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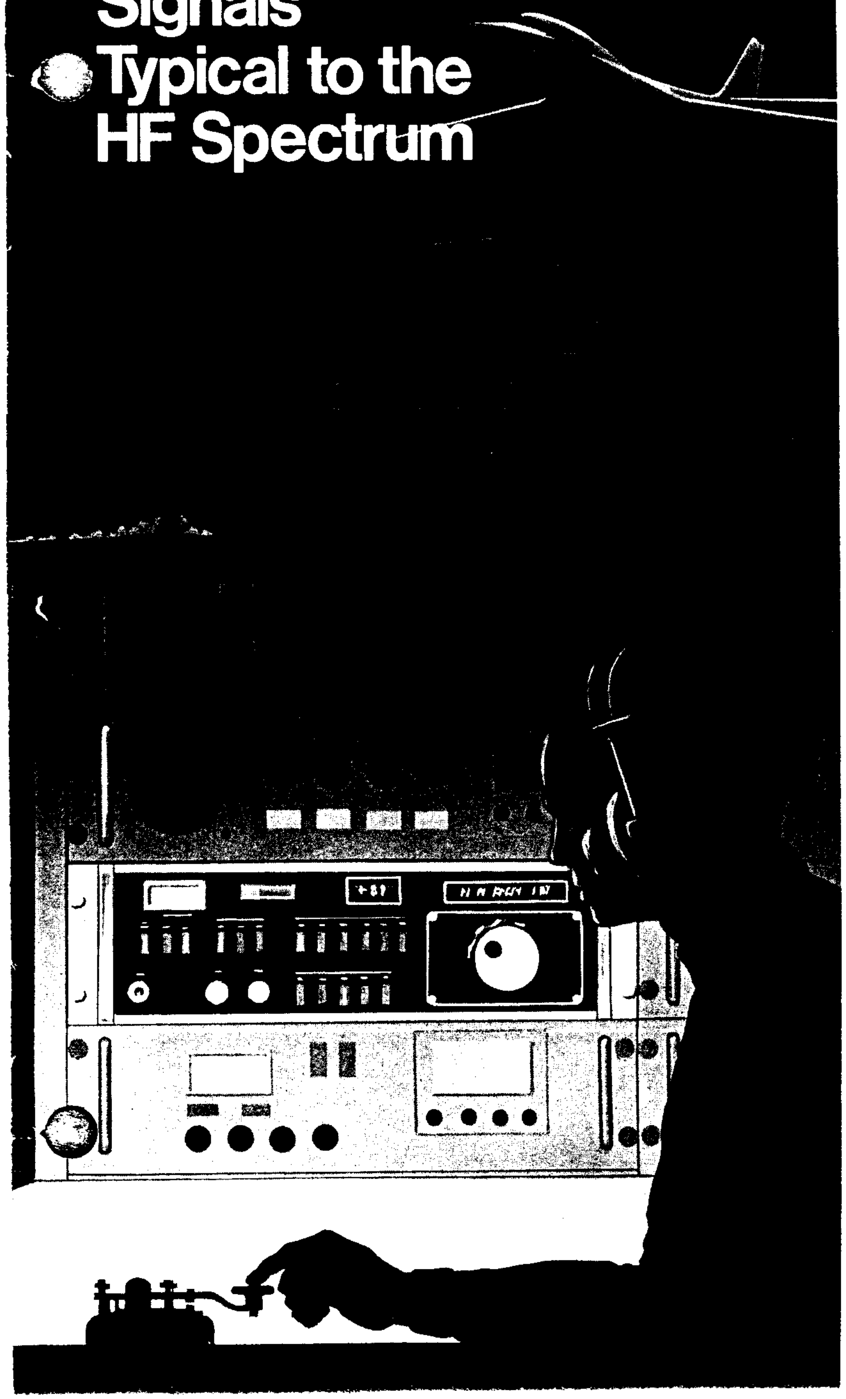
Signals Typical to the HF Spectrum



WATKINS-JOHNSON COMPANY Tech-notes

The HF receiver exists in the oldest RF environment used for radio communication. Since the early experiments that began in 1900, significant advances have been made in many aspects of receiver design, including tuning accuracy, selectivity, high-dynamic-range signal handling, and computer control of receivers. The basic signals that receivers intercept, however, have largely remained unchanged. While experienced operators, Government agencies, and amateur radio operators are familiar with HF-spectrum signals, new entrants to the HF field may benefit from a review of basic HF signal fundamentals. To this end, this article reviews for the reader some of the basic characteristics of the various types of signals used in the HF environment.

Modulation

Modulation is the process of translating information into intelligence-bearing signals which can be transmitted via some intervening medium. A phonograph record may be thought of as "frozen modulation" awaiting the correct demodulating technique to be applied to recover the recorded or stored information.

Many of the fundamental concepts of modulation are almost as old as the telegraph itself. In 1753, a Scotsman named Charles Morrison proposed an electric telegraph which used a separate wire for each letter of the alphabet. This is considered to be the first practical scheme pertaining to telegraphy, and it distinguishes Morrison as the first to put forth the idea of a world-wide telegraph network. Samuel Morse is credited with the invention of the telegraph in 1837, but the period between 1800 and 1850 also saw the fundamental development of the concepts of time-division and frequency-division multiplexing. Around 1870, a two-tone telegraph system that used separate frequencies for the "mark" and "space" indications was developed. This system was a very simple form of frequency modulation.

Progress in the development of modulation techniques and their application to radio began with the invention of the telephone in 1875, and continued through the period of the implementation of time-division multiplexing of the commercial telephone in 1905 and frequency-division multiplexing in 1914. A major impact on the development of modulation techniques came with the application of mathematics, which led to the theory that an amplitude-modulated wave consists of a carrier and two identical sidebands. Subsequent experiments in single sideband (SSB) led to John R. Carson's conceptions, in 1915, of what is known today as single sideband. By 1928, methods of measuring message bandwidth and message-transmitting capacity were put into effect.

Single-sideband techniques have been used in wire-telephone systems and low-frequency transoceanic radio telephone systems since the 1930's, but the extension to high-frequency radio telephone was not practical until 1936. By World War II, the U.S. Armed Forces extensively used SSB for global communications. In the wake of single-sideband developments came progress in pulse and pulse-code modulation.

Types of Modulation

The choice of type of modulation may involve such considerations as bandwidth requirements to optimize the balance between signal bandwidth and signal-to-noise ratio characteristics of a transmitting system, or effecting a change in the signal environment to allow for multiple modulation techniques as in frequency division multiplexing.

The most common types of modulation used in the HF spectrum are:

(1) Keyed CW (Continuous Wave)
(2) AM (Amplitude Modulation)
(3) SSB (Single Sideband)
(4) FSK (Frequency Shift Keying)

Continuous Wave (CW)

A keyed CW transmitter is turned on and off by a hand-operated telegraph key. The waveform of an RF carrier and the information or modulatory signal are shown in Figure 1. The maximum efficiency of a keyed CW arrangement depends on the operator's proficiency with Morse code. Many high-frequency stations, particularly marine-mobile stations, use keyed CW, or ON-OFF keying (OOK) because of the relatively simple equipment necessary and the high reliability of communications. When using an HF communication receiver to receive keyed CW modulation, the CW or product demodulation mode is selected.

Amplitude Modulation (AM)

When AM is utilized, the transmitted energy is varied according to the information in both amplitude and frequency rate. AM is a widely used signal in the HF spectrum, since the required equipment is only slightly more sophisticated than that used for CW, and no skill in code transmission is required to convey information. The voice is directly used to modulate the transmitter. AM's main disadvantages are that it occupies a wide spectrum (6 kHz) relative to CW and is inefficient in the sense that a great deal of carrier energy is needed to support the modulation energy. AM is usually received in the receiver's AM mode with an envelope detector. Figure 2 illustrates an AM modulated carrier with the information, or modulating signal shown above the composite signal.

In the "no information" condition the unmodulated carrier is shown. As the amplitude and frequency rate are varied, the effect on the composite modulated carrier can be seen. As the modulation signal increases in amplitude or loudness, the peak-to-valley ratio of the envelope of the carrier signal becomes larger. This peak-to-valley ratio of the envelope defines the modulation percent (m) as,

$$m = \frac{p - v}{p + v} \times 100$$

where,

p = peak-to-peak maximum of the envelope

v = peak-to-peak minimum of the envelope.

Signal amplitude may be increased only to a certain magnitude before distortion begins to occur. That limit is reached when the amplitude of the modulating signal equals the amplitude of the unmodulated carrier or the percent of modulation equals 100%.

The process of modulating an RF carrier with a much lower frequency-modulating signal via a heterodyning action produces a number of frequencies. If one modulating signal is used, two additional signals are produced, as shown in Figure 3A. The upper sideband signal consists of the sum of the two heterodyning signals. The lower sideband consists of the difference between the two heterodyning signals. If a group, or band of frequencies is used to

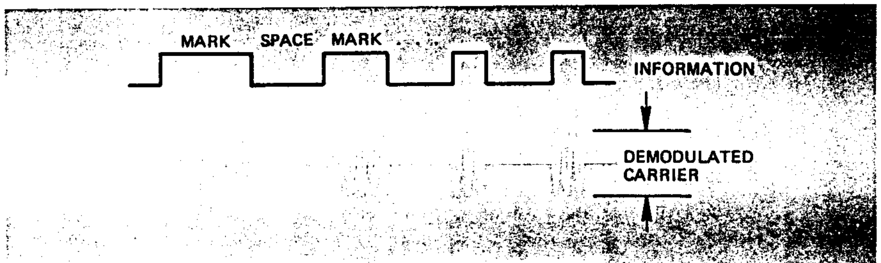


Figure 1. ON-OFF keyed signal.

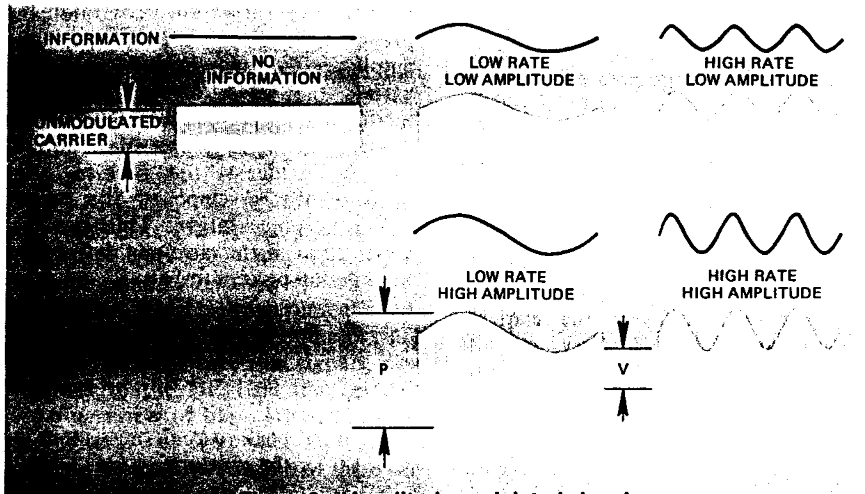


Figure 2: Amplitude modulated signal.

heterodyne or modulate the carrier, then these groups or sidebands will duplicate their relative positions on either side of the carrier. This is depicted in Figure 3B by the triangles labeled USB (upper sideband) and LSB (lower sideband). In the process of modulation, all intelligence or information is translated to the generated sidebands of the modulated wave; none of this information is contained in the carrier. The upper and lower sidebands contain identical information and can be considered mirror images of each other on either side of the carrier. If the sideband energy is created from a 3-kHz modulating spectrum, then the resultant AM or double sideband spectrum utilizes 6 kHz of bandwidth.

AM Power Considerations

The power distribution in an AM signal, for a 100% modulated signal, is as follows: the voltage in each sideband is one-half the carrier voltage. If the signal is applied to a constant resistance load, then the power in each sideband will be one-quarter the carrier power ($P = E^2/R$). For a carrier power of 100 watts, the maximum sideband power (100% modulation) or information power is 25 watts and the total power required is 150 watts. The information-to-power efficiency may be defined as a maximum of 16.67% (25/150) because the same information is contained in the other sideband. Assuming 30% average modulation, which is typical for speech, the efficiency is only about 4.1%.

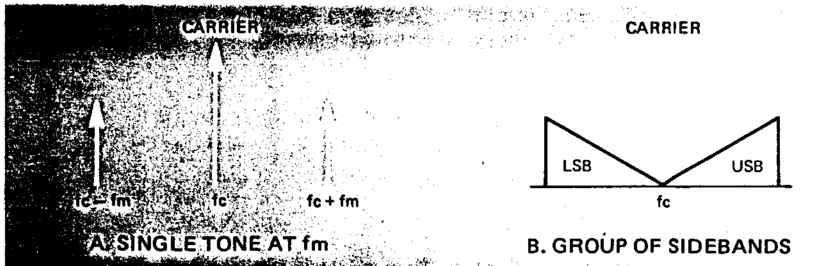


Figure 3: Spectral representation of amplitude modulation.

Single Sideband (SSB)

The transmitted single-sideband signal is the same as the original desired information spectrum, but shifted in frequency to the desired transmitted frequency. The SSB method is such that both the RF carrier and the unwanted sideband are suppressed, leaving only one information-bearing sideband to be transmitted. The spectral representation of the standard AM, double-sideband (DSB) signal shown in Figure 3B may be compared with the spectral representation of a single-sideband signal depicted in Figure 4. The dashed lines appearing in Figure 4 represent the suppression of the RF carrier and the unwanted sideband. The suppression of the unwanted carrier and sideband is generally accomplished by filtering or by the use of balanced modulators (mixers) and quadrature input signals.

Early SSB equipment carried only one channel (LSB or USB) on one side of the carrier, but soon to follow were provisions for the transmission of two separate, independent sidebands, one on each side of the apparent or suppressed carrier. This method of transmission is called independent sideband (ISB), since each sideband is truly independent of the other (see Figure 5). In the process of generating an SSB signal, all intelligence or information is translated to the generated sideband of the modulated wave, where the spectrum is just as it appeared in the original modulated signal.

Comparison of Power in AM and SSB

Taking into consideration the AM power-distribution characteristics previously discussed in this article, a significant comparision can be made with SSB. When single-sideband transmission is used, only the power necessary to transmit the information in the desired sideband is expended. Therefore, for the same information given in the earlier section on AM power considerations, only 25 watts of power is necessary and the information-to-power ratio is 100%, regardless of the loudness of the desired transmission. This yields a 9-dB advantage over AM transmission, for the same coverage. The 9 dB can be translated directly to a 9-dB signal-to-noise ratio advantage for a single-sideband system or an equivalent-performance AM system.

Summary of AM and SSB Characteristics

Some of the advantages of single-sideband modulation over amplitude modulation include:

(1) Reduced frequency spectrum
(2) High information-to-power ratio
(3) Signal-to-noise ratio advantage
(4) Elimination of high-power carrier
(5) Better signal performance in the presence of certain atmospheric conditions
(6) Smaller size for the same coverage.

Figure 4: Spectral representation of single sideband

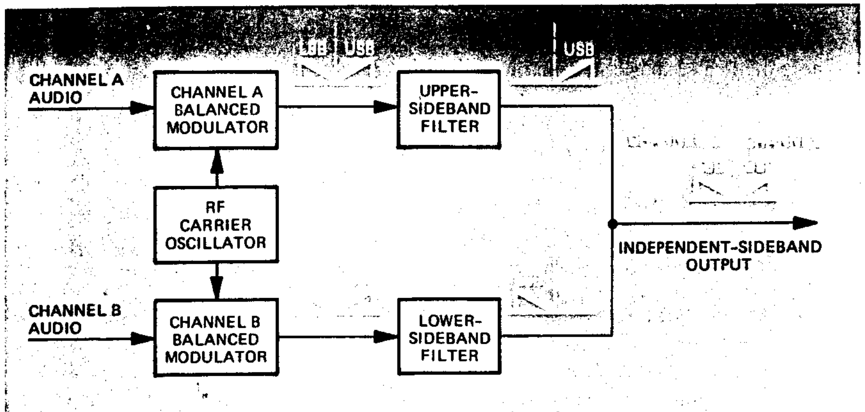


Figure 5. Independent sideband system.

Some disadvantages of single-sideband modulation, compared with amplitude modulation, are as follows:

(1) Extreme stability is required for both the transmitter and receiver.

(2) Higher complexity of the functional circuitry, e.g., demodulator section, AGC section.

(3) Need to re-create the suppressed carrier for demodulation.

(4) Higher receiver cost due to greater complexity.

Demodulation Requirements for CW, AM, and SSB

The simplest receiver demodulation circuits are those required for AM demodulation. As shown in Figure 2, the AM waveform modifies the unmodulated carrier to an envelope identical to the modulating, or information, signal. If the envelope is passed through a half-wave rectifier circuit, and the load R-C time constant is properly adjusted, the resulting output signal is the envelope of the applied signal (see Figure 6). Basically, the R-C time constant requirement is that it be long compared to the inverse of the carrier frequency and short compared to the highest modulating frequency. This is a simplistic definition of the requirements for a linear AM DSB envelope detector that yields an output signal which is a duplicate of the original modulating signal.

When a keyed CW signal is applied to an envelope detector, depending on the keying intelligibility rate, the audio output can be a group of clicks associated with each edge of the modulating signal (see Figure 7) or a lower frequency group of audible "thumps." In either case, the intelligibility of the coded signal is greatly reduced. To overcome the problem of reduced intelligibility, a circuit called a product detector may be used. Since the keyed CW signal is at the RF carrier frequency, for proper reception of the signal the receiver must be tuned directly to the RF carrier.

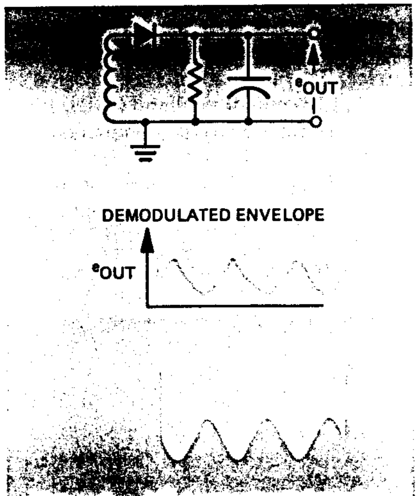


Figure 6. AM or envelope detector.

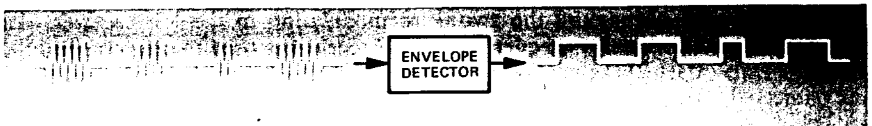


Figure 7. Action of envelope detector on keyed CW.

In an HF receiver, such as the WJ-8718, a CW input is converted to the final IF frequency (455 kHz). If, following the IF filter (typically 300 Hz bandwidth for hand-keyed CW), a signal is introduced which can be beat with the received IF signal, then the low-frequency beat note (difference frequency) can be amplified and used to produce an audible tone each time the transmitter is keyed. Normally, the introduced signal is from a section of the receiver called the beat frequency oscillator (BFO). The BFO signal is normally offset in frequency above or below the receiver's IF frequency by a controlled amount, usually in the 400-Hz to 1200-Hz range. In the WJ-8718, the BFO offset can be controlled in 10-Hz steps to a maximum of ± 8.99 kHz and the offset is read directly on the front panel.

Selecting a +1.4 kHz offset automatically sets the internal BFO synthesizer to 456.4 kHz, and the resultant beat note is 1400 kHz (456.4 kHz - 455 kHz = 1.4 kHz). The sum frequency (911.4 kHz) is easily eliminated by filtering. The product detector function is usually accomplished in a mixer circuit followed by a low-pass filter. As can be seen from the above discussion, it is possible to provide an audio output frequency (1.4 kHz) independent of the IF filter bandwidth (300 Hz), and this audio frequency can be much greater than the filter bandwidth. This allows a radio operator to discriminate against interfering signals (close in frequency), and to limit the receiver noise bandwidth, thereby improving the signal-to-noise ratio of the received signal.

Demodulation of SSB also requires a product detector. Figure 8 shows the waveforms of an SSB signal consisting of four equal-amplitude audio tones set in the original spectrum as 1-, 2,- 3-, and 4-kHz tones, and modulated as a USB single-sideband suppressed-carrier waveform with an apparent carrier at 100 kHz. As stated earlier, the spectrum is translated in frequency and is identical in its spectral characteristics to the original audio spectrum distribution. If a 100-kHz signal is beat in a product detector with the signal shown in Figure 8, and only the difference terms are passed on, 1-, 2-, 3-, and 4-kHz tones would be recovered. The function of the reinjected 100-kHz signal is to replace the suppressed apparent carrier. In an

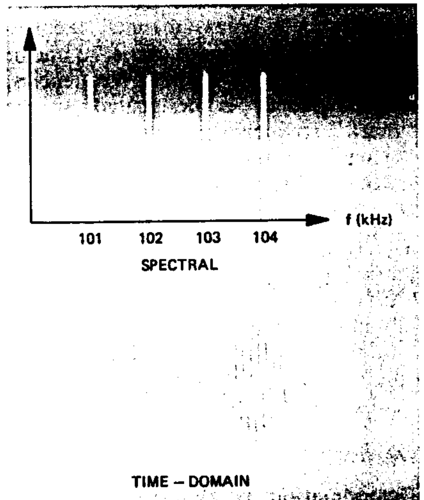


Figure 8. Single sideband spectral and time-domain representations.

HF receiver, the beating of the two signals is done at the final IF frequency, so that a zero-offset BFO signal will be the reinjected carrier.

In receivers such as the WJ-8718, SSB reception is performed by separate USB and LSB IF filters with controlled group-delay characteristics. These filters remove all but the SSB frequencies of interest (normally, the band from 250 Hz to 3200 Hz) from the suppressed carrier frequency. All required receiver frequency-translation oscillators are synthesized from the same reference, thereby providing the needed recovered-signal stability to enhance and maintain intelligibility of the recovered information.

The demodulation technique used in the WJ-8718 HF receiver allows the reception of ISB by adding an ISB amplifier, a product detector, and an audio amplifier channel to process the ISB/USB channel.

Frequency Shift Keying (FSK)

Frequency shift keying is a modulation scheme that is usually used to send digital information between digital equipment such as teleprinters or computers. The data are typically transmitted by shifting, in a binary manner, the frequency of a continuous carrier to one or the other of two discrete frequencies. One frequency is designated as the "mark" frequency and the other is the "space" frequency. The mark and space correspond to binary one and zero, respectively.

The frequency difference between the mark and space is called the "shift." Shifts for different systems are generally in the range of 50 to 1000 Hz. The minimum duration of a mark or space condition is typically between 5 to 22 milliseconds.

Demodulation of FSK

Demodulation is almost always performed with a special FSK demodulator because the FSK signal is too system-specific for high-quality, economical demodulation in the HF receiver. An HF receiver is used to convert the FSK radio frequency to the input frequency of the special FSK demodulator. This frequency may be at audio through use of the CW product detector (BFO) or at the 455-kHz IF output. For best demodulation, the HF receiver must be very frequency-stable because narrow shift (200 Hz) signals are sensitive to receiver drift.

Comparison of FSK and CW

Both FSK and CW have very high transmitter power efficiency, since neither requires linear amplification. Traditionally, CW has been dominant for transmission of text and digital data. In part, this is because of its relative simplicity and low cost. In the past, it has been easier to train an operator to send and receive Morse code than to pay the additional expense required for FSK terminal equipment. Recently, however, the advent of integrated circuits has reduced FSK terminal cost, and operator costs have risen. An additional consideration is the higher speed possible with FSK. A good CW operator,under good conditions,can typically transmit or receive about 40 words per minute.

In contrast, an FSK system can easily operate at 100 words per minute with only limited operator skills and poor signal conditions. Another factor in CW popularity has been reliability during poor signal conditions. Modern FSK systems use sophisticated signal processing so that with a 3-kHz bandwidth, during atmospheric fading, a 0-dB average SNR will typically produce only one error in 100 bits, and a 10-dB SNR only one error in 10,000. For a nonfading signal, a 0-dB SNR will typically produce only one error in 10^7 bits. All this performance is achieved at data rates faster than the fastest human CW operator can copy. For these reasons, FSK is beginning to dominate in HF digital transmissions.

Other Modulation Schemes

Having addressed the four most common signal formats of HF communications, and their creation and unique demodulation requirements, the following specific signal formats can now be discussed:

(1) MCW—Modulated CW is a signal in which the carrier is modulated with a constant audio tone, resulting in an AM DSB signal in which the modulating signal is keyed as in CW. This allows the receiver to detect and create audio tones with the envelope detector. The demodulated audio is the same frequency as the modulating tone frequency.

(2) FSK on SSB
One or more FSK signals may be transmitted on a SSB system by modulating the SSB signal with an audio FSK submodulation. For example, an FSK signal with a 2-kHz mark and a 1-kHz space can be directly transmitted in a SSB system. The transmitted USB will contain the mark and space in the same relative frequency positions, but shifted to the HF spectrum. Several FSK signals may be sent simultaneously over a single SSB link if the mark/space tone pairs for each FSK channel are separated in frequency from the other channels. A typical signal of this type has 16 FSK channels with apparent center frequencies spaced 170 Hz apart, e.g., 425, 595, . . . 2805, 2975 Hz. Each channel has an 85-Hz shift and can operate independently from the others or in pairs for frequency diversity. Complex signals of this type require high receiver frequency stability which is usually obtained through frequency synthesis, as in the WJ-8718. The complex nature of this type of signal requires a well-matched FSK demodulator that will match both the FSK channel frequencies and transmission rates. A good example of this type of demodulator is the WJ-9470.

(3) SSB has a number of different formats primarily concerning carrier power. In the military nomenclature of emission designations, the letter A stands for amplitude modulation, a number defines the type of modulation, and a letter suffix describes supplementary characteristics (see MIL-STD-188C, Appendix A). Some examples of designations include:

- (a) Single sideband, reduced carrier (A3A)
- (b) Single sideband, suppressed carrier (A3J)
- (c) Single sideband, full carrier (A3H)
- (d) Two independent sidebands, ISB (A3B)

There is also a class of ISB signals which, by means of multiplexing techniques, a 4-channel ISB system is provided instead of the normal two-channel ISB system. This is accomplished by multiplexing two additional 3-kHz SSB signals on either side of the standard ISB signals. The total required receiver bandwidth for this system is 12 kHz.

Conclusion

This article has reviewed some of the basic relationships between various types of signals used in the HF environment. The intent of this article has been to present an introduction to the world of HF by briefly summarizing the evolution of signals that are typical of those used in today's HF spectrum as well as to compare the advantages and disadvantages of different modulation schemes and discuss some of the unique characteristics of these schemes.

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Mr. Glaz has also served as HF Product Line Manager, coordinating all activities within the division to ensure the growth of the HF Receiver Section. His responsibilities in this area included proposals, marketing, budgets, schedules, product quality, and costs.

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