Figure 26. Effects of seasonal and solar cycle variations on circuit compatibility for a mobile service path with a fixed service path (Monrovia to Beirut) - - July, sunspot number 110, 2400 GMT, U = 100%, fixed service MUF = 21.6 MHz.

For the specific sunspot activity, months, and paths studied the frequencies of concern for interference increase with increasing sunspot number. An example of this effect can be seen in figures 21 and 23. In figure 21, the frequencies 23, 25, and 27 MHz have the maximum possible circuit compatibility; whereas, in figure 23 these same frequencies are shown to have much lower circuit compatibility over much of the interference-to-desired path length ratio. This increase in upper limit of the interference potential is primarily due to the increase on the path MUF with increasing sunspot number. Table 5 gives the MUF and FOT on the Monrovia to Beirut path as a function of solar cycle and seasonal conditions. Note that, during the daytime, the MUFs during January are higher than for July at all phases of the solar cycle. However, during the night the MUFs are higher during January at the low end of the solar cycle, but the MUFs at night for July are higher with sunspot numbers greater than 50.

Table 5. MUFs and FOTs for Monrovia to Beirut as a function of solar cycle and season.

Month	Sunspot number	Time (GMT)	MUF (MHz)	FOT (MHz)
JAN	10	1200	24.3	18.2
		2400	12.3	9.6
	50	1200	28.1	21.1
		2400	14.3	11.2
	110	1200	31.1	27.7
		2400	18.3	14.2
JULY	10	1200	17.4	17.1
		2400	11.1	8.6
	50	1200	20.8	18.2
		2400	16.0	12.3
	110	1200	25.2	21.7
		2400	21.6	17.5

An important factor related to the increasing MUFs is the so-called skip distance or skip zone. Within this distance, no signals are received from the ionosphere by the regular process of ionospheric refraction. The higher the frequency, or the lower the critical frequency, the larger will be the skip zone (refs 21, 22). Since the path MUF is proportional to the critical frequency, one would expect the skip zone about the desired receiver (at a particular frequency) to decrease as the path MUF increases with increasing sunspot number. Examination of figures 15 through 26 will confirm that at high solar cycle (SSN=110), the skip zone separation is smaller than at low solar cycle. Hence, at a constant frequency, interference can occur at a closer range to the desired receiver during high solar cycle than at low solar cycle. Figures 15 through 26 also show that, as the frequency is raised, the skip zone increases as expected. Therefore, higher frequencies are less susceptible to interference close to the desired receiver.

[21] Rower K, The Ionosphere, 1st ed., p 155, Frederick Ungar Publishing Co., 1952.

[22] Davies K, Ionospheric Radio Propagation, 1st ed., p 172-173, U.S. Government Printing Office, 1965.

The time availability of the interfering modes is affected by the change in solar cycle. The time availability of an F mode is determined by the relationship of the operating frequency to the mode MUF. If the mode MUF increases with increasing sunspot number, as it does, then the time availability of an F mode will increase at a constant operating frequency so long as the mode is geometrically possible. This has a direct bearing on the probability of interference. Earlier, it was observed that an increase in compatibility could occur if a change in the dominant interfering mode occurred (from a one hop E mode to a two hop F mode, or from a one hop F mode to a two hop F mode). The results of this particular effect were quite dramatic, particularly so, when the dominating interfering mode changed from an E mode to the 2 hop F mode.

For example, observe the results illustrated in figures 21 through 23 at 15 MHz, the frequency discussed earlier in connection with figure 2. In these figures, except figure 23, a mode change is illustrated for an interfering transmitter placed at about 2500 km from the desired receiver. With increasing sunspot number, the circuit compatibility decreases at this range. In fact, in figure 23 the peak is not present; no mode change occurs. The effect at 17 MHz is even more dramatic. In figure 21, illustrated for sunspot number 10, there are four mode changes. In figure 22, at a sunspot number of 50, there are three mode changes. In figure 23, at a sunspot number of 110, there is only one mode change. In each of these figures, at 15 and 17 MHz, the mode change at about 2500 km was from a one hop E mode to either a one or two hop F mode and then to a two hop E mode. At 15 MHz, at sunspot number 110, the dominating mode was a two hop E mode.

A contrasting example is given in figures 16 and 17 at 21 MHz, with an interferer in the range from 3600 km to 5200 km. In figure 16, for sunspot number 50, a mode change is shown; the interfering mode changes from a one hop F mode to a 2 hop F mode. In figure 17, for sunspot number 110, no change in circuit compatibility is shown at 21 MHz in this range. Examination of the computer output shows that a mode change did occur, but its time availability did not change. Hence, in general, beyond the skip zone of the desired receiver, at a constant frequency, the circuit compatibility is less dependent on the range of the interferer at sunspot number 110 than at sunspot number 10, due to a decreased number of dominant interfering modes and the increased time availability of these modes.

On the other hand, at a constant frequency, the compatibility is slightly lower at high sunspot number, particularly during the daytime when there is an increase in D-region absorption. This effect is illustrated in figures 15 and 17, where the frequency 17 MHz is less compatible at sunspot number 110 than at sunspot number 10 with interference-to-desired path range ratios greater than 1.0.

There is a broad region of high compatibility for all frequencies above the FOT, given in table 5, for interferers located beyond 5000 km. At night, as shown in figures 18 through 20, this effect becomes strongest during January.

Figures 15–26 show a seasonal dependence on the skip zone, which is related to the path MUF. Those months which have higher MUFs have smaller skip zones. Hence, interference can occur at a closer range in January (in the daytime at all extremes of the solar cycle) than in July. Conversely, at night, with moderate and high levels of solar activity, interference can occur at a closer range in July than in January. In addition, lower compatibilities result beyond the skip zone in the same months, due to the increased availability of the interfering modes.

FIXED-SERVICE PATHS OF DIFFERENT LENGTH

Examples of the effect of interference on fixed service paths of different length are presented in figures 22 and 27 through 30 for daytime, and in figures 25 and 31 through 34 for nighttime.

At a constant frequency, the circuit compatibility increases as the length of the desired circuit decreases. For instance, at 11 MHz and at an interference to-desired path length ratio of 4.0, figure 30 shows (for a desired path of 705 km) a circuit compatibility of 40 percent. In figure 27, for a desired path of 4239 km, this same interferer is located at an interference-to-desired path length ratio of 0.66 (2820 km) and has a circuit compatibility of 1 percent with the same interferer.

The range of frequencies of concern for interference changes as the desired path length changes. As the desired path length decreases, the upper frequency of concern decreases as its MUF decreases with range. This can be seen in figures 27 and 30, for daytime conditions (MUF changes from 27.7 MHz to 10.6 MHz), and in figures 31 and 34 for nighttime conditions (MUF changes from 18.9 MHz to 7.5 MHz). For instance, in figure 27, at 15 MHz and for a desired fixed path of 4239 km, an interferer at a range of 5652 km from the desired receiver (at an interference-to-desired path length ratio of 1.33) has a circuit compatibility of 5 percent; whereas, in figure 30, for a desired fixed path of 705 km, the same interferer is located at an interference-to-desired path length ratio of 8.0 and has a circuit compatibility of 99 percent.

For the lowest frequencies used during the daytime, the circuit compatibility decreases as the desired path length decreases. This occurs because, at the lowest frequencies, the reliability in the absence of interference is zero at the longer ranges; therefore, the frequency is not subject to interference effects. As the desired path length decreases the lowest usable frequency (LUF) decreases, causing lower and lower frequencies to be subject to interference effects. For instance, at 5, 7 and 9 MHz, on the desired path of 4239 km illustrated in figure 27, the circuit compatibility is 99 percent for all interference path lengths; whereas, in figure 30 for a desired path length of 705 km, all three frequencies have much lower circuit compatibilities at a broad range of interference-to-desired path length ratios.

At night, not only does the MUF decrease, causing the circuit compatibility on higher frequencies to rise, but also, the absence of D-region absorption causes the lower frequencies to decrease in circuit compatibility as the desired fixed path length increases. For example, in figure 27 for a desired path length of 4239 km, 5, 7, and 9 MHz have a circuit compatibility of 99 percent during the day. Figure 31 shows these same frequencies, at night and for the same desired path length, to have a circuit compatibility of 1 percent. Also, at night the MUF decreases, causing the circuit compatibility of the higher frequencies to rise. Combined with the decrease in MUF, the effect of a decrease in desired fix path range becomes more dramatic, as can be seen in figures 29 and 33, and in figures 30 and 34.

One very unique effect is shown in figure 29, for a fixed service path of 1413 km, which has a path MUF of 16.3 MHz. For the frequencies 21, 23, and 25 MHz there is a depression in the circuit compatibility centered about an interference path of about 5000 km. This effect can be understood by referring to figure 35, a plot of the desired fixed and interfering path MUFs as a function of range. At about 5000 km, the MUF at 1200 GMT for the interference path is about 22 MHz. Hence, the time availability on the interference path is about 50 percent. On the fixed path the upper decile of the

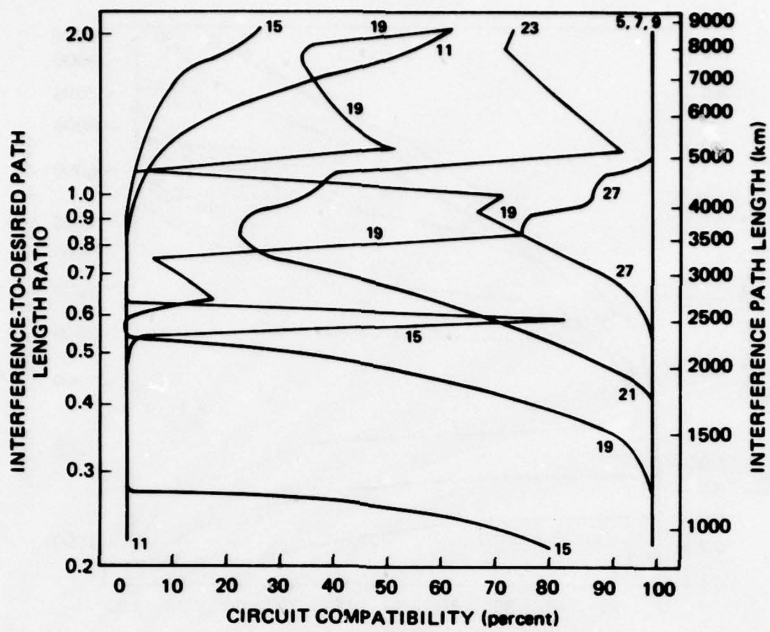

Figure 27. Effects of interference on a fixed service path of 4239 km (Upper Volta to Beirut) - - July, sunspot number 50, 1200 GMT, U = 100%, fixed service MUF = 27.7 MHz.

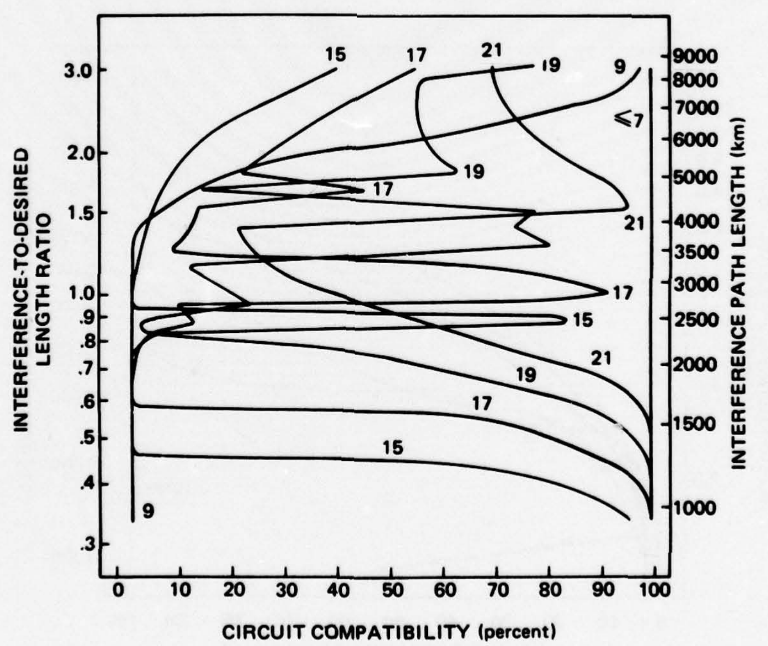

Figure 28. Effects of interference on a fixed service path of 2826 km (Nigeria to Beirut) - - July, sunspot number 50, 1200 GMT, U = 100%, fixed service MUF = 25.9 MHz.

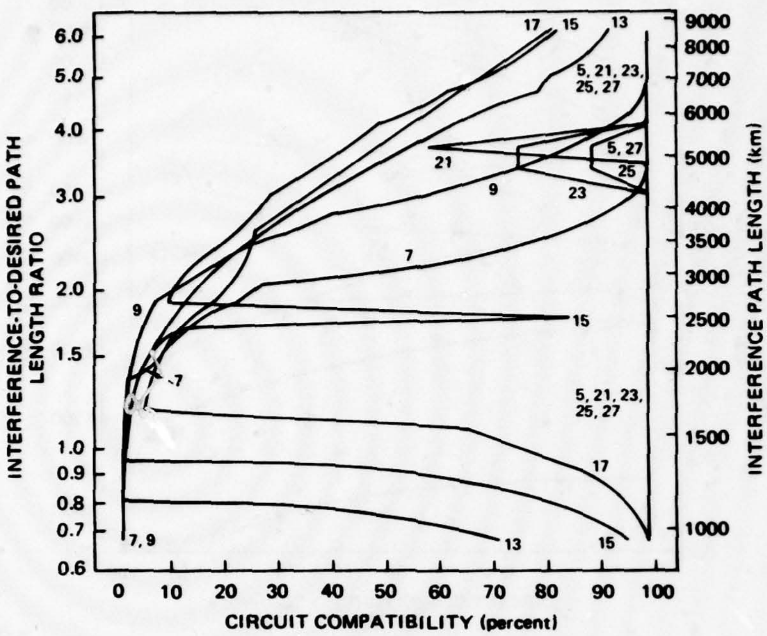

Figure 29. Effects of interference on a fixed service path of 1413 km (Libya to Beirut) - - July, sunspot number 50, 1200 GMT, U = 100%, fixed service MUF = 16.3 MHz.

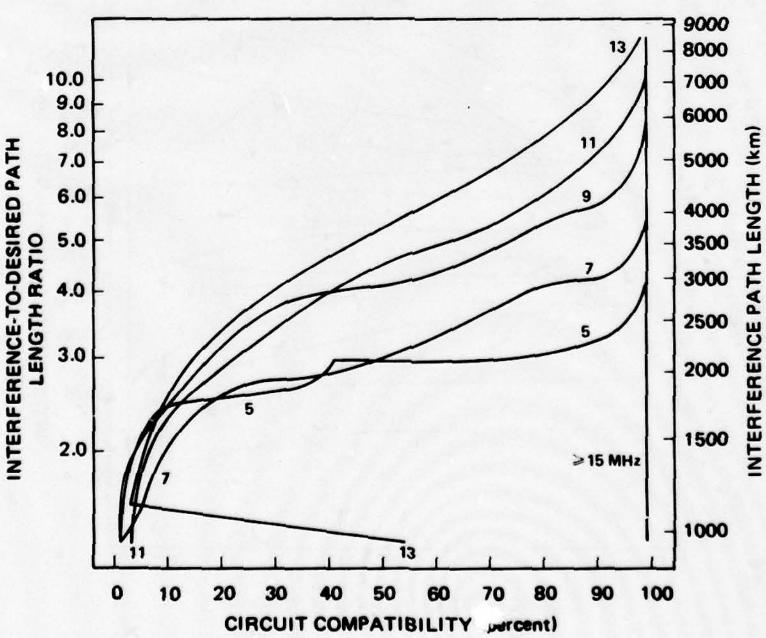

Figure 30. Effects of interference on a fixed service path of 705 km (Egypt to Beirut) - - July, sunspot number 50, 1200 GMT, U = 100%, fixed service MUF = 10.6 MHz.

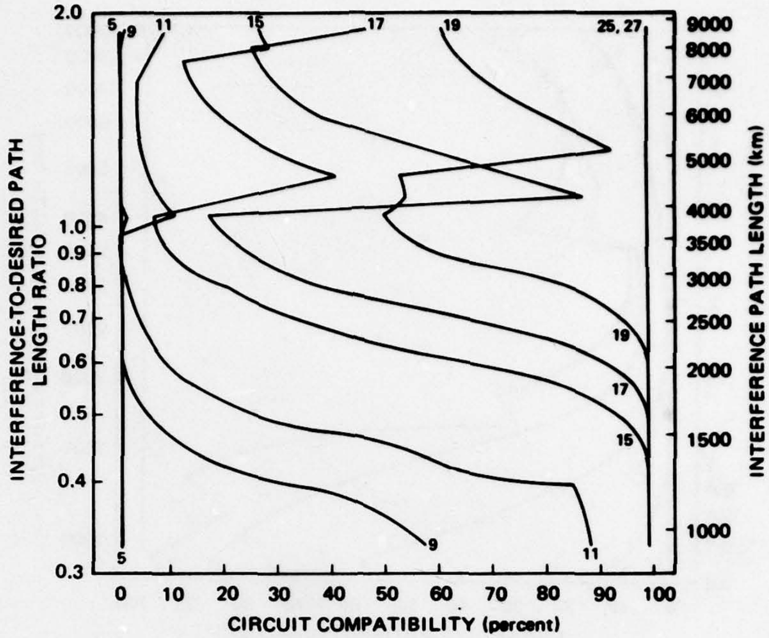

Figure 31. Effects of interference on a fixed service path of 4239 km (Upper Volta to Beirut) - - July, sunspot number 50, 2400 GMT, U = 100%, fixed service MUF = 18.9 MHz.

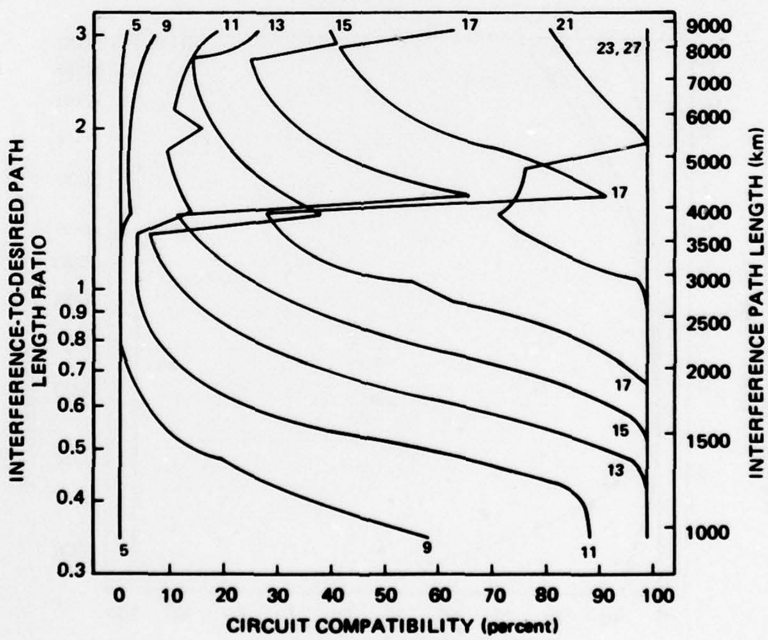

Figure 32. Effects of interference on a fixed service path of 2826 km (Nigeria to Beirut) - - July, sunspot number 50, 2400 GMT, U = 100%, fixed service MUF = 17.3 MHz.

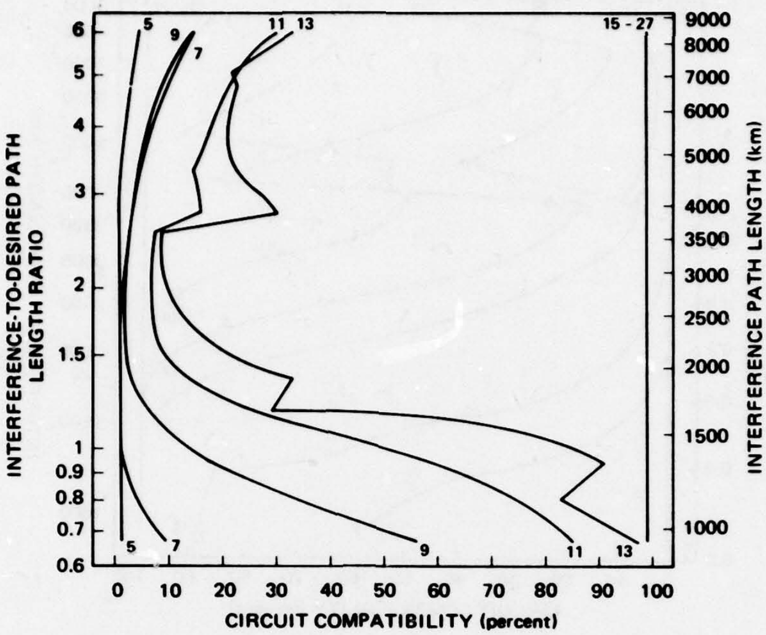

Figure 33. Effects of interference on a fixed service path of 1413 km (Libya to Beirut) - - July, sunspot number 50, 2400 GMT, U = 100%, fixed service MUF = 11.2 MHz.

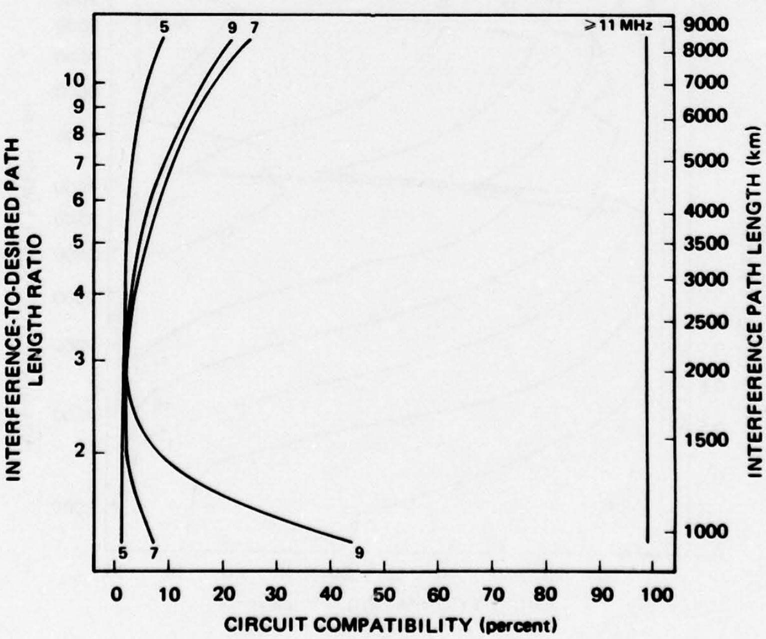

Figure 34. Effects of interference on a fixed service path of 705 km (Egypt to Beirut) - - July, sunspot number 50, 2400 GMT, U = 100%, fixed service MUF = 7.5 MHz.

MUFs is approximately 1.25-times its MUF for this month and hour (about 20.4 MHz). Thus, some interference can occur. As the frequency is raised above the upper decile of the MUFs on the fixed path, the impact of the effect is decreased until no interference can occur.

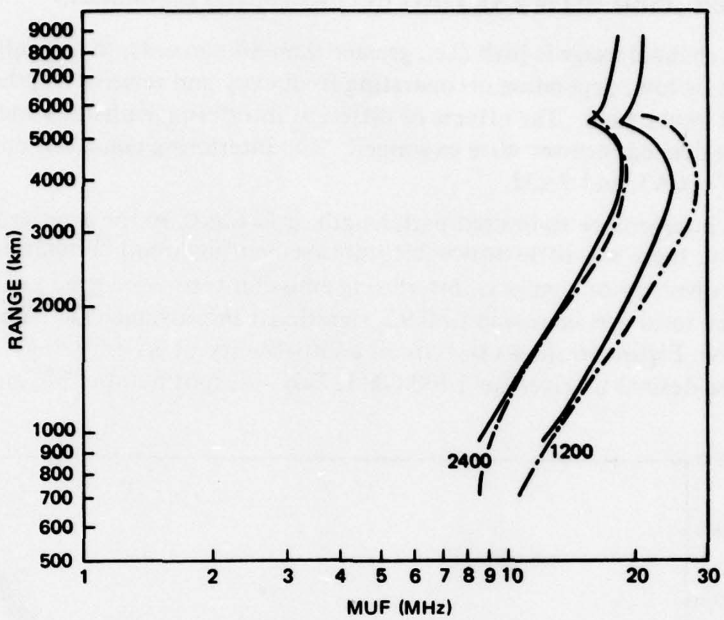

Figure 35. Variation of the MUF for the fixed (– - –) and interference (–) paths as a function of range, July, 1200 and 2400 GMT, sunspot 50.

TECHNIQUES TO DECREASE INTERFERENCE

When the mobile channel usage is high, several techniques are available which can be employed to decrease the effects of interference.

DIVERSITY EXERCISED WITH VARYING INTERFERING EMISSIONS

When the channel usage is high (i.e., greater than 80 percent), the circuit compatibility can be low, depending on operating frequency and relative lengths of the desired and interference path. The effects of different interfering emissions and the use of diversity at the desired receiver were examined. The interfering emissions considered were 0.5A1, 1.1F1, 6A3, and 3A3J.

When the interference-to-desired path length ratio was 0.36 for a desired path length of 5651 km, there was little noticeable improvement in circuit compatibility when either dual space diversity or change of interfering emission type were tried at the desired receiver. When this ratio was increased to 0.92, significant improvement in circuit compatibility was obtained. Figure 36 shows the circuit compatibility of an interferer at a range of 5202 km from the desired receiver for 1200 GMT, July, sunspot number 50, and with an

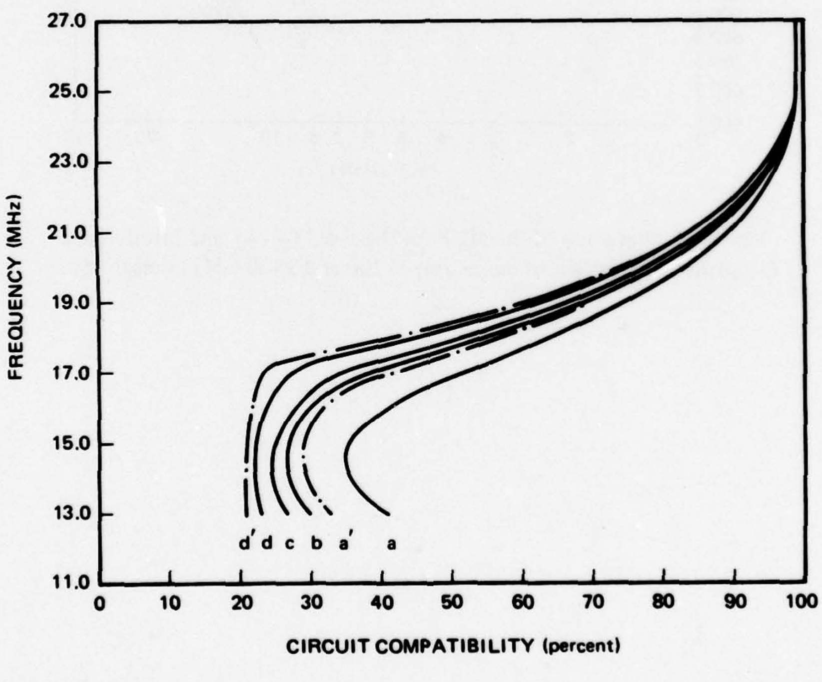

Figure 36. Effects of varying interfering emissions and utilization of diversity by the fixed service receiver. Interference range of 5202 km, 1200 GMT, July, sunspot number 50, U = 100%. Desired emission 6A3. Interfering emissions (a) 6A3, (b) 1.1F1, (c) 0.5A1, and (d) 3A3J with selection switching space diversity at the desired receiver and interfering emissions (a') 6A3 and (d') 3A3J with no diversity.

interfering channel usage of 80 percent. Curves are illustrated for the interfering emissions 0.5A1, 1.1F1, 6A3, and 3A3J with dual space diversity of the selection switching type at the desired receiver, and for interfering emissions 6A3 and 3A3J without diversity at the desired receiver (ref 23).

At frequencies above 23 MHz little difference is seen. At the lowest frequency (13 MHz), with the interfering emission 3A3J and diversity used at the desired receiver, the circuit compatibility is 21 percent. Changing the interfering emission to 6A3 increases the circuit compatibility to 41 percent. At 17 MHz, and for the same two types of emission for the interfering signal, the circuit compatibility increased from 23 to 52 percent. Little change in circuit compatibility is seen for diversity, or no diversity reception, for a 3A3J interfering signal. However, for a 6A3 interfering signal, diversity does provide an improvement.

CHANGING ANTENNAS

Because of the large difference in circuit compatibility, noted for desired paths of different length, the effects of changing antennas were examined. The antennas used in the previous part of the study were, for fixed service, the minimum standard antennas given in CCIR Recommendation 162-2 (ref 11); and, for mobile service, a twin whip antenna with constant gain of 0.85 dB/isotropic and a standard deviation of 4.1 dB. Both antennas had constant gain at all elevation angles. The calculations previously done, for interference to the fixed service circuit of 705 km, were repeated.

Three antennas for the fixed circuit were considered: (1) a horizontal half-wave dipole located one-quarter wavelength above ground of conductivity of 0.004 mhos/m and dielectric constant of 8, (2) a 16-element array of half-wave dipoles all in the same horizontal plane quarter-wave length above earth (ref 24), and (3) a commercial, horizontally polarized, log periodic antenna, with its vertex on the ground, intended for point-to-point communications over path lengths of 200 km to 1000 km for the F-layer propagation (ref 25). A twin whip antenna with gain 0.85 dB/isotropic at the horizon was used for the mobile antenna, with 10 log (cos Δ) added in the vertical plane, where Δ is the elevation angle above the horizon. In figure 37, the results for 7 and 9 MHz are compared against those of the minimum standard antenna. At 7 MHz, propagation on the fixed path is via the F-layer at an elevation angle of 34.7 degrees for the conditions given. At 9 MHz, propagation is via the E-layer at an elevation angle of 15.1 degrees. In each case, the circuit compatibility was greater with the minimum standard antenna rather than the selected antenna. In the case of the log-periodic antenna, the 15.1 degrees elevation angle was below the lower half-power angle of the vertical radiation pattern, and hence, was not optimally designed for the path. The conclusion to be drawn is that the maximum gain is more important than the directivity, but that the main beam of the vertical radiation pattern must be broad enough to include the variations in ionospheric conditions.

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23. International Radio Consultative Committee 13th Plenary Assembly, Geneva, 1974 Opinion 44; Classification and Designation of Emissions, International Telecommunications Union, Geneva, 1975.

24. Adorian P and Dickinson AH, High Frequency Broadcast Transmission with Vertical Radiation, J. of the British Institute of Radio Engineers, Vol 12 (new series) No. 2, p 111-116, February 1952.

25. DuHamel RH and Berry DG, A New Concept in High Frequency Antenna Design, paper presented at IRE National Convention, 1959.

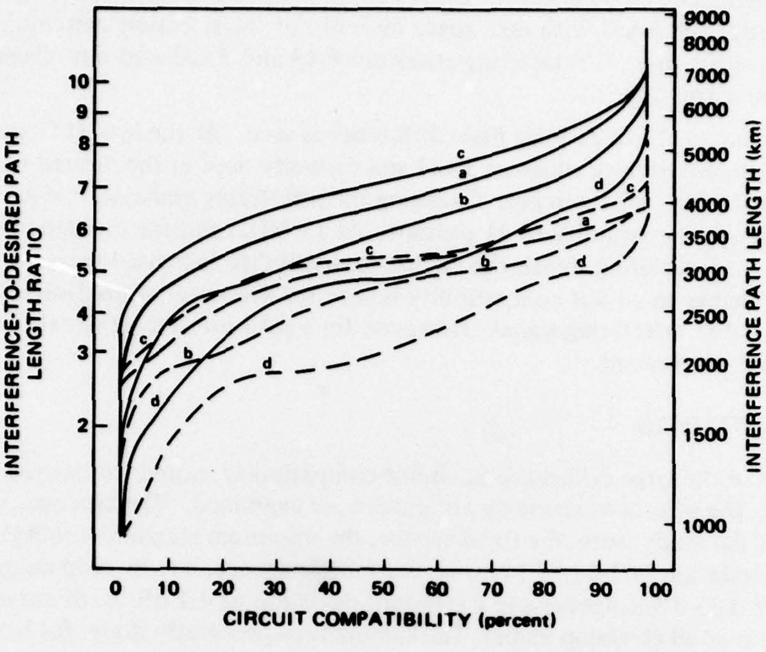

Figure 37. Effects of changing antennas on a fixed service path of 705 km (Egypt to Beirut) - - 1200 GMT, July, sunspot number 50, U = 100%. Fixed service antennas: (a) horizontally polarized log periodic, (b) 16-element λ/2 horizontal dipole array, and (c) λ/2 horizontal dipole, all λ/4 above ground with conductivity 0.004 mhos/m and dielectric constant 8 and (d) CCIR *Recommendation* 162-2 minimum standard antenna. Frequencies (–) 9 MHz and (– –) 7 MHz.

DuHamel and Berry suggest that the antenna pattern's half-power vertical angles should lie such that they intersect the extreme vertical heights encountered over a given range of operation (ref 25). Such an antenna would produce a radiation pattern having its upper half-power angle intersect the highest virtual height at the control point of the closest point of desired operation and also, having its lower half-power angle intersect the lowest virtual height at the control point of the longest path. They further state that log periodic type antennas are capable of producing vertical radiation patterns which have these attributes over a wide frequency range. They illustrate examples of three different log periodic antennas with these characteristics, usable over three different operating ranges. In addition, they state that other horizontally polarized antennas in current use in hf point-to-point circuits (such as rhombics, billboard arrays, dipoles, etc.) have characteristics that fall far short of being ideal under conditions of changing virtual height and wide frequency range.

OTHER TECHNIQUES

The previous two parts of this section have considered the more traditional methods of decreasing interference. The purpose of this section is to introduce two new promising techniques to reduce the effects of interference. The first is the application of adaptive array technology. The second is the use of processing techniques which are based upon using large time-bandwidth (TW) signals, where TW is much larger than the symbol alphabet size; whereby, large portions of the symbol TW space can be altered or totally eliminated, while still maintaining quality communication due to the symbol coding redundancy (ref 27).

Hansen has shown that adaptive array technology can be used to provide enhanced hf communication capabilities by: (1) providing antenna array gain plus element pattern diversity, (2) discrimination against other user interference, and (3) discrimination against multipath (ref 26). In order to provide the above capabilities, the communication signal needs to have some unique feature such as a pilot signal that allows the adaptive array processor to identify the desired signal. In order to eliminate multipath effects, the bandwidth of the pilot signal must be wider than the inverse of the differential delay between propagation modes to discriminate between them. For a 4 element array of quarter-wave monopoles with quarter wavelength spacing, endfire to the path, he determined that the array could produce about 15 dB of discrimination against multipath. For a full scale conformal hf adaptive array, the typical measured processing gain was 28 dB for a voice modem and nearly approached the maximum possible 42 dB in an adapt/hold mode on a standard digital modem.

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26. Naval Ocean Systems Center Technical Report 155, High-Frequency Interference Suppression. Interference is Identified and then Eliminated, by GJ Brown, 8 August 1977.
27. Hansen PM, Application of Adaptive Array Technology to HF Communication Systems, paper presented at IEEE 1977 European Conference on Electrotechnics, Communications, Venice, Italy, 3–7 May 1977.

EFFECTS OF FIXED USERS ON MOBILE USERS

Since the primary issue has been the band sharing of fixed and mobile users in the hf fixed service bands, the report has mainly related the effects of the mobile users on the fixed services. The effects of fixed systems on mobile systems is briefly considered here.

Although mobile systems require a high probability of not having to wait for a channel, their circuit quality requirements are only moderate, owing to the type of messages and the possibility of using simple repetition for redundancy without creating traffic backlogs. On the other hand, the interfering fixed service is normally operated on a more-or-less full-time basis (i.e., channel usage greater than say 83 percent). The feasibility of sharing has been examined, by computing circuit compatibility using the same transmit powers considered in the effects of the mobile systems on the fixed service. In addition, the antenna gain used for the fixed service was that in the interference sector of the minimum standard fixed service antenna for the nondirective antenna case, and the main beam directivity of the minimum standard fixed service antenna for directive antenna effects (ref 11).

Figures 38 and 39 show the circuit compatibility of a mobile service receiver with a fixed service interferer, using a nondirective antenna at the interfering transmitter (i.e., the mobile receiver is not in the main beam of a fixed transmitting antenna). Figures 38 and 39 are for desired mobile paths of 502 km and 1702 km, respectively. Below 13 MHz the circuit compatibility is seen to increase with increasing interference path length and with decreasing frequency at a constant interference path length. At these frequencies, the frequency is well below the MUF on both paths and the dominating factor is the ionospheric path attenuation. In figure 38, above 11 MHz, the frequencies are well above the desired path MUF of 9.4 MHz and, hence, are not subject to interference. Because the path in figure 39 is illustrated for interference-to-desired path length ratios less than one, the effect of the operating frequency relative to the desired path MUF of 17.5 MHz is noticeable. With frequencies at or above 13 MHz and at range ratios less than 1.3, the path geometry is the controlling factor; whereas, above 1.3 the ionospheric path attenuation is the controlling factor.

Figures 40 and 41 show the effect of the desired receiver being in the main beam of the interfering fixed transmitter. In general, the compatibility is lower, except for the desired path of 502 km at frequencies at or above 13 MHz where the path MUF controls. Reductions in circuit compatibility as large as 30 percent can be seen. The effect is more serious for the longer desired path.

In all the cases presented, the compatibility is never lower than 17 percent (100 - 83 = 17 percent). Hence the circuit compatibility has a minimum of 100–U percent. If the circuit requirements of mobile circuits are only moderate, then frequency sharing with the fixed services is possible. For mobile circuits of low power (15 watt) the effects of the fixed service will be as great as the effect of directive antennas. The use of diversity and other techniques for reducing interference would be beneficial when the mobile receiver is in the main beam of the fixed transmitter.

The mobile service could reduce the interference to it from the fixed service by employing narrow band telegraphy wherever practical. For instance, from the appendix, if a 1.1F1 single channel NCFSK 45 baud start-stop modulation is used, the signal-to-interference protection ratio against double sideband telephony is reduced by 29.8 dB for a character error rate of 0.001 and also, the required signal-to-noise ratio is reduced by 7.2 dB.

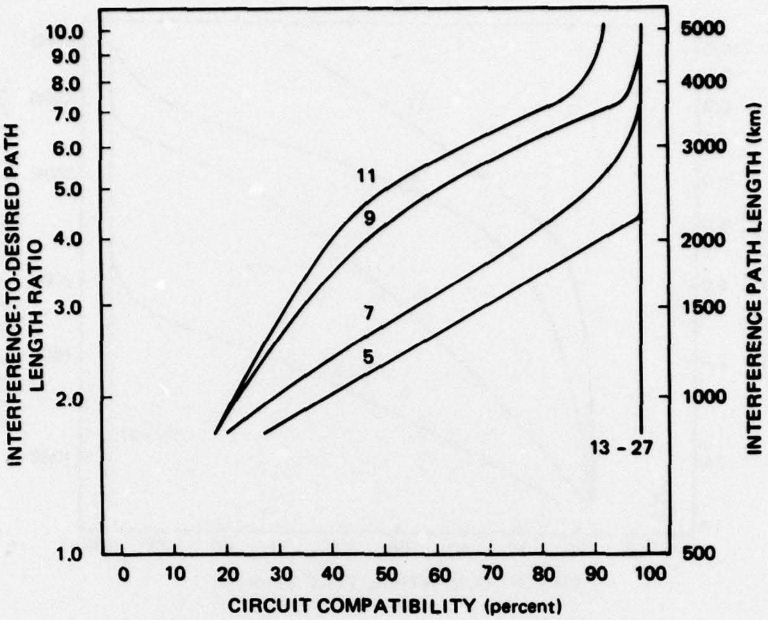

Figure 38. Effects of fixed paths on a mobile circuit of 502 km, mobile receiver not in main beam of the fixed transmitting antenna - - 1200 GMT, July, sunspot number 50, U = 83%.

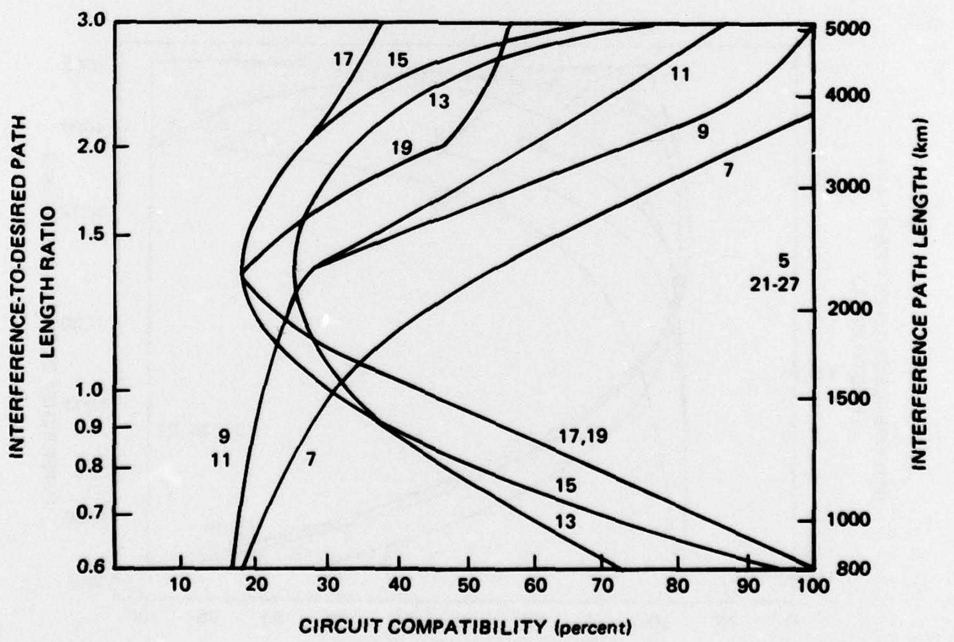

Figure 39. Effects of fixed paths on a mobile circuit of 1702 km, mobile receiver not in the main beam of fixed transmitting antenna - - 1200 GMT, July, sunspot number 50, U = 83%.

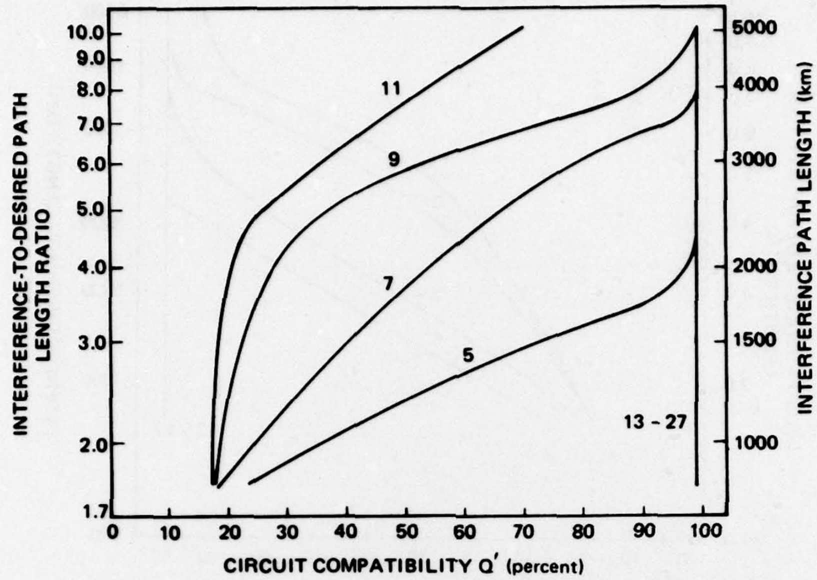

Figure 40. Effects of fixed paths on a mobile circuit of 502 km, mobile receiver in main beam of fixed transmitter - - 1200 GMT, July, sunspot number 50, U = 83%.

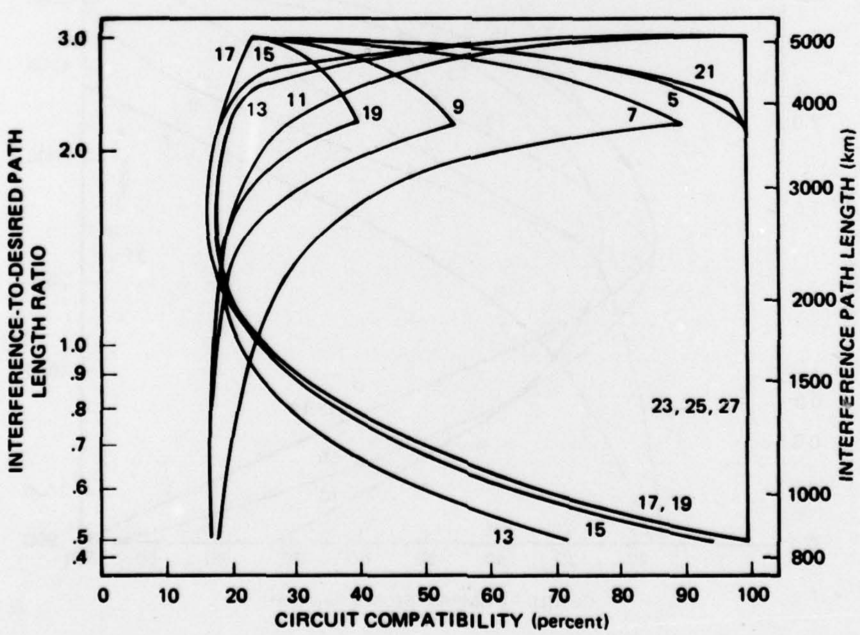

Figure 41. Effects of fixed paths on a mobile circuit of 1702 km, mobile receiver in the main beam of fixed transmitter - - 1200 GMT, July, sunspot number 50, U = 83%.

CONCLUSIONS

For the particular paths studied and conditions assumed, it was found that the circuit compatibility of the fixed service with the mobile service on co-channel assignments was dependent on:

1. the *channel usage* of the interfering service;
2. *traffic characteristics*, as they effect uniformity in channel usage of a given service;
3. the *technical characteristics* of both equipment and operating frequency of sharing services;
4. the relative lengths of the desired and interfering *propagation paths*; and
5. solar activity and the geophysical/electromagnetic *environment*.

In all cases studied, the circuit compatibility had a minimum value of 100–U percent, where U is the channel usage (in percent) of the potential interferer.

CHANNEL USAGE

For communication circuits which are operated sporadically, during any hour of the month, the channel usage will be low; thus, circuit compatibility between sharing services will be high. Generally, a single mobile user's channel usage per hour is minimal, ranging from a low of 0.2 percent to a high of 3.9 percent.

The limiting channel usage per hour of a particular system is a function both of the average waiting time for a channel (as the number of users per hour $N \rightarrow \infty$) and of the average message length. High channel usage (i.e., $U > 50$ percent) can only occur when the average waiting time for the channel is greater or equal to the average message length. Thus, provision of greater channel availability will tend to insure low channel usage. Currently, the mean maximum channel usage of mobile systems ranges from 30.3 to 54 percent. In some systems, such as the radiotelephone system, the channel is used so inefficiently that it is necessary to use trunking techniques. This only increases the channel usage to 0.44 Erlangs per frequency.

TRAFFIC CHARACTERISTICS

There is a wide variation in traffic characteristics among different users in a single service. Thus, the uniformity in channel usage of a particular mobile system is important. Those services that display high uniformity in usage probably share fairly homogeneous operating characteristics. This homogeneity may be due to a fairly tight definition of communications mission, or to the very large number of assignments per channel which effectively smooth-out mission related differences.

TECHNICAL CHARACTERISTICS

If the circuit compatibility requirements of mobile circuits are only moderate, then frequency sharing with the fixed service is possible. However, circuit compatibility is reduced whenever the desired mobile receiver falls within the main beam of the interfering fixed transmitter, or with mobile circuits of low power (i.e., 15 watts).

This interference can be reduced by having the mobile service employ narrowband telegraph modulation wherever practical, instead of double sideband telephony. This affords an additional 29.8 dB of protection to the mobile service and is equivalent to the difference in maximum power transmitted by the fixed service and the minimum power transmitted by the mobile service (80 kw/0.1 kw = 29.0 dB).

PROPAGATION PATHS

The skip zone is a region where no signal can be received by regular ionospheric refraction at a particular frequency. The higher the frequency, or the lower the solar cycle, the larger will be the skip zone. At a constant frequency, months providing higher MUFs also provide smaller skip zones.

Very high circuit compatibility can exist when the fixed system receiving station(s) falls in the skip zone of the mobile system transmitter(s). High compatibility can also be achieved during times when the circuit reliability for the fixed system at the shared frequency approaches zero (e.g., because that frequency is well above the MUF for the fixed system propagation path, or that frequency is below the lowest usable frequency (LUF) for that path).

As a desired path length decreases during the daytime, its LUF also decreases (due to D layer absorption), causing lower and lower frequencies to be subject to interference. At night however, for a fixed interference path length, the absence of D-region absorption causes the same lower frequencies to increase in circuit compatibility as the desired fixed path length decreases.

Maximum absorption over a given path coincides with maximum daylight (i.e., when local noon is at the midpoint of the path). In theory, the D layer absorption varies with the cosine of the solar zenith angle; so in northern latitudes, the absorption in December should be lower than in June. However, there is a winter anomaly which causes additional absorption during local winter. Moreover, special conditions are found on paths which pass through the auroral belts that also cause additional loss.

During daytime, at an interference-to-desired path length ratio of about one, an increase in circuit compatibility occurs due to a relative increase in D-layer absorption on the interference path. At a constant frequency, the circuit compatibility increases as the length of the desired path decreases and also as the sunspot number decreases. In general, the higher frequencies near the MUF are the most compatible.

ENVIRONMENT

In addition to an increase in D-layer absorption, an increase in natural atmospheric noise at the receiver will cause the LUF to rise. Sunspot activity has only a very slight effect on noise of atmospheric origin; however, the geographical distribution of this noise is of great importance. Generally, polar regions have little noise, while the equatorial and tropical zones show very high levels of atmospheric noise.

In variations of the MUF throughout the day, a minimum MUF is usually observed just before sunrise and a maximum MUF near, or shortly after, local noon. Moreover, since the sun's zenith angle at local noon differs according to season, the diurnal MUF will also vary.

For example, in the temperate northern latitudes, the F2–MUF curves show a lower daily minimum and a higher daily maximum MUF in December than in June, when they are nearly flat throughout the twenty-four hour day.

For the E and F1 ionospheric layers, the diurnal and seasonal variations are repeated all along the same parallel of latitude at the same local time. Because the sun is higher in the sky at low latitudes, there is more ionization there and the E–MUFs and F1–MUFs are accordingly higher. The F2 layer MUFs show a rather complex dependence on latitude; dependence with latitude is related to sunspot activity and season. However, at high latitude the diurnal variation is generally flat. There is also a longitudinal variation in F2–MUF.

While the variations of MUF with time of day and season are due to changing solar zenith angle, a third variation (solar radiation in time) depends on the sunspot cycle.

In years of intense sunspot activity, there is more ionization and all MUFs are generally higher. By contrast, in years of low sunspot activity, the MUFs decrease, causing the useful range of frequencies to become narrower toward the lower part of the spectrum. This is particularly evident during nighttime operation.

MAJOR ISSUES

As a result of this study, the following issues emerged as central to the feasibility of hf band sharing between the fixed and mobile services.

- The need for a sharing procedure which would divide the shared bands according to the relative propagation path lengths of the two services.
- Within this procedure, the use of ionospheric variability of the MUF and LUF in determining frequency sharing opportunities.
- Desirability of single sideband modulation with a suppressed carrier for radio telephony in the fixed services.
- Desirability of employing narrowband telegraphy in the mobile services wherever practical, instead of double sideband telegraphy.
- Subdivision of the new shared bands according to mobile channel usage.
- Consideration of the uniformity of mobile channel usage in assigning particular mobile systems to the shared bands.

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APPENDIX A

SIGNAL ACCEPTABILITY CRITERIA FOR HF SKYWAVE FREQUENCY SHARING

A technique for computing the electromagnetic compatibility of hf skywave communication systems has been described by Sailors, et al. (ref 10). The circuit reliability methodology, normally used at hf to estimate expected circuit performance in the absence of interference, has been extended there to estimate the expected performance in the presence of skywave interference. Two specific signal acceptability thresholds are required by that technique to evaluate the circuit compatibility of hf skywave communication systems.

The first signal threshold, R_1, is the required signal-to-noise density ratio for the grade of service required. For both fading and stable conditions, values of the required signal-to-noise density ratios have been estimated by Akima, et al. (ref 28), for specific hf communication systems and have been incorporated into CCIR Recommendation 339-3 (ref 29). Required signal-to-noise ratios are given in decibels as the ratio of unmodulated carrier power to average noise power in a 1-Hz-rf bandwidth for single-sideband amplitude modulated (DSB-AM) systems and as the ratio of signal peak-envelope-power to average noise power in a 1-Hz-rf bandwidth for other modulation systems. In the case of digital systems, the required signal-to-noise ratios are given as a function of character error rate.

The second threshold, R_2, is the required signal-to-interference ratio necessary for the protection of the desired received signal emission against the undesired signal emission. CCIR Report 525 (ref 30), based on a receiver degradation handbook (ref 31), provides provisional signal-to-interference protection ratios for various combinations of desired and undesired modulation required under stable conditions. The protection ratios are given in terms of the power ratio of mean desired signal to mean interference at the receiver input for continuous (nonpulsed) transmissions. The ratio is given in terms of peak powers for pulsed signals (i.e., mean desired signal to peak interference for pulsed interference; peak desired signal to mean interference for a pulsed desired signal). In the case of digital systems, bit error rate is used, rather than character error rate as was used in CCIR Recommendation 339-3.

It is the purpose of this appendix to coalesce all the power level references into one, to relate the performance of digital systems to a common performance criteria, to

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[10] Sailors DB, Kugel CP, and Haydon GW, Predicting the Compatibility of High Frequency Skywave Communication Systems, IEEE Trans. Electromag. Compat. Vol EMC-19, p 332-343, August 1977.

[28] ESSA Technical Report ERL 131-ITS 92, Required Signal-to-Noise Ratios for HF Communications, by H Akima, GG Ax, and WM Beery, August 1969.

[29] International Radio Consultative Committee, 13th Plenary Assembly, Geneva, 1974, Recommendation 339-3; Bandwidths, Signal-to-Noise Ratios for HF Communication Systems, Geneva International Telecommunication Union, 1975.

[30] International Radio Consultative Committee, 13th Plenary Assembly, Geneva, 1974, Report 525; Provisional Signal-to-Interference Protection Ratios Required for Spectrum Utilization Investigations, Geneva International Telecommunication Union, 1975.

[31] Office of Telecommunications & Electromagnetic Compatibility Analysis Center ESD-TR-75-013, Communication/Electronics Receiver Degradation Handbook, F Dravitz and M Lemke, August 1975.

include the effects of fading in the signal-to-interference protection ratios, and to include some commonly used modulation types given in CCIR Recommendation 339-3, but not included in CCIR Report 525. The results appear in Table A1.

The values of R_1 given by Akima, et al., were converted to mean power using the tables given in CCIR Recommendation 326-2 (ref 32). The footnotes to Table A1 give the conversion factors used in each case.

Akima, et al., gave the bit error rates corresponding to the character error rates given in CCIR Recommendation 339-3. Therefore, it was possible to interpolate the values of the signal-to-interference protection ratios given as a function of bit error rate in CCIR Report 525 and in the receiver degradation handbook. Thus, protection ratios as a function of character error rate are included in Table A1.

If the desired signal, the interference, or the received noise is fading, the amount of interference that can be tolerated is modified (generally decreased). Bond and Meyer have analyzed the statistical performance of radio communication circuits in the presence of interference, for cases where either the desired or undesired signal, or both, are subject to Rayleigh fading over the propagation path (ref 33). In the case of skywave interference to a skywave signal, both the signal and interference will be subject to fading. Table A1 includes a factor to allow for satisfactory operation 95 percent of the time, (13.4 dB) obtained from curve 2 of figure 1 given by Bond and Meyer, for the *nondiversity case.*

Neither CCIR Report 525, nor the receiver degradation handbook, contains three commonly used modulations included in CCIR Recommendation 339-3. These are a 16-channel frequency-division-multiplexed (FDM) NCFSK system, 3A7J, and two independent-sideband amplitude-modulation (ISB-AM) systems transmitting 16 teletypewriter signals plus one or three voice signals. It was assumed here, as Akima had assumed, that the teletypewriter signals were multiplexed to form a 16-channel FDM-NCFSK signal. Akima assumed that the teletypewriter channels are generally the essential services and the quality is assessed or specified in terms of character error probability in teletypewriter messages. For composite systems, he adds 1.0 dB and 3.0 dB to the required signal-to-noise ratio for the 16-channel FDM-NCFSK systems when one and three voice signals, respectively, are transmitted together with the teletypewriter signals.

The performance of an FDM-NCFSK is obtained by multiplying the required ratio for a single-channel system not only by the number of subchannels, but also by a factor corresponding to the ratio of the peak envelope power to the average power of the rf signal (ref 28). Hence, the procedure is: (1) add $N=10 \log_{10} n$, where n is the number of teletypewriter channels; and (2) add an appropriate crest factor (or loading factor) when the required signal-to-interference is expressed in terms of the ratio of signal peak power to interference power. However, as the protection ratio here is expressed in terms of mean signal power to interference power, the latter term may possibly be ignored. The values in table A1, for 3A7J treated in this manner, are those interfered by 1.1F1 and 3A3J. The values for 3A7J interfered by 0.5A1 and 6A3, were extrapolated from OT/ECAC degradation handbook, with 4.2 added to allow for 16 channels rather than 6 channels, and 4.6 dB added to allow for a 3 kHz bandwidth rather than a

[32] International Radio Consultative Committee, 13th Plenary Assembly, Geneva, 1974, Recommendation 326-2; Power of Radio Transmitters, Geneva, International Telecommunication Union, 1975.

[33] Bond FE and Meyer HF, The Effect of Fading on Communication Circuits, Subject to Interference, Proc. IRE, Vol 45, p 636-642, May 1957.

1.05 kHz bandwidth. On the average, these values are 4 dB more conservative than those given by the above procedure when the crest factor was ignored. To make the values for interference by 1.1F1 and 3A3J equally conservative, this 4 dB has also been added as a crest factor for these two cases.

Table A1. Required signal-to-noise (a) and signal-to-interference (b) ratios for hf skywave frequency sharing

Wanted Signal \ Interference	Performance Level (t)	0.5A1	1.1F1	6A3	3A3J	White Gaussian Noise (c)
0.25 Al Telegraphy, 50 baud, Printer (d)	$P_E=10^{-4}$	19.0 (o)	20.0 (o)	14.0 (o)	27.0 (p)	57.0 (f)
1.1F1 Single Channel NCFSK, 45 baud Start-Stop Telegraphy	$P_c=0.01$	13.4 (q)	19.0 (q)	14.4 (q)	21.4 (q)	60.0
	$P_c=0.001$	13.4 (q)	19.6 (q)	15.6 (q)	23.8 (q)	70.2
6A4A Photo-telegraphy 60 rpm						60.6 (g)
6A9B Composite 16 Channels, 75 baud each, 1 Telephony Channel (j)	$P_c=0.01$	31.7	36.0	31.7	38.4	64.1 (h)
	$P_c=0.001$	32.7	36.6	32.7	40.8	74.3 (h)
12A9B Composite 16 Channels, 75 baud each, 3 Telephony Channels (k)	$P_c=0.01$	33.7	38.0	33.7	40.4	66.1 (i)
	$P_c=0.001$	34.7	38.6	34.7	42.8	76.3 (i)
6A3 Telephony Double Sideband	GCQ	52.4 (o)	50.4 (o)	45.4 (o)	57.4 (o)	77.2 (e,l)
	JUQ	25.4 (o)	23.4 (o)	18.4 (o)	30.4 (o)	66.6 (l)
3A3J Telephony Single-Sideband Suppressed Carrier	GCQ	23.4 (o)	43.4 (o)	26.4 (o)	44.4 (o)	64.0 (e,m)
	JUQ	-3.6 (o)	16.4 (o)	-0.6 (o)	17.4 (o)	40.0 (m)
3A7J 16 Channel FDM-NC FSK, 75 baud each, Start-Stop Telegraphy	$P_c=0.01$	30.7 (r)	35.0 (s)	30.7 (r)	37.4 (s)	62.9 (n)
	$P_c=0.001$	31.7 (r)	35.6 (s)	31.7 (r)	39.8 (s)	73.1 (n)

(a) Mean signal in the occupied bandwidth to noise in a 1 Hz bandwidth.

(b) Mean signal in the occupied bandwidth to mean interference in the occupied bandwidth.

(c) Rayleigh fading, non-diversity. 2 dB multicoupler and transmission line losses at the transmitter included.

(d) Dual diversity, selection switching.

(e) Assuming 10 dB improvement due to the use of noise reducers.

(f) Ratio of mean power to peak-envelope-power (-3 dB) added to value given in CCIR Recommendation 339-3 (ref 29).

(g) Ratio of mean power to peak-envelope-power (-0.4 dB) added to value given in CCIR Recommendation 339-3 (ref 29).

(h) Ratio of mean power to peak-envelope-power (-5.8 dB) added to values given in CCIR Recommendation 339-3 (ref 29).

(i) Ratio of mean power to peak-envelope-power (-5.8 dB) added to values extrapolated from values given in Akima, et al. (ref 28).

(j) Assuming that the transmitter is loaded in such a way that the values of the peak-envelope-power of the multiplexed teletypewriter signals are 80 percent and the values of the voice signals are 20 percent of the rated peak envelope power of the transmitter, when the composite signal is transmitted. The required ratios are based on the Telegraphy channels plus 1 dB.

(k) Assuming that the transmitter is loaded in such a way that the values of the peak-envelope-power of the multiplexed teletypewriter signals are 50 percent of the rated peak envelope power of the transmitter, when the composite signal is transmitted. The required ratios are based on the telegraphy channels plus 3 dB.

(l) Ratio of mean power to carrier power (.2 dB) added to values given in CCIR Recommendation 339-3 (ref 29).

(m) Ratio of mean power to peak-envelope-power (-10 dB) added to values given in CCIR Recommendation 339-3 (ref 29).

(n) Ratio of mean power to peak-envelope-power (-6 dB) added to values given in CCIR Recommendation 339-3 (ref 29).

(o) Obtained from CCIR Report 525 (ref 30). A factor has been added to obtain satisfactory operation 95 percent of the time for both the signal and interference Rayleigh fading (ref 33).

(p) Obtained from CCIR Report 525 (ref 30). A factor has been added to obtain satisfactory operation 95 percent of the time for both the signal and interference Rayleigh fading (ref 33).

(q) Extrapolated from CCIR Report 525 (ref 30). A factor has been added to obtain satisfactory operation 95 percent of the time for both the signal and interference Rayleigh fading (ref 33).

(r) Extrapolated from OT/ECAC Degradation Handbook (ref 31). 4.2 dB added to allow for 16 channels rather than 6 channels. 4.6 dB has been added to allow for 3 kHz bandwidth rather than 1.05 kHz bandwidth. A factor has been added to obtain satisfactory operation 95 percent of the time for both the signal and interference Rayleigh fading (ref 33).

(s) Obtained from single channel performance by adding 10 log n where n is the number of channels plus 4 dB.

(t) P_E=bit error rate; P_C=character error rate; GCQ=Good Commercial Quality; and JUQ=Just Usable Quality.