CHAPTER 1

INTRODUCTION TO SINGLE SIDEBAND

1. NEED FOR SINGLE SIDEBAND

The need for single-sideband communication systems has arisen because present day radio communications require faster, more reliable, spectrum conservative systems. The quantity of commercial and military traffic is presently so great in the high-frequency (2 to 30 mc) spectrum that it has become necessary to restrict the use of this spectrum to those services which cannot be accommodated by other means. Land-lines, microwave links, and uhf scatter propagation are employed to relieve the load from the high-frequency spectrum. In many instances, these provide a better and more reliable service.

There are, however, many communication services which need the propagation characteristics obtainable only in the high-frequency range. Among these are ship-to-shore communications, air-to-ground communications, and the many military and naval systems which require independence, mobility, and flexibility. Since high-frequency spectrum space is limited, it is essential that the best possible use be made of the space available. This means that communication systems must use a minimum bandwidth, that the guard bands between channels to allow for frequency drift and poor selectivity be minimized, and that spurious radiation be kept to a very low value to avoid interference between services. In addition to this, a more reliable signal is desirable if not essential. Single-sideband communication systems in their present state of development provide these assets.

2. WHAT SINGLE SIDEBAND MEANS

A single-sideband (SSB) signal is an audio signal converted to a radio frequency, with or without inversion. For instance, an intelligible voice signal contains audio frequencies over the range of 300 to 3000 cycles per second (cps). If this audio signal is converted to a radio frequency by mixing it with a 15 mc r-f frequency, the resultant sum frequencies cover the range of 15,000,300 to 15,003,000 cps. Such a signal is an SSB signal without inversion and is referred to as an upper sideband, because it occupies the spectrum space above the r-f conversion frequency. Note that the 15 mc carrier is not included in the range of the SSB signal. The above example does not indicate the presence of a difference frequency. However, when the voice signal is mixed with the r-f frequency, a difference frequency does develop which covers the range from 14,999,700 to 14,997,000 cps. This signal is also an SSB signal but is an SSB signal with inversion . This SSB signal is referred to as a lower sideband signal because it occupies the spectrum space below the r-f conversion frequency. Figure 1-1 illustrates the position of the SSB signal in the r-f spectrum.

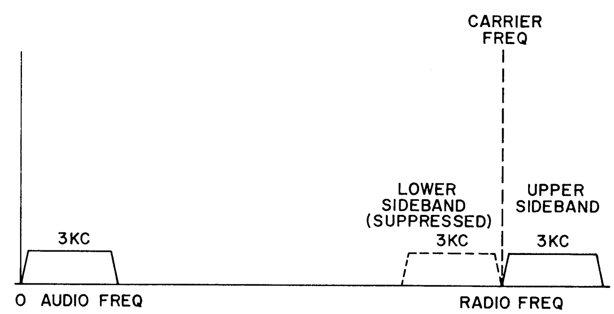


Figure 1-1. Location of SSB Signal in R-F Spectrum

From the above description of the SSB signal, it is apparent that only one sideband signal need be transmitted to convey the intelligence. Since two sideband signals are obtained from the mixing process, it is also necessary to remove one sideband before transmission. To receive the SSB signal, it is necessary to convert the SSB signal back to the original audio signal. This requires identical transmitter and receiver conversion frequencies. In the past, a low-power, pilot carrier was transmitted for automatic frequency control (afc) purposes to provide this end. However, with present day frequency stabilities (1 cps at 10 mc in ground and 10 cps at 10 mc in mobile equipment) the need for afc and pilot carriers is eliminated.

Several methods of sideband communication are in use or under development. The "single-sideband" method as the term is used throughout this book refers to the method which is, perhaps, more accurately termed "single-sideband, suppressed carrier." In this method, only one sideband is transmitted and the carrier is suppressed to the point of non-existence. To demodulate the single-sideband signal requires conversion of the signal with a locally-generated signal close to the proper frequency but with no phase relationship required. In the "single-sideband, pilot carrier" system only one sideband is transmitted, but a low-level carrier of sufficient amplitude for reception is also transmitted. To demodulate this signal, the pilot carrier is separated from the sideband in the receiver, then amplified and used as the conversion frequency to demodulate the sideband signal. In another method, the pilot carrier is used for automatic frequency control of the receiver. In the "double-sideband" (DSB) system, both the upper and lower sidebands of the signal are transmitted with the carrier suppressed to the point of nonexistence. To demodulate the double sideband requires insertion of a locally-generated carrier of both the proper frequency and the proper phase. This system depends upon an automatic frequency and phase control, derived from the double-sideband signal, for control of the locally-generated carrier. In the "single-sideband, controlled carrier" system only one sideband is transmitted, but a carrier which varies inversely with the signal level is also transmitted. This allows an appreciable average carrier level for automatic-frequency-control without reducing the sideband power below the full transmitter rating.

3. HISTORICAL DEVELOPMENT OF SINGLE-SIDEBAND COMMUNICATION SYSTEMS

Although SSB transmission has only received publicity in the last few years, the knowledge of the sideband and the development and use of SSB techniques have progressed over the last 40 years. The acoustical phenomenon of combining two waves to produce sum and difference waves carried over into electric-wave modulation. The presence of the upper and lower sidebands in addition to the carrier frequency were tacitly assumed to exist but were not concretely visualized in the earliest modulated transmissions. Recognition that one sideband contained all the signal elements necessary to reproduce the original signal came in 1915. It was then, that at the Navy Radio Station at Arlington, Va., that an antenna was tuned to pass one sideband well, even though the other was attenuated.

From 1915 until 1923, the physical reality of sidebands was vigorously argued with the opponents contending that sidebands were mathematical fiction. However, the first trans-Atlantic radiotelephone demonstration in 1923 provided a concrete answer. This system employed an SSB signal with a pilot carrier. Single sideband was used in this system because of the limited power capacity of the equipment and the narrow resonance bands of efficient antennas at the low frequency (57 kc) used. By 1927 trans-Atlantic SSB radiotelephony was open for public service.

The first overseas system was followed by short-wave systems, 3 to 30 mc, which transmitted double sideband and carrier because SSB development did not permit practical SSB transmission in this frequency range. However, SSB techniques were employed in various telephony applications and in various multiplexing systems. It has not been until recently that equipment developments have permitted the advantages of SSB communication to be fully exploited. These developments have been in the fields of frequency stability, filter selectivity, and low-distortion linear power amplifiers. These developments have led to military and commercial acceptance of SSB communication systems. There are presently available several radio amateur and commercial SSB radio sets, fixed-station SSB exciters up to 45 kw linear power amplifiers, and airborne transceivers capable of reliable communications with unlimited range. Some of these equipments, especially the military equipments, are provided with automatic frequency selection and automatic tuning to further enhance their value as reliable, easily operated systems.

4. BASIC FUNCTIONAL UNITS OF A SINGLE-SIDEBAND TRANSMITTING SYSTEM

Some of the basic functional units of an SSB system have been previously mentioned. Figure 1-2 shows these units in their functional relationship for an SSB transmitter.

The audio amplifier is of conventional design. Audio filtering is not required because the highly selective filtering which takes place in the SSB generator attenuates the unnecessary frequencies below 300 cps and above 3000 cps. It should be noted that a voice signal is used only as a convenience for explanation. The input signal may be any desired intelligence signal and may cover all or any part of the frequency range between 100 and 6000 cps. The upper limit of the input audio signal is determined by the channel bandwidth and the upper cutoff frequency of the filter in the SSB generator. The lower limit of the input audio signal is determined by the lower cutoff frequency of the filter in the SSB generator.

The SSB generator produces the SSB signal at an i-f frequency. The most familiar way to produce the SSB signal is to generate a double-sideband (DSB) signal and then pass this signal through a highly selective filter to reject one of the sidebands. The SSB signal is generated at a fixed i-f frequency because highly selective circuits are required. The highly selective filter requirements for the filter method of SSB generation are met by either crystal or mechanical filters. Both of these filters have been improved in performance and reduced in size and cost to make their application practical.

The generated SSB signal at a fixed i-f frequency then goes through mixers and amplifiers where it is

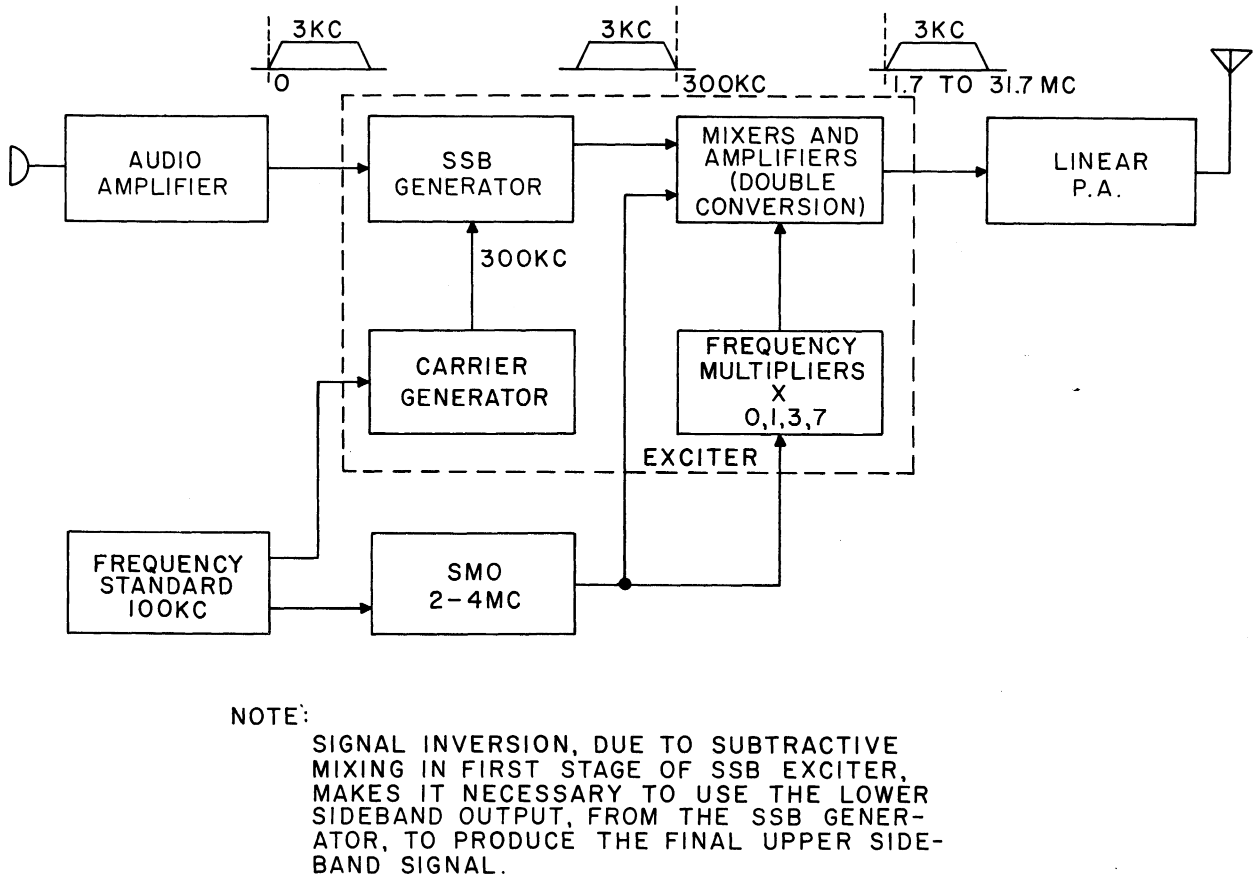


Figure 1-2. Functional Units of an SSB Transmitting System

converted up in frequency to the transmitted r-f frequency. Two stage conversion is shown with the second conversion frequency being a multiple of the first conversion frequency. The frequency conversions required to produce the r-f frequency produce sum and difference frequencies as well as higher order mixing products inherent in mixing circuits. However, the undesired difference frequency or the undesired sum frequency, along with the higher order mixing products, is attenuated by interstage tuned circuits.

The SSB exciter drives a linear power amplifier to produce the high power r-f signal. A linear power amplifier is required for SSB transmission, because it is essential that the plate output r-f signal be a replica of the grid input signal. Any nonlinear operation of the power amplifier will result in intermodulation (mixing) between the frequencies of the input signal. This will produce not only undesirable distortion within the desired channel but will also produce intermodulation outputs in adjacent channels. Distortion in the linear power amplifier is kept low by the design choice of power amplifier tubes, their operating conditions, and use of r-f feedback circuits. The low distortion obtainable in modern linear power amplifiers is not essential to the SSB system nor is it essential for good voice transmission, but it is essential to minimize the guard band between channels and thereby permit full utilization of the spectrum space.

Because an SSB system without a pilot carrier demands an extremely stable frequency system, the frequency standard and stabilized master oscillator (smo) are extremely important. The standard frequency is obtained from a crystal oscillator with the crystal housed in an oven. Since the stability of the crystal frequency depends directly upon the stability of the oven temperature, stable thermal control of the oven is necessary. This thermal control of the oven is obtained by using heat-sensitive semiconductors in a bridge network. Any variation in the oven temperature, then, is indicated and corrected by an unbalance in the control bridge. This system will limit changes in oven temperature to 0.001°C. Such oven stability will provide a standard frequency which will vary no more than 1 cps in 10 mc per day when used in fixed-station equipment and no more than 10 cps in 10 mc per day when used in mobile station equipment.

The carrier generator provides the i-f carrier used to produce the fixed i-f SSB signal, and the smo provides the necessary conversion frequencies to produce the r-f SSB signal. The frequencies developed in these units are derived from or phase locked to the single standard frequency so that the stability of the standard frequency prevails throughout the SSB system. Choice of the fixed i-f frequency and the conversion frequencies to obtain the r-f frequency is an extremely important design consideration. Optimum operating frequencies of the various circuits must be considered as well as the control of undesirable mixing products. The frequency scheme shown is the result of extensive study and experimental verification. It produces minimum spurious output in the high-frequency range (2 to 32 mc). The use of harmonically related conversion frequencies in the mixer permits the frequency range to be covered with a single 2 to 4 mc oscillator, a very practical range for obtaining high oscillator stability. Use of the 300 kc fixed i-f frequency is the optimum operating frequency for the mechanical filter required in the SSB generator.

The foregoing discussion may give the erroneous impression that only single channel communication is possible with an SSB system. Quite the opposite is true. To add additional channels to the SSB system requires only additional circuits in the SSB generator. One method is to use the upper sideband of one signal and the lower sideband of the other signal. Figure 1-3 shows the circuit for producing these two channels and the location of each channel with respect to the carrier frequency. It should be noted that with this method a twin sideband is transmitted, and that the signal in the lower sideband is inverted. Another method of adding channels is shown in figure 1-4. Different fixed i-f frequencies, one raised 4 kc from the original, are injected into separate SSB generators, and the upper sideband is filtered from each output. This produces two channels both using the upper sideband. It should be realized that as additional channels are added to the system, less transmitter power output is available for each channel.

The SSB transmitter is designed for linear operation from the audio input amplifier through the output power amplifier. That is, the transmitter faithfully transmits the original input intelligence with negligible distortion. This distortion-free system is ideally suited for the transmission of multiplex and Kineplex signals, because the original pulses are transmitted without distortion of their wave shape.

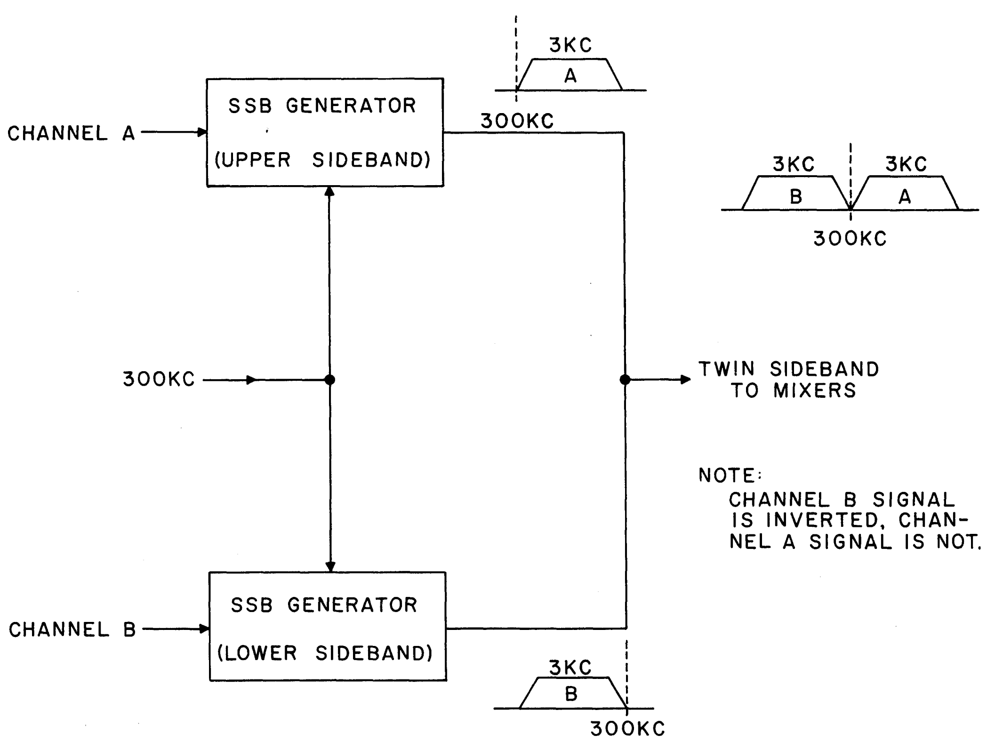


Figure 1-3. Generation of the Twin-Channel Sideband Signal

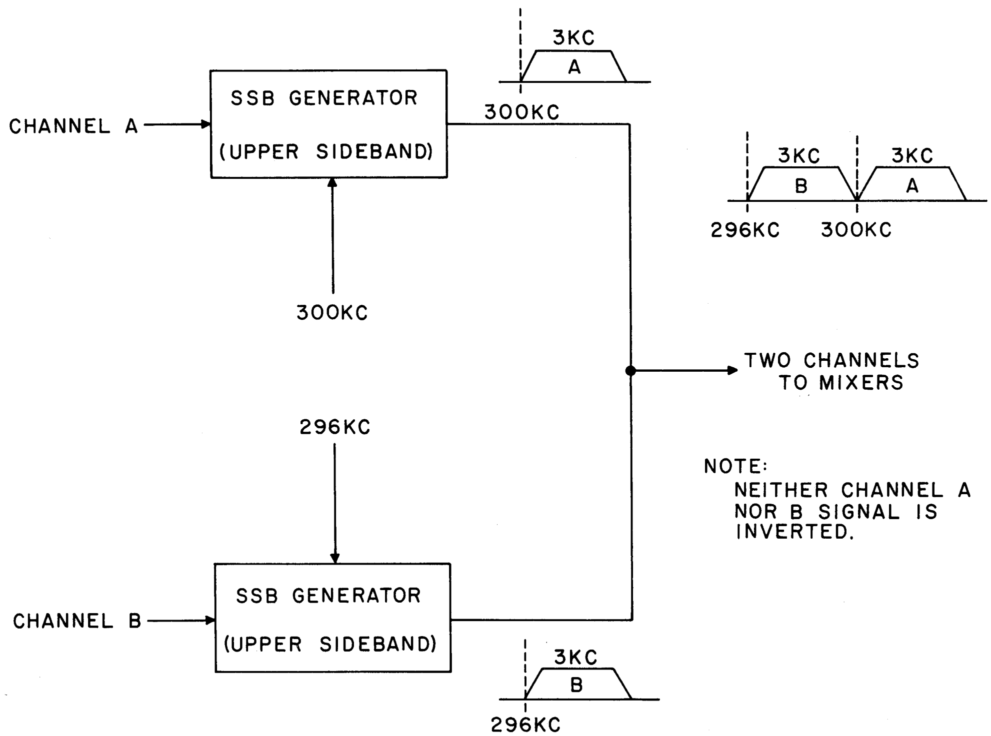


Figure 1-4. Generation of Two Channel SSB Signal

5. BASIC FUNCTIONAL UNITS OF A SINGLE-SIDEBAND RECEIVING SYSTEM

To receive the SSB signal requires a heterodyning system which will convert the radio-frequency signal back down to its original position in the audio spectrum. The basic functional units of such a receiver are shown in figure 1-5. It can be seen that the SSB receiver is almost identical to a conventional heterodyne receiver except for the detection circuit. The r-f signal is amplified and converted down in frequency to a fixed i-f frequency. Then a final fixed i-f injection frequency is required to bring the signal down to its original position in the audio spectrum.

Many of the units of an SSB receiver are identical with units of the SSB transmitter as can be seen by comparing figure 1-2 with figure 1-5. The frequency standard, carrier generator, and smo are identical. The double conversion mixer and amplifier unit of the receiver can be made identical to the double conversion mixer and amplifier unit of the transmitter. This similarity of functions permits the construction of transceivers with much of the circuitry used for both receiving and transmitting by merely adding switching to reverse the direction of signal flow. By using dual purpose units and adding switching to reverse the direction of the signal, equipment size, weight, cost, and power consumption are substantially reduced.

6. COMPARISON OF SSB WITH AM.

a. POWER COMPARISON OF SSB AND AM.

There is no single manner which can be used to evaluate the relative performance of AM. systems and SSB systems. Perhaps the most straightforward manner to make such a comparison is to determine the transmitter power necessary to produce a given signal-to-noise (s/n) ratio at the receiver for the two systems under ideal propagating conditions. Signal-to-noise ratio is considered a fair comparison, because it is the s/n ratio which determines the intelligibility of the received signal. Figure 1-6 shows such a comparison between an AM. system and an SSB system where 100 percent, single-tone modulation is assumed.

Figure 1-6A shows the power spectrum for an AM. transmitter rated at 1 unit of carrier power. With 100 percent sine-wave modulation, such a transmitter will actually be producing 1.5 units of r-f power. There is .25 unit of power in each of the two sidebands and 1 unit of power in the carrier. This AM. transmitter is compared with an SSB transmitter rated at

.5 unit of peak-envelope-power (PEP). Peak-envelope-power is defined as the rms power developed at the crest of the modulation envelope. The SSB transmitter rated at .5 unit of peak-envelope-power will produce the same s/n ratio in the output of the receiver as the AM. transmitter rated at 1 unit of carrier power.

The voltage vectors related to the AM. and SSB power spectrums are shown in figure 1-6B. The AM. voltage vectors show the upper and lower sideband voltages of .5 unit rotating in opposite directions around a carrier voltage of 1 unit. For AM. modulation, the resultant of the two sideband voltage vectors must always be directly in phase or directly out of phase with the carrier so that the resultant directly adds to or subtracts from the carrier. The resultant shown when the upper and lower sideband voltage are instantaneously in phase produces a peak-envelope-voltage (PEV) equal to twice the carrier voltage with 100 percent modulation. The .5 unit of voltage shown in each sideband vector produces the .25 unit of power shown in A, .25 unit of power being proportional to the square of .5 unit of voltage. The SSB voltage vector is a single vector of .7 unit of voltage at the upper sideband frequency. The .7 unit of voltage produces the .5 unit of power shown in A.

The r-f envelopes developed by the voltage vectors are shown in figure 1-6C. The r-f envelope of the AM. signal is shown to have a PEV of 2 units, the sum of the two sideband voltages plus the carrier voltage. This results in a PEP of 4 units of power. The PEV of the SSB signal is .7 unit of voltage with a resultant PEP of .5 unit of power.

When the r-f signal is demodulated in the AM. receiver, as shown in figure 1-6D, an audio voltage develops which is equivalent to the sum of the upper and the lower sideband voltages, in this case 1 unit of voltage. This voltage represents the output from the conventional, diode detector used in AM. receivers. Such detection is called coherent detection becausc the voltages of the two sidebands are added in the detector. When the r-f signal is demodulated in the SSB receiver, an audio voltage of .7 unit develops which is equivalent to the transmitter upper sideband signal. This signal is demodulated by heterodyning the r-f signal with the proper frequency to move the SSB signal down in the spectrum to its original audio position.

If a broadband noise level is chosen as .1 unit of voltage per 6 kc bandwidth, the AM. bandwidth, the same noise level is equal to .07 unit of voltage per 3 kc bandwidth, the SSB bandwidth. This is shown in figure 1-6E. These values represent the same noise power level per kc of bandwidth; that is, $.1^2/6$ equals $.07^2/3$. With this chosen noise level, the s/n ratio for the AM. system is 20 log s/n in terms of voltage, or 20 db. The s/n ratio for the SSB system is also 20 db, the same as for the AM. system. The 1/2 power unit of rated PEP for the SSB transmitter, therefore, produces the same signal intelligibility as the 1 power unit rated carrier power for the AM.

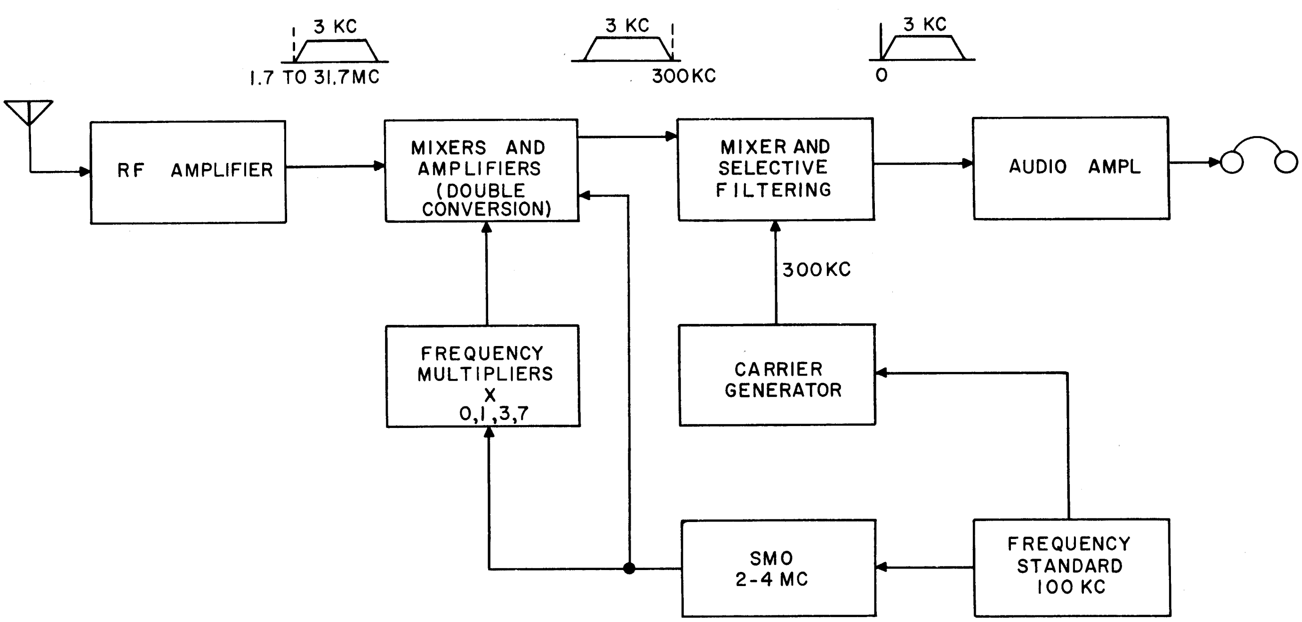


Figure 1-5. Functional Units of an SSB Receiving System

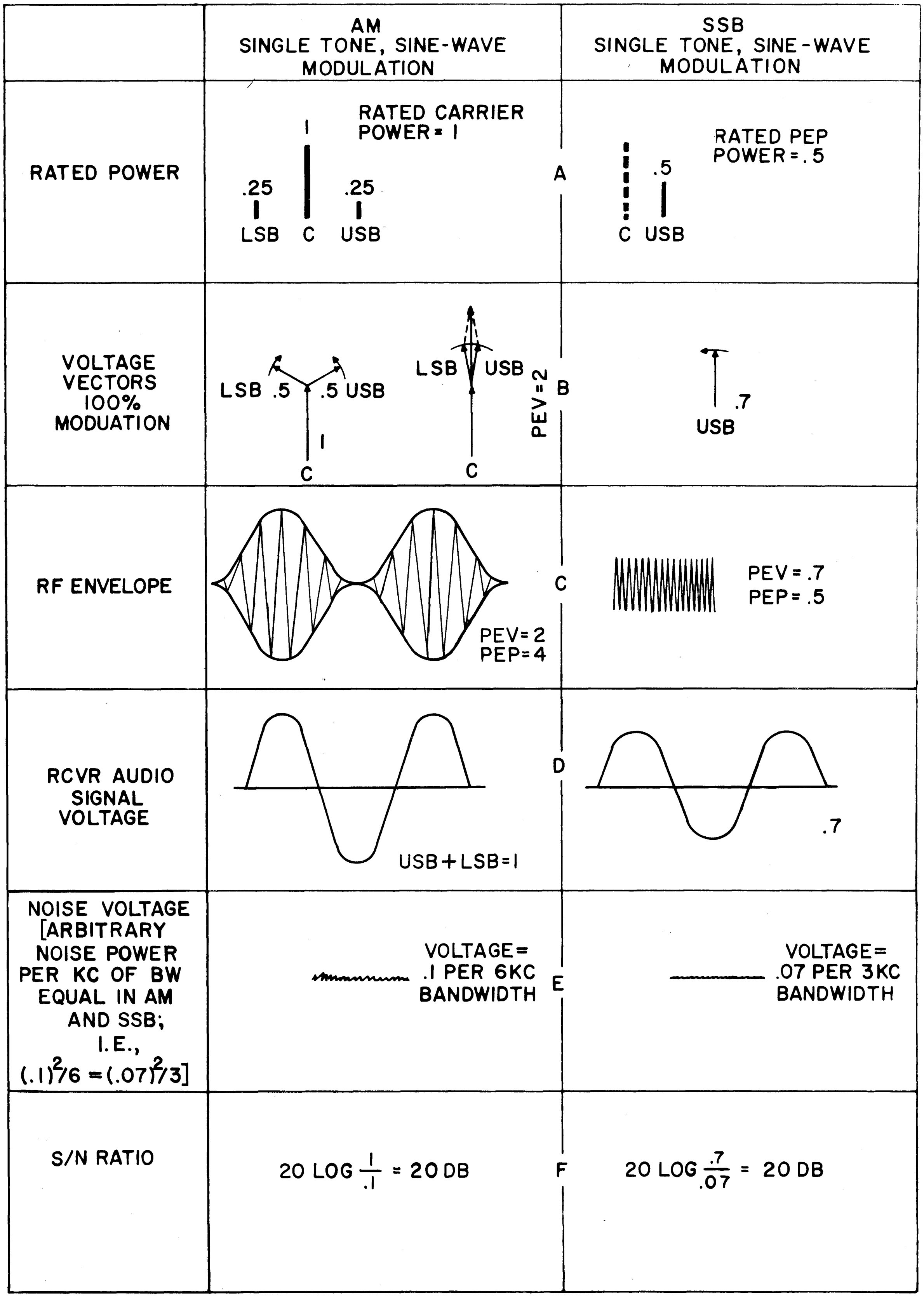


Figure 1-6. SSB and AM. Comparison with Equal Signal-to-Noise Ratio

transmitter. This conclusion can be restated as follows:

Under ideal propagating conditions but in the presence of broadband noise, an SSB and AM. system perform equally (same s/n ratio) if the total sideband power of the two transmitters is equal. This means that an SSB transmitter will perform as well as an AM. transmitter of twice the carrier power rating under ideal propagating conditions.

b. ANTENNA VOLTAGE COMPARISON OF SSB AND AM.

Of special importance in airborne and mobile installations where electrically small antennas are required, is the peak antenna voltage. In these installations, it is often the corona breakdown point of the antenna which is the limiting factor in equipment power. Figure 1-6C shows the r-f envelopes of an SSB transmitter and an AM. transmitter of equal performance under ideal conditions. The peak-envelope-voltage produced by these two transmitters is shown to be in the ratio 2 for the AM. transmitter to .7 for the SSB transmitter. This indicates that for equal performance under ideal conditions, the peak antenna voltage of the SSB system is approximately 1/3 that of the AM. system.

A comparison between the SSB power and the AM. power which can be radiated from an antenna of given dimensions is even more significant. If an antenna is chosen which will radiate 400 watts of peak-envelope-power, the AM. transmitter which may be used with this antenna must be rated at no more than 100 watts. This is true because the PEP of the AM. signal is four times the carrier power. An SSB transmitter rated at 400 watts of PEP, all of which is sideband power, may be used with this same antenna. Compared with the 50 watts of sideband power obtained from the AM. transmitter with a 100-watt carrier rating.

c. ADVANTAGE OF SSB WITH SELECTIVE FADING CONDITIONS

The power comparison between SSB and AM. given in the previous paragraph is based on ideal propagation conditions. However, with long distance transmission, AM. is subject to selective fading which causes severe distortion and a weaker received signal. At times this can make the received signal unintelligible. An AM. transmission is subject to deterioration under these poor propagation conditions, because all three components of the transmitted signal, the upper sideband, lower sideband, and carrier must be received exactly as transmitted to realize fidelity and the theoretical power from the signal. Figure 1-7 shows the deterioration of an AM. signal with different types of selective fading.

The loss of one of the two transmitted sidebands results only in a loss of signal voltage from the demodulator. Even though some distortion results, such a loss is not basically detrimental to the signal, because one sideband contains the same intelligence as the other. However, since the AM. receiver operates on the broad bandwidth necessary to receive both sidebands, the noise level remains constant even though only one sideband is received. This is equivalent to a 6 db deterioration in s/n ratio out of the receiver. Although the loss of one of the two sidebands may be an extreme case, a proportional deterioration in s/n ratio results from the reduction in the level of one or both sidebands.

The most serious result of selective fading, and the most common, occurs when the carrier level is attenuated more than the sidebands. When this occurs, the carrier voltage at the receiver is less than the sum of the two sideband voltages. When the carrier is attenuated more than the sidebands, the r-f envelope does not retain its original shape, and distortion is extremely severe upon demodulation. This distortion results upon demodulation because a carrier voltage at least as strong as the sum of the two sideband voltages is required to properly demodulate the signal. The distortion resulting from a weak carrier can be overcome by use of the exalted carrier technique whereby the carrier is amplified separately and then reinserted before demodulation. In using the exalted carrier, the carrier must be reinserted close to the original phase of the AM. carrier.

Selective fading can also result in a shift between the relative phase position of the carrier and the sidebands. An AM. modulation is vectorally represented by two counter-rotating sideband vectors which rotate with respect to the carrier vector. The resultant of the sideband vectors is always directly in phase or directly out of phase with the carrier vector. In an extreme case, the carrier may be shifted 90° from its original position. When this occurs, the resultant of the sideband vectors is ±90° out of phase with the carrier vector. This results in converting the original AM. signal to a phase modulated signal. The envelope of the phase modulated signal bears no resemblance to the original AM. envelope and the conventional AM. detector will not produce an intelligible signal. Any shift in the carrier phase from its original phase relationship with respect to the sidebands will produce some phase modulation with a consequential loss of intelligibility in the audio signal. Such a carrier phase shift may be caused by poor propagating conditions. Such a carrier phase shift will also result from using the exalted carrier technique if the reinserted carrier is not close to its original phase, as previously mentioned.

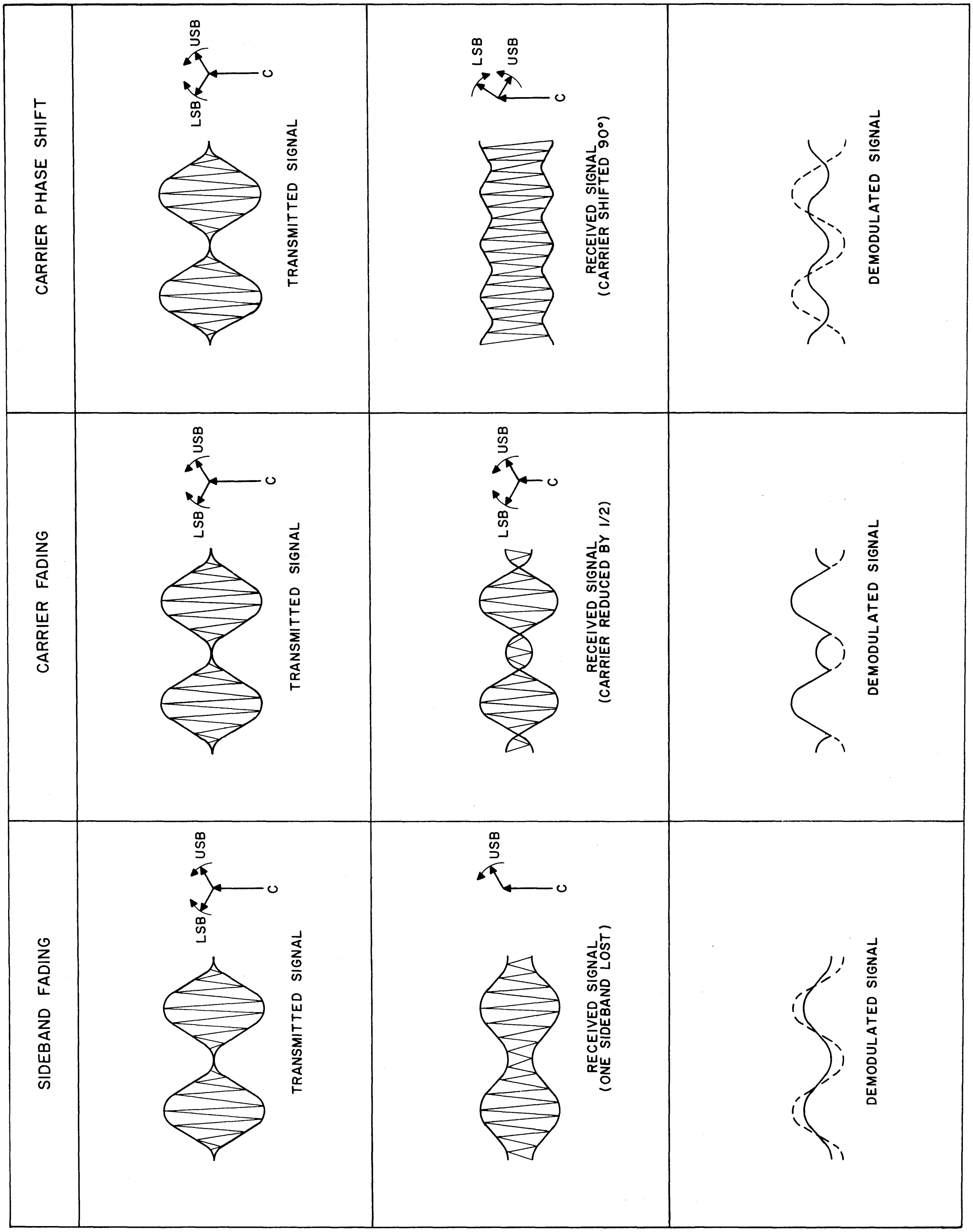


Figure 1-7. Deterioration of an AM. Signal with Selective Fading

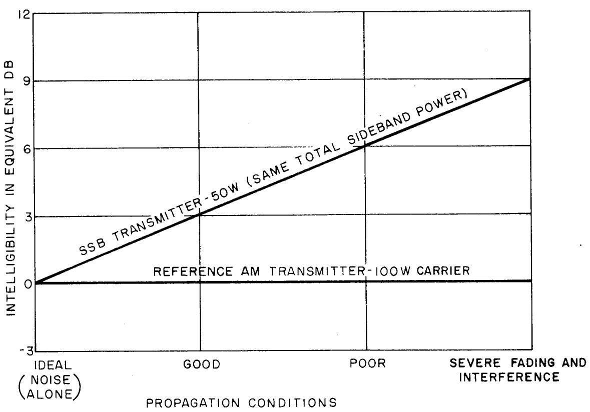


Figure 1-8. Relative Advantage of SSB over AM. with Limiting Propagating Conditions

An SSB signal is not subject to deterioration due to selective fading which varies either the amplitude or the phase relationship between the carrier and the two sidebands in the AM. transmission. Since only one sideband is transmitted in SSB, the received signal level does not depend upon the resultant amplitude of two sideband signals as it does in AM. Since the receiver signal does not depend upon a carrier level in SSB, no distortion can result from loss of carrier power. Since the receiver signal does not depend upon the phase relationship between the sideband signal and the carrier, no distortion can result from phase shift. Selective fading within the one sideband of the SSB system only changes the amplitude and the frequency response of the signal. It very rarely produces enough distortion to cause the received signal or voice to be unintelligible.

d. COMPARISON OF SSB WITH AM. UNDER LIMITING PROPAGATING CONDITIONS

One of the main advantages of SSB transmission over AM. transmission is obtained under limiting propagating conditions over a long-range path where communications are limited by the combination of noise, severe selective fading, and narrow-band interference. Figure 1-8 illustrates the results of an intelligibility study performed by rating the intelligibility of information received when operating the two systems under varying conditions of propagation.[1] The two transmitters compared have the same total sideband power. That is, a 100 watt AM. transmitter puts 1/4 of its rated carrier power in each of two sidebands, while a 50 watt SSB transmitter puts its full rated output in one sideband. This study shows that as propagation conditions worsen, and interference and fading become prevalent, the received SSB signal will provide up to a 9 db advantage over the AM. signal. The result of this study indicates that the SSB system will give from 0 to 9 db improvement under various conditions of propagation when total sideband power in SSB is equal to AM. It has been found that 3 of the possible 9 db advantage will be realized on the average contact. In other words, in normal use, an SSB transmitter rated at 100 watts (PEP) will give equal performance with an AM. transmitter rated at 400 watts carrier power. It should be pointed out that in this comparison the receiver bandwidth is just enough to accept the transmitted intelligence in each case and no speech processing is considered for SSB transmission.

e. COMPARISON OF AIRBORNE HIGH-FREQUENCY SYSTEMS

Figure 1-9 shows a comparison in weight, volume, input power, effective output power, and peak antenna voltage between Radio Set AN/ARC-38 and Radio Set AN/ARC-58. These sets are both airborne transceivers operating in the 2 to 30 mc, high-frequency range. The AM. set, AN/ARC-38, is rated at 100 watts r-f output, and the SSB set, AN/ARC-58, is rated at 1000 watts r-f output.

The effective output power of the SSB transceiver is shown to be 16 db higher than the AM. transceiver. This 16 db is equivalent to a power advantage of 40 to 1, which is an enormous advancement in the communication ability of an airborne system. In addition to the power advantage of the SSB system of significance in airborne equipment is the more efficient use of the antenna with the SSB system.

f. SUMMARY

For long-range communications in the low-, medium-, and high-frequency ranges, SSB is well suited because of its spectrum and power economy and because it is less susceptible to the effects of selective fading and interference than is AM. The principal advantages of SSB result from the elimination of the high-energy AM. carrier and from improved performance under unfavorable propagating conditions. On the average contact, an SSB transmitter will give equal performance to an AM. transmitter of four times the power rating. The advantage of SSB over AM. is most outstanding under unfavorable propagating conditions. For equal performance, the

[1] J. F. Honey, "Performance of AM. and SSB Communications," Tele-Tech, September 1953.

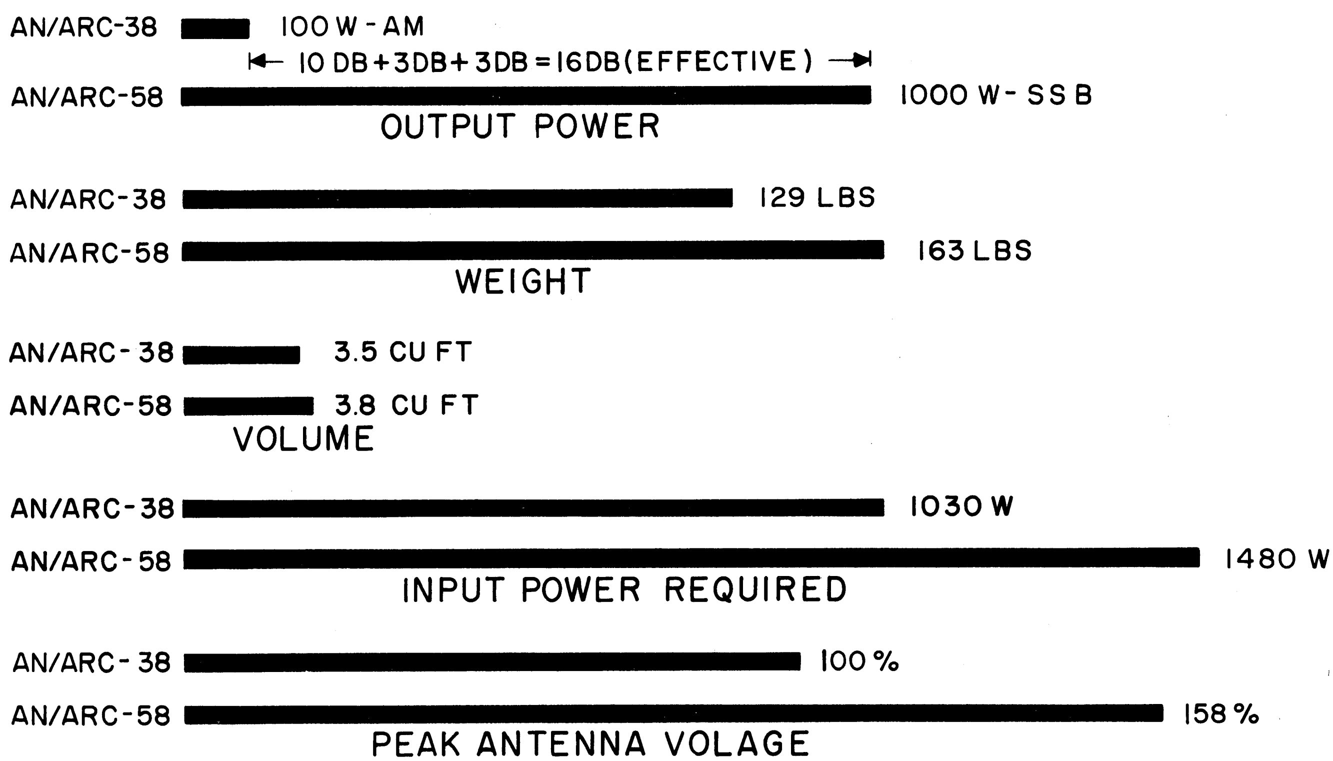


Figure 1-9. AN/ARC-38 and AN/ARC-58 Comparison

size, weight, power input, and peak antenna voltage of the SSB transmitter is significantly less than the AM. transmitter.

7. COMPARISON OF SSB WITH FM

Although much experimental work has been done to evaluate the performance of SSB systems with AM. systems, very little work has been done to evaluate the performance of SSB systems with FM systems. However, figure 1-10 shows the predicted result of one such study based on a mobile FM system as compared to a mobile SSB system of equal physical size.[1] The two systems compared also used the same output tubes to their full capacity so that the final r-f amplifiers dissipated the same power during normal speech loading. The study is complicated by evaluating the effects of speech processing, such as clipping and pre-emphasis, with its resultant distortion. Such speech processing is essential in the FM system but has little benefit in the SSB system.

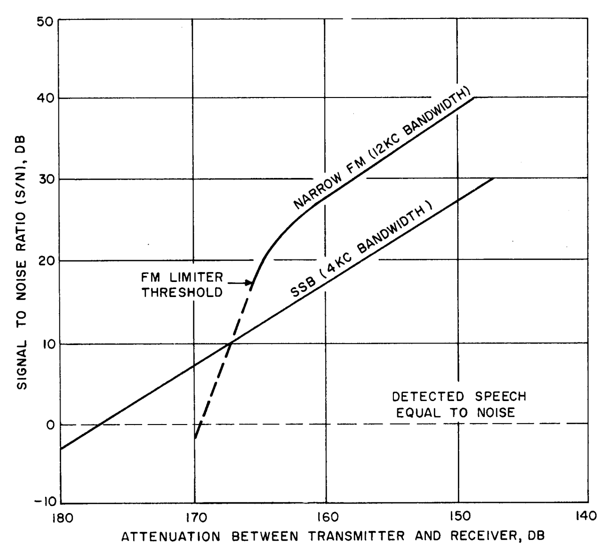


Figure 1-10. SSB Performance Compared with FM

[1] H. Magnuski and W. Firestone, "Comparison of SSB and FM for VHF Mobile Service," Proceedings of the IRE, December 1956.

Figure 1-10 shows the signal-to-noise ratio in decibels on the y-axis and the attenuation between transmitter and receiver in decibels on the x-axis. This graph indicates that with between 150 to 160 db of attenuation between the transmitter and receiver, a strong signal, the narrow-band FM system provides a better s/n ratio than the SSB system. Under weak signal condition, from 168 and higher db of attenuation between transmitter and receiver, the s/n ratio of the FM system falls off rapidly, and the SSB system provides the best s/n ratio. This fall-off in the FM s/n ratio results when the signal level drops below the level required for operation of the limiter in the FM receiver.

The conclusions which can be drawn from figure 1-10 are as follows: (1) For strong signals, the FM system will provide a better s/n ratio than the SSB system. However, this is not an important advantage because when the s/n is high, a still better s/n ratio will not improve intelligibility significantly. (2) For weak signals, the SSB system will provide an intelligible signal where the FM system will not. (3) The SSB system provides three times the savings in spectrum space as the narrow-band FM system.

8. NATURE OF SINGLE-SIDEBAND SIGNALS

a. INTRODUCTION

As defined in paragraph 2, chapter 2, a single-sideband signal is an audio signal converted to a radio frequency, with or without inversion. To facilitate illustrating the manner and the results of this conversion, it is necessary to use pure sine-wave tones, rather than the very complex waveforms of the human voice. For this reason single tones or combinations of two or three tones are generally used in the following discussion.

b. THE SSB GENERATOR

The most familiar SSB generator consists of a balanced modulator followed by an extremely selective mechanical filter as shown in figure 1-11. The balanced modulator produces basically two output frequencies: (1) An upper sideband frequency equal to the injected i-f frequency plus the input audio frequency. (2) A lower sideband frequency equal to the injected i-f frequency minus the input audio frequency. Theoretically, the injected i-f frequency is balanced out in the modulator so that it does not appear in the output.

It should be especially noted that the generation of undesirable products occur in any mixing operation as well as the generation of the desired products. The equipment must be so designed to minimize the generation of undesirable products and to attenuate those undesirable products which are generated. This is accomplished by designing good linear operating characteristics into the equipment to minimize the generation of undesirable frequencies and by choosing injection frequencies which will facilitate suppression of undesirable frequencies.

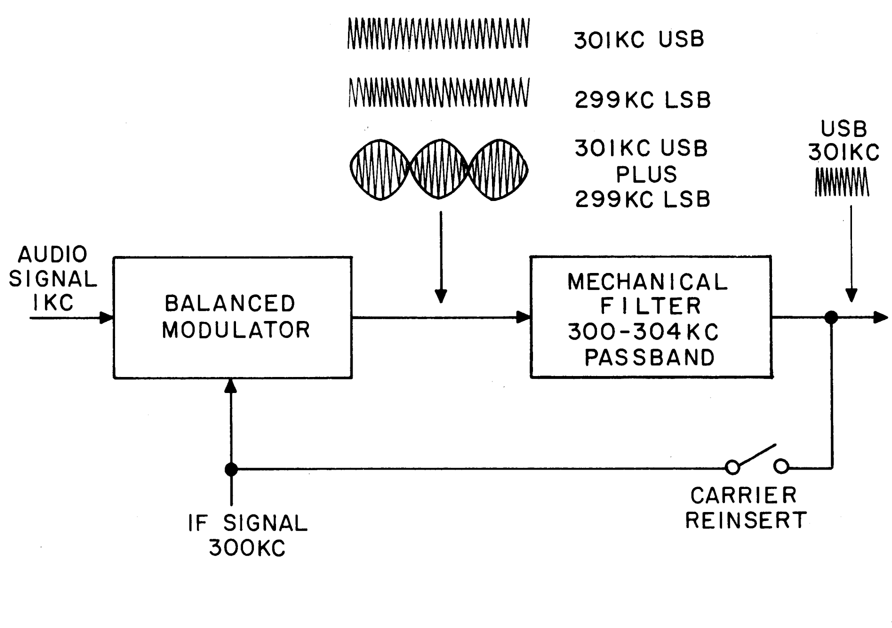


Figure 1-11. Filter-Type SSB Generator

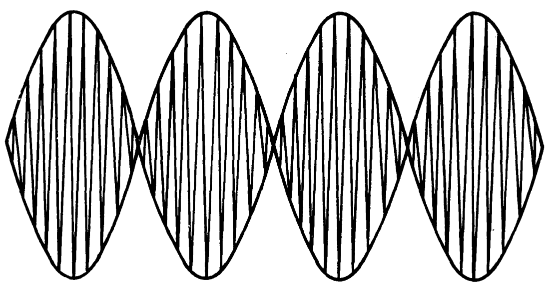


Figure 1-12. Single-Tone, Balanced Modulator Output

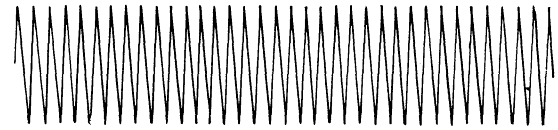


Figure 1-13. Single-Tone Balanced Modulator Output After Filtering Out the LSB

It should also be noted that the i-f carrier injected into the balanced modulator is only theoretically canceled from the output. Practical design considerations determine the extent to which the carrier can be balanced out. Present balanced modulators, using controlled carrier leak to balance out uncontrolled carrier leak, result in carrier suppression of from 30 db to 40 db below the PEP of the sidebands. Further suppression of the carrier by the SSB filter results in an additional 20 db of carrier suppression. Total carrier suppression of from 50 db to 60 db can, therefore, reasonably be expected from the transmitter system.

c. GENERATING THE SINGLE-TONE SSB WAVEFORM

The most fundamental SSB waveform is generated from the single audio tone. This tone is processed through the SSB generator to produce a single i-f frequency. As pointed out in paragraph 4, chapter 1, the SSB signal is actually generated at an i-f frequency and is subsequently converted up in frequency to the transmitted r-f frequency. It is the generation of the SSB signal at the i-f frequency with which we are concerned.

Figures 1-12 and 1-13 show the waveforms obtained in a filter-type SSB generator. The audio tone injected into the balanced modulator is 1 kc and the i-f frequency injected is 300 kc. The output from the balanced modulator contains the 299 kc lower sideband and 301 kc upper sideband frequencies. These two sideband frequencies, being of equal amplitude, produce the characteristic half sine-wave envelope shown in figure 1-12. The repetition rate of this envelope with a 1-kc tone is 2 kc, the difference between the two frequencies represented by the envelope. This i-f signal, which contains both the upper sideband and lower sideband signal, is called a double-sideband signal (DSB).

By passing the DSB signal through a highly selective filter with a 300 kc to 303 kc passband, the upper sideband signal is passed while the lower sideband signal is attenuated. The 301 kc signal which remains is the upper sideband signal and appears as shown in figure 1-13. Note that the SSB signal remaining is a pure sine wave when a single-tone audio signal is used for modulation. This SSB signal is displaced up in the spectrum from its original audio frequency by an amount equal to the carrier frequency, in this case 300 kc. This SSB signal can be demodulated at the receiver only by converting it back down in the frequency spectrum. This is done by mixing it with an independent 300 kc i-f signal at the receiver.

d. GENERATING THE SSB WAVEFORM OF A SINGLE TONE WITH CARRIER

From the single-tone SSB signal without carrier, it is a simple step to generate the single-tone SSB signal with carrier. This is done by reinserting the carrier after the filtering operation, as shown in figure 1-11. When the carrier reinserted is of the same amplitude as the SSB signal, the waveform shown in figure 1-14 results. Note that this waveform is similar to the double-sideband signal obtained directly out of the balanced modulator, as shown in

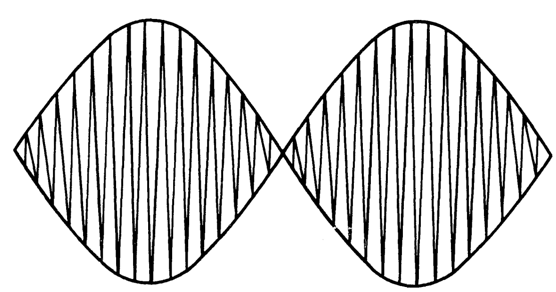


Figure 1-14. Single-Tone SSB Signal with Carrier--Carrier Equal in Amplitude to Tone

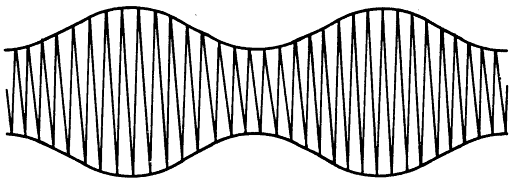


Figure 1-15. Single-Tone SSB Signal with Carrier--Carrier 10 DB Below Tone

figure 1-12. However, the frequency components of the two waveforms are not the same. The frequency components of the SSB signal with carrier are 301 kc and 300 kc when a 1-kc audio signal is used. The SSB signal with full carrier can be demodulated with a conventional diode detector used in AM. receivers without serious distortion or loss of intelligibility.

If the reinserted carrier is such that the carrier level is less than the level of the single-tone SSB signal, the waveform shown in figure 1-15 results. To successfully demodulate this signal, the carrier must be separated, amplified, exalted, and reinserted in the receiver, or locally supplied. The separate carrier amplification should be sufficient to raise the reinserted carrier to a level greater than the level of the sideband signal. The waveform shown in figure 1-15 represents the waveform used in the SSB with pilot carrier systems. The exalted carrier technique is used to demodulate such a signal.

e. GENERATING THE TWO-TONE SSB WAVEFORM

The two-tone SSB waveform is generated by combining two audio tones and then injecting this two-tone signal into the balanced modulator. One sideband is then suppressed by the filter, leaving the SSB waveform shown in figure 1-16. This two-tone SSB signal is seen to be similar to the single-tone DSB signal as well as the SSB signal with full carrier. However,

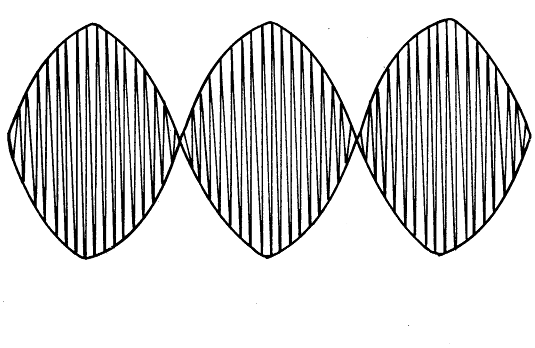


Figure 1-16. Two-Tone SSB Signal-Tones of Equal Amplitude

the two-tone SSB signal contains a different two frequencies than either of the other two. In the two-tone SSB signal shown in figure 1-16, 1 kc and 2 kc audio signals of equal amplitude are injected into the balanced modulator. After filtering, this results in a two-tone SSB signal containing frequencies of 301 kc and 302 kc. If a pilot carrier is reinserted with the two-tone test signal, the pilot carrier will be indicated by the appearance of a sine-wave ripple on the two-tone waveform. This waveform is shown in figure 1-17.

The generation of this two-tone envelope can be shown clearly with vectors representing the two audio frequencies, as shown in figure 1-18. When the two vectors are exactly opposite in phase, the envelope value is zero. When the two vectors are exactly in phase, the envelope value is maximum. This generates the half sine-wave shape of the two-tone SSB envelope which has a repetition rate equal to the difference between the two audio tones.

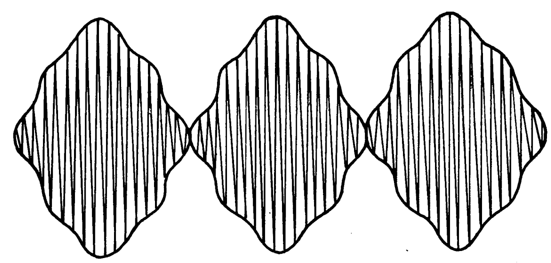
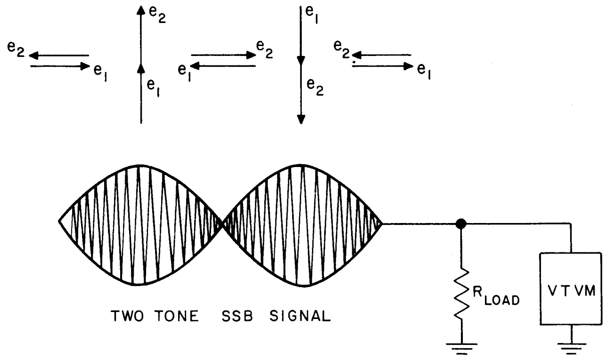


Figure 1-17. Two-Tone SSB Signal with Small Reinserted Pilot Carrier

The two-tone SSB envelope is of special importance because it is from this envelope that power output from an SSB system is usually determined. An SSB transmitter is rated in peak-envelope-power output with the power measured with a two equal-tone test signal. With such a test signal, the actual watts dissipated in the load are one-half the peak-envelope-power. This is shown in figure 1-18. When the half sine-wave signal is fed into a load, a peak-reading, rms-calibrated vtvm across the load indicates the rms value of the peak-envelope-voltage. This voltmeter reading is equal to the in-phase sum of $e_1 + e_2$, where e_1 and e_2 are the rms voltages of the two tones. Since in the two-tone test signal e_1 equals e_2, the PEP equals $(2e_1)^2/R$ or $(2e_2)^2/R$. The average power dissipated in the load must equal the sum of the power represented by each tone, $e_1^2/R + e_2^2/R$, $4e_1^2R$ or $4e_2^2/R$. Therefore, with a two equal-tone SSB test signal, the average power dissipated in the load is equal



$$V_{vtvm} = (e_1 + e_2),$$

with e_1 and e_2 in phase and rms values

$$PEP = V^2_{vtvm}/R_{load} = 4e_1^2/R \text{ or } 4e_2^2/R,$$

where $e_1 = e_2$

$$P_{average} = e_1^2/R + e_2^2/R = 2e_1^2/R \text{ or } 2e_2^2/R$$

Therefore: (1) $PEP = V^2_{vtvm}/R$

(2) $P_{average} = 1/2 \; PEP$

(3) $P_{tone\,1}$ or $P_{tone\,2} = 1/4 \; PEP$

Figure 1-18. Power Measurements from Two-Tone SSB Test Signal

to 1/2 of the PEP, and the power in each tone is equal to 1/4 of the PEP. Peak-envelope-power can be determined from the relationship "$PEP = V^2_{vtvm}/R$;" the average power can be determined from the relationship "$P_{average} = 1/2 \, V^2_{vtvm}/R$." This is true only where the vtvm used is a peak-reading, rms-calibrated voltmeter. Similar measurements can be made using an a-c ammeter in series with the load instead of the vtvm across the load.

The above analysis can be carried further to show that with a three equal-tone SSB test signal, the power in each tone is 1/9 of the PEP, and the average power dissipated in the load is 1/3 the PEP. These relationships are true only if there is no distortion of the SSB envelope, but since distortion is usually small, its effects are usually neglected.

f. GENERATING THE SQUARE WAVEFORM

Transmitting an audio square wave at a radio frequency imposes severe requirements on any transmitting system. This is true because the square wave is composed of an infinite number of odd-order harmonics of the fundamental frequency of the square wave. Therefore, to transmit such a signal without distortion requires an infinite bandwidth, an infinite spectrum. This, of course, is impossible because tuned circuits will not pass an infinite bandwidth. The idealized SSB square wave, where all frequency components are present, shown in figure 1-19, indicates that the SSB signal requires infinite amplitude as well as infinite bandwidth. This occurs because the harmonically related SSB components will add vectorally to infinity when the modulating signal switches from maximum positive to maximum negative and vice versa. This infinite amplitude is not present in an AM. envelope, because the AM. envelope contains both sidebands with the frequency components in one sideband counter-rotating vectorally from the frequency components in the other sideband. The result is, then, when the resultant amplitude of one sideband is plus infinity; the resultant amplitude of the other sideband is minus infinity, which produces a net amplitude of zero.

The significance of the SSB square wave lies in its relationship with conventional clipping techniques used to limit the modulation level. Figure 1-20 shows the SSB envelope which results from severely clipping a 300 cps sine wave. The clipping level is such that the modulating signal is essentially a square wave. In generating the SSB envelope from the modulating signal, all harmonics above the ninth are removed by the highly selective SSB filter. Figure 1-19 shows that speech clipping, as used in AM., is of no practical value in an SSB transmitter because the SSB envelope is so different from the audio envelope. In an SSB transmitter, automatic load control, rather than clipping, is used to prevent overdriving the power amplifier by holding down the modulation level. It is possible to use a significant amount of clipping in an

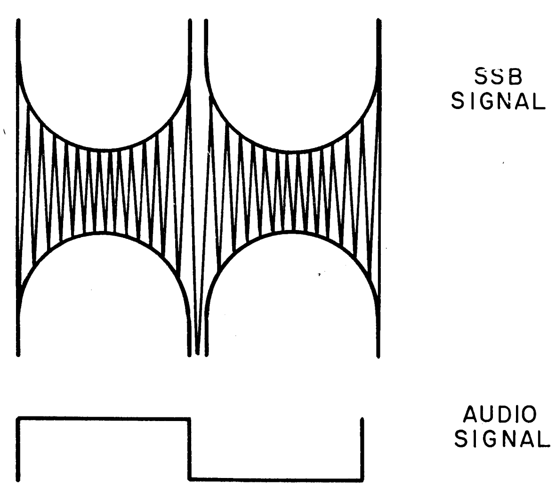


Figure 1-19. Square Wave SSB Signal--All Frequency Components Present

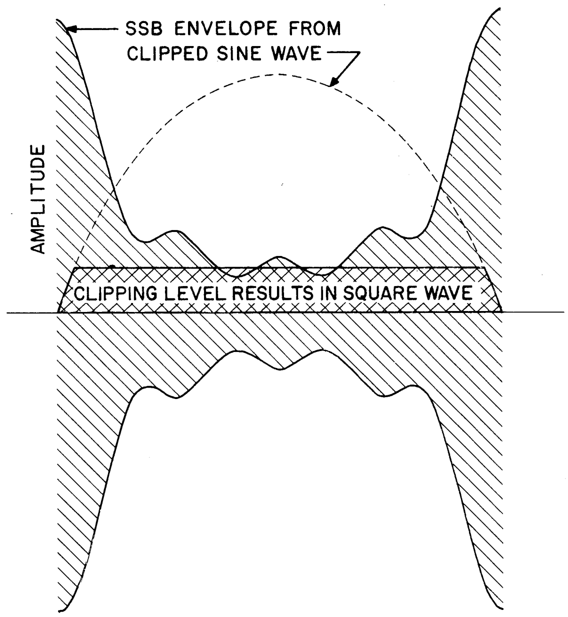


Figure 1-20. SSB Envelope Developed from 300 CPS, Clipped Sine-Wave (Harmonics above 9th Attenuated)

Over-all transmission efficiency depends upon the average power transmitted, while transmitter power is limited to the peak power capability of the transmitter. Therefore, for voice transmission, it behooves the transmitter designer to use speech-processing circuits which will increase the average power in the voice signal without increasing the peak power. This can be done in three different ways: (1) by clipping the power peaks, (2) by emphasizing the low-power, high-frequency components of the speech signal and attenuating the high-power, low-frequency components of the speech signal, and (3) by using automatic-gain-control circuits to keep the signal level near the maximum capability of the transmitter.

Figure 1-23 shows a power vs frequency distribution curve for the average human voice, after filtering below 200 cps and above 3000 cps. This curve shows that the high-power components of speech are concentrated in the low frequencies. Fortunately, it is the low-frequency components of speech which contribute little to intelligibility since these frequencies are concentrated in the vowel sounds. The low frequencies, therefore may be attenuated without undue loss

SSB transmitter if the clipping is performed on the i-f SSB signal rather than on the audio signal. If clipping were performed at this time, additional filtering would be required to remove the harmonic products caused by the clipping. However, clipping at this stage is satisfactory, because the harmonic products produced are not in the passband of the filter and only small intermodulation products are generated in the passband.

g. GENERATING THE VOICE WAVEFORM

The human voice produces a complex waveform which can be represented by numerous frequency components of various amplitudes and various instantaneous phase relationships. No human voice is exactly like another voice, but statistical averages concerning the frequencies and amplitudes in the human voice can be determined. The average power level of speech is relatively low when compared to the peak power level. An audio frequency waveform of an ā sound is shown in figure 1-21. This same ā sound, raised in frequency, is shown in figure 1-22 as it appears as an SSB signal. From the "Christmas-tree" shape of these waveforms, it is evident that the peak power, which is related to the peak voltage of a waveform is considerably higher than the average power.

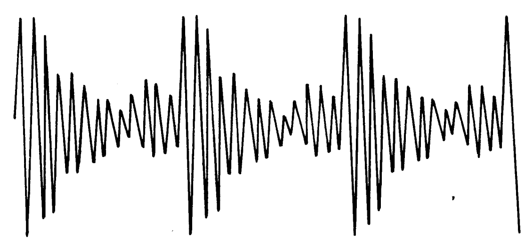


Figure 1-21. Voice Signal at Audio Frequency--ā Sound

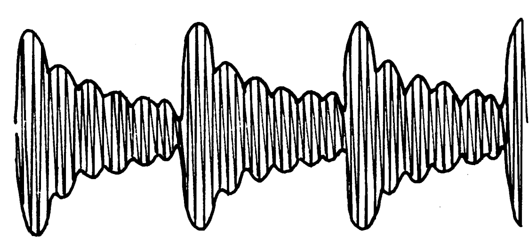


Figure 1-22. SSB Voice Signal--a Sound

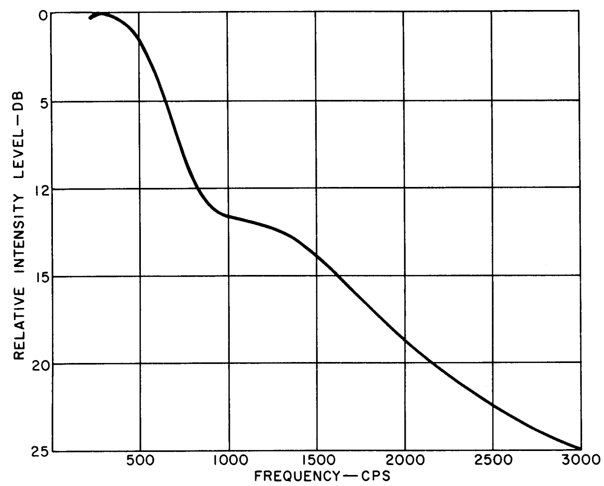


Figure 1-23. Power Distribution in Speech Frequencies--Low and High Frequencies Removed

of intelligibility of the speech. The low-power, high-frequency components present in a voice signal can be pre-emphasized to increase the average power of the signal. Since it is the high-frequency components which are predominate in the consonant sounds, some emphasis of the high frequencies will improve intelligibility. However, to emphasize the high frequencies sufficiently to raise the average power level significantly would require compatible de-emphasis at the receiver to prevent loss of fidelity.

Clipping power peaks results in flattening the waveform at the clipping level, and with severe clipping the voice signal becomes a series of square waves. Since an SSB square wave envelope requires infinite amplitude as well as infinite bandwidth, clipping the audio signal must be done with discretion. In the SSB transmitter, automatic load control is used to control the average power level input, rather than clipping, to prevent overdriving the power amplifier. Clipping then is used only to remove the occasional power peaks.

Speech-processing methods are being reinvestigated in relationship to SSB transmission to determine the most suitable method or combination of methods. Several circuits are presently used in SSB transmitters which effect some speech processing, although the primary purpose of most of these circuits is to process the input signal to prevent overdriving the power amplifier. These circuits include the following: (1) Automatic-load-control to maintain signal peaks at the maximum rating of the power amplifier. (2) Speech compression, along with some clipping, to maintain a constant signal level to the single-sideband generator. (3) Highly-selective filters used in filter-type SSB exciters attenuate some of the high-power, low-frequency components of the voice signal. There are also several speech processing circuits under investigation which, if effective and practical, will be used to improve the efficiency of voice transmission. These circuits include (1) increased audio clipping with additional filtering to remove the harmonics generated, (2) reduction of the power level of frequencies below 1000 cps by shaping the audio amplifier characteristics for low-frequency roll-off, and (3) use of speech clipping at an i-f level where the generated harmonics can be more easily filtered. See paragraph 2-2a for input signal processing circuits used in an SSB exciter.

9. MECHANICAL FILTERS

Both SSB transmitters and SSB receivers require very selective bandpass filters in the region of 100 kc to 500 kc. In receivers, a high order of adjacent channel rejection is required if channels are to be closely spaced to conserve spectrum space. In SSB transmitters, the signal bandwidth must be limited sharply in order to pass the desired sideband and reject the other sideband. The filter used, therefore, must have very steep skirt characteristics and a flat bandpass characteristic. These filter requirements are met by LC filters, crystal filters, and mechanical filters. Until recently, crystal filters used in commercial SSB equipment were in the 100-kc range. These filters have excellent selectivity and stability characteristics, but their large size makes them subject to shock or vibration deterioration and their cost is quite high. Newer crystal filters are being developed which have extended frequency range and are smaller. These newer crystal filters are more acceptable for use in SSB equipment. LC filters have been used at i-f frequencies in the region of 20 kc. However, generation of the SSB signal at this frequency requires an additional mixing stage to obtain a transmitting frequency in the high-frequency range. For this reason, LC filters are not widely used. The recent advancements in the development of the mechanical filter have led to their acceptance in SSB equipment. These filters have excellent rejection characteristics, are extremely rugged, and are small enough to be compatible with miniaturization of equipment. Also to the advantage of the mechanical filter is a Q in the order of 10,000 which is about 100 times the Q obtainable with electrical elements.

Although the commercial use of mechanical filters is relatively new, the basic principles upon which they are based is well established. The mechanical filter is a mechanically resonant device which receives electrical energy, converts it into mechanical

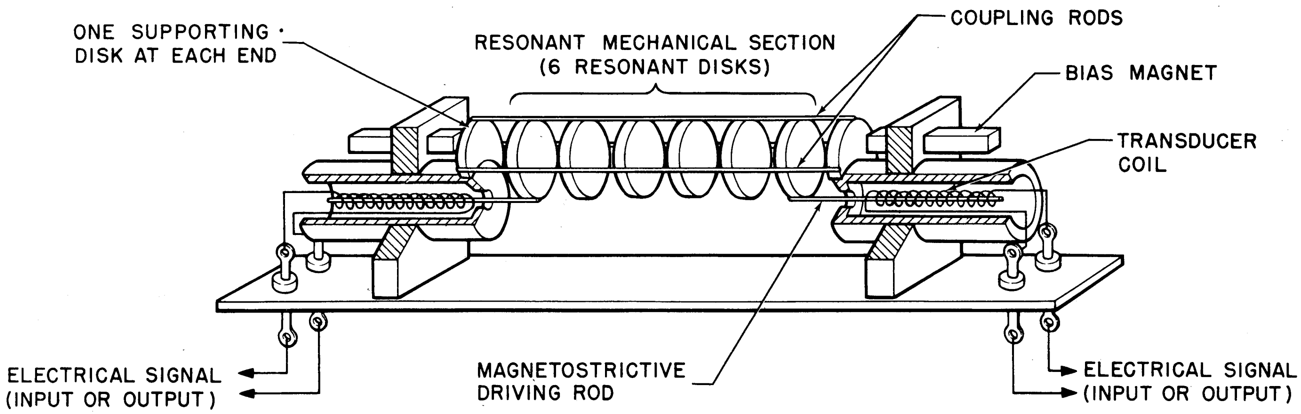


Figure 1-24. Elements of a Mechanical Filter

vibration, then converts the mechanical energy back into electrical energy at the output. The mechanical filter consists of basically four elements: (1) an input transducer which converts the electrical input into mechanical oscillations, (2) metal disks which are mechanically resonant, (3) coupling rods which couple the metal disks, and (4) an output transducer which converts the mechanical oscillations back into electrical oscillations. Figure 1-24 shows the elements of the mechanical filter, and figure 1-25 shows the electrical analogy of the mechanical filter. In the electrical analogy the series resonant circuits L_1C_1 represent the metal disks, the coupling capacitors C_2 represent the coupling rods, and the input and output resistances R represent the matching mechanical loads.

The transducer, which converts electrical energy into mechanical energy and vice versa, may be either a magnetostrictive device or an electrostrictive device. The magnetostrictive transducer is based on the principle that certain materials elongate or shorten when in the presence of a magnetic field. Therefore, if an electrical signal is sent through a coil which contains the magnetostrictive material as the core, the electrical oscillation will be converted into mechanical oscillation. The mechanical oscillation can then be used to drive the mechanical elements of the filter. The electrostrictive transducer is based on the principle that certain materials, such as piezoelectric crystals, will compress when subjected to an electric current. In practice, the magnetostrictive transducer is more commonly used. The transducer not only converts electrical energy into mechanical energy and vice versa; it also provides proper termination for the mechanical network. Both of these functions must be considered in transducer design.

From the electrical equivalent circuit, it is seen that the center frequency of the mechanical filter is

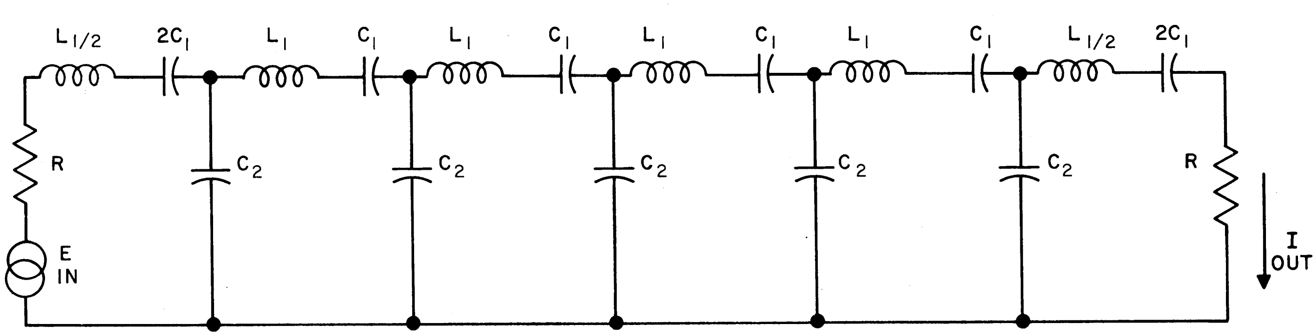


Figure 1-25. Electrical Analogy of a Mechanical Filter

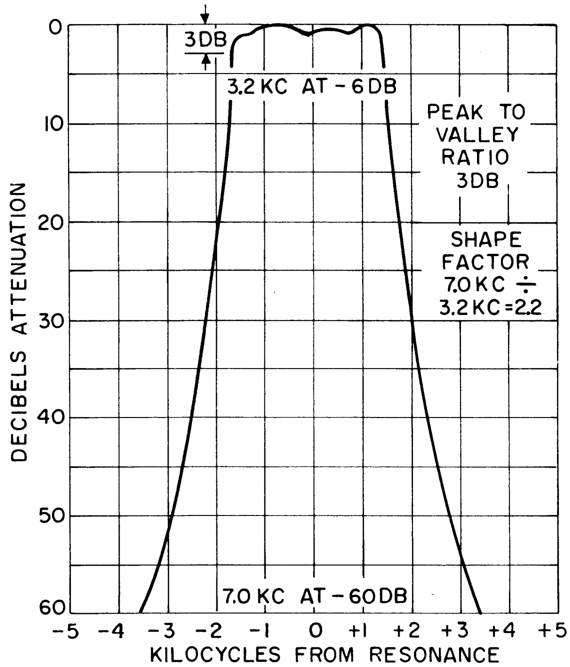


Figure 1-26. Mechanical Filter Characteristic Curve

determined by the metal disks which represent the series resonant circuit L_1C_1. In practice, filters between 50 kc and 600 kc can be manufactured. This by no means indicates mechanical filter limitations, but is merely the area of design concentration in a relatively new field. Since each disk represents a series resonant circuit, it follows that increasing the number of disks will increase skirt selectivity of the filter. Skirt selectivity is specified as shape factor which is the ratio (bandpass 60 db below peak)/(bandpass 6 db below peak). Practical manufacturing presently limits the number of disks to eight or nine in a mechanical filter. A six-disk filter has a shape factor of approximately 2.2, a seven-disk filter a shape factor of approximately 1.85, a nine-disk filter shape factor of approximately 1.5. The future development of mechanical filters promises even a faster rate of cutoff.

In the equivalent circuit, the coupling capacitors C_2 represent the rods which couple the disks. By varying the mechanical coupling between the disks, that is, making the coupling rods larger or smaller, the bandwidth of the filter is varied. Because the bandwidth varies approximately as the total area of the coupling wires, the bandwidth can be increased by either using larger or more coupling rods. Mechanical filters with bandwidths as narrow as 0.5 kc and as wide as 35 kc are practical in the 100 kc to 500 kc range.

Although an ideal filter would have a flat "nose" or passband, practical limitations prevent the ideal from being obtained. The term "ripple amplitude" or "peak-to-valley ratio" is used to specify the nose characteristic of the filter. The peak-to-valley ratio is the ratio of maximum to minimum output level across the useful frequency range of the filter (figure 1-26). A peak-to-valley ratio of 3 db can be obtained on a production basis by automatic control of materials and assembly. Mechanical filters with a peak-to-valley ratio of 1 db can be produced with accurate adjustment of filter elements.

Spurious responses occur in mechanical filters due to mechanical resonances other than the desired resonance. By proper design, spurious resonances can be kept far enough from the passband to permit other tuned circuits in the system to attenuate the spurious responses.

Other mechanical filter characteristics of importance include insertion loss, transmission loss, transfer impedance, input impedance, and output impedance. Since the input and output transducers of the mechanical filter are inductive, parallel external capacitors must be used to resonate the input and output impedances at the filter frequency. With such capacitors added, the input and output impedances are largely resistive and range between 1000 ohms to 50,000 ohms. The insertion loss is measured with both the source and load impedance matched to the input and output impedance of the filter. The value of insertion loss ranges between 2 db and 16 db, depending upon the type of transducer. The transmission loss is an indication of the filter loss with

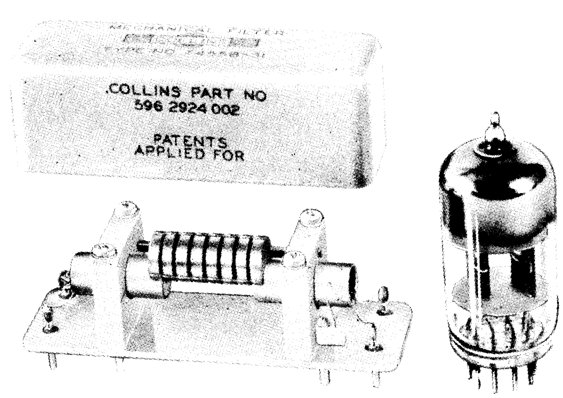


Figure 1-27. Size Comparison Between a Mechanical Filter and a Miniature Tube

source and load impedances mismatched. The transmission loss is of importance when using a mechanical filter in pentode i-f amplifiers where both source and load impedance are much greater than the filter impedances. The transfer impedance is useful to determine the over-all gain of a pentode amplifier stage which utilizes a mechanical filter. The transfer impedance of the filter multiplied by the transconductance of the pentode gives the gain of the amplifier stage.

The physical size of the mechanical filter makes it especially useful for modular and miniaturized construction. Figure 1-27 shows a mechanical filter compared with a miniature tube. The mechanical filter is about 1 inch square by 3 inches long. More recent development has resulted in a smaller tubular filter which is about 1/2 inch in diameter by 1-3/4 inches long.

Mechanical filter types other than the disk type are presently being used. These include the plate type which is a series of flat plates assembled in a ladder arrangement. Another type which has recently been developed is the neck-and-slug type. This filter consists of a long cylinder which is turned down to form the necks which couple the remaining slugs. All mechanical filters are similar in that they employ mechanical resonance. Mechanical filters differ in that they employ various modes of mechanical oscillation to achieve their purpose. They may also use different types of transducers.

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