The Lenkurt® Demodulator
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HF RADIO TRANSMISSION

Reliable global communication is increasing in importance as jets and rockets shrink the earth, and international commerce and traffic grow. The major burden of long distance communication falls on "high-frequency" radio, a method fraught with difficulties and irregularities. This article reviews the nature of HF transmission and some techniques for improving its quality and reliability.

With the exception of artificial earth satellites, which are still highly experimental, long distance radio communication around the perimeter of the earth has been practical only in the so-called high frequency band lying in the range of approximately two to thirty megacycles. Other frequencies have also been used, but are usually very limited. For instance, global transmission at very low frequencies is possible, but requires extremely high power and is limited to relatively slow transmission rates. Transmission at near-microwave frequencies requires extremely large antennas and expensive radio equipment, and even then the distance which can be spanned is sharply limited.

All of these techniques are made possible by accumulations of ions and electrons in the earth's upper atmosphere. At altitudes above about forty miles, the atmosphere is very rarified. Radiation and high energy particles from the sun constantly disassociate some of the gas molecules into free electrons and positive ions. These charged particles, which may have a relatively short life, have a pronounced effect on radio waves passing through the area, and the magnitude of the effect is directly related to the density of the electrons.

One way of regarding this effect is to assume that each electron acts as a small antenna that extracts energy from the radio wave and then reradiates the energy. As the radio wave passes through the ionized region, the electrons are displaced or moved by the interaction of the electron's charge and the energy of the passing wave. Because of the "drag" resulting from the electron's mass and the influence of the earth's magnetic field, the reradiated energy is slightly out of phase with the transmitted wave. This has the effect of changing the velocity of propagation of the wave as it passes through the medium, and thus alters its direction. Ions have a similar effect, but because of their larger mass respond more sluggishly and thus influence the radio wave less.

As altitude increases the atmosphere becomes more and more rarified. At the same time, the effect of solar radiation is greater since there is less absorption and shielding by the atmosphere itself. Because of these two factors and the fact that the atmosphere has slightly different composition at various altitudes, ionization tends to occur in stratified layers which vary somewhat according to the season, the degree of solar activity, and whether it is day or night. The "lifetime" of the free electrons is determined by the rarefaction of the atmosphere; random collisions between free electrons and positive ions cause them to recombine and become neutral. Where the air is dense these collisions are very frequent, whereas at higher altitudes recombination is much less likely. For this reason, the lower layers illustrated in Figure 1 may vanish at night. The *F* layer (or layers) is able to persist through the night, although the number of free electrons decreases from about 10^6 electrons per cubic centimeter to about 10^5. In the lower *E* region, electron density is typically about 10^5 electrons per cc, largely disappearing at night. These *E* and *F* layers make possible virtually all radio propagation beyond the horizon.

Although the return of radio energy to the earth by these layers is commonly

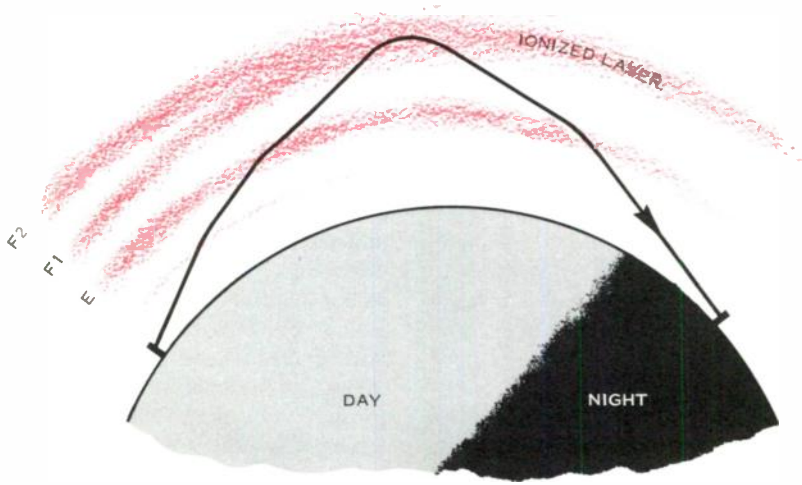


Figure 1. Intense solar radiation disassociates some gas molecules and atoms into ions and free electrons. The free electrons bend HF radio waves back to earth, permitting radio communication around the curvature of the earth. Stratification into layers results from varying composition of atmosphere at high altitudes. At night, recombination lowers electron density, causes lower layers to disappear.

called "reflection", it is actually a form of refraction which is controlled by both the frequency of the signal and the density of the electrons. At high frequencies the radio wave is less strongly affected than at lower frequencies. For a given frequency, the greater the electron density the greater the refraction or bending of the wave. In other words, the *index of refraction* of the ionized medium, which determines the amount of deflection of the ray, is a function of both the electron density and the operating frequency.

If the ray enters the ionized medium vertically, it will penetrate the medium only if it is above a certain so-called *critical frequency*. Frequencies higher than this frequency will penetrate the layer, while all lower frequencies will be returned to earth, as if by reflection. Frequencies higher than the critical frequency may return to earth if they enter the ionized layer at such a shallow angle that only a little deflection is necessary to direct them back toward the earth. The critical frequency can be calculated from the relationship $F^2 = 81N$, where N is the number of electrons per cubic centimeter and F is the frequency in kilocycles. Thus, the higher the electron density, the lower the critical frequency.

Figure 4 illustrates how a radio signal may be propagated from one point to another using ionospheric refraction. Radio energy enters the ionosphere at several angles. Note that as the angle of incidence becomes more nearly vertical, the radio waves are not returned to earth but are merely deflected as they penetrate the ionized layers. As the angle of incidence becomes greater some rays are deflected just parallel to the ionized layer. At a slightly lower angle radio energy is returned to earth. Thus, this minimum angle at which reflection can occur determines the "skip distance" which must be exceeded before reflected signals can be received. Beyond the skip distance, radio waves may be able to reach the receiver by several different paths.

One of the natural results of this is *multipath fading*, in which signals which have traveled slightly different routes arrive slightly out of phase with each other, thus causing cancellation. Complete cancellation of the signal occurs when two components of equal strength arrive exactly 180° out of phase. At a frequency of four megacycles this will occur if the two transmission paths differ by some multiple of about 125 feet; at thirty megacycles a path length difference of about 40 feet will produce the same cancellation.

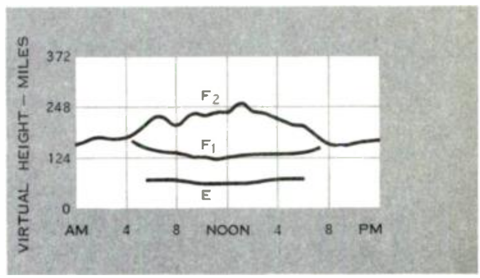
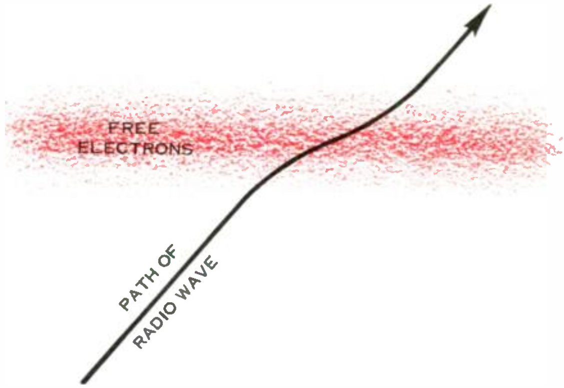


Figure 2. The E layer is lowest "full-time" ion belt. During peak sunlight hours F layer divides into two well-separated regions called F1 and F2. Not shown are D and "sporadic E" layers, both of which occur randomly.

As the length of one or more paths change, due to turbulence or changes in electron density, the frequency at which complete cancellation occurs shifts. A channel will often suffer severe fading at discrete frequencies within the channel, but not at others. As the multipath characteristics change, a fade may

Figure 3. Free electrons alter direction of radio waves by a refraction-like process. Amount of bending is proportional to electron density and inversely proportional to radio frequency. At some lower frequency, the wave would not penetrate, but would be "reflected" to earth.



"drift" from one end of the channel passband to the other, perhaps attenuating low frequencies at one moment and higher frequencies the next.

This is a major reason why double-sideband amplitude modulation is no longer used for HF transmission. When both sidebands are transmitted, a carrier frequency having an explicit phase relationship with both of the two sidebands is required. Although the carrier may be suppressed in order to save power, it must be accurately reinserted at the receiver. If the reinserted carrier is as much as 90° (¼ cycle) out of phase with the original carrier frequency the transmission is completely garbled. In the case of double sideband transmission over HF circuits, selective fading may remove the carrier. The two sidebands then attempt to demodulate each other and the signal is destroyed.

This can be avoided by eliminating one of the two sidebands. Now, the phase relationship between the two sidebands is no longer a factor and the reinserted carrier need only be held to within a few cycles of the transmitter carrier frequency. Selective fading within the single transmitted sideband may be virtually unnoticeable. In addition to reducing the effects of selective fading, single-sideband transmission requires only about one-eighth the power of a double-sideband signal for comparable quality, and results in much greater transmission reliability.

Propagation Reliability

It is important to note that the ionosphere is not homogeneous or "smooth." The atmosphere is subject to winds, turbulence and irregularities. Solar activity has several effects: solar storms and eruptions cause upper atmosphere ionization to increase very greatly. At such times, the atmosphere literally "swells", reaching farther into space than during periods of lower solar activity times. On a smaller scale, hour to hour variations occur so that the ionosphere behaves as though it consisted of numerous separate reflecting surfaces, all shifting and changing independently. The received signal seems to "twinkle," suffering continuous phase irregularities and disturbances. Although this has little effect on voice signals, certain types of data transmission are strongly disturbed.

Since the ability to send a signal around the curvature of the earth depends on a so-called reflection from the ionosphere, the natural changes in the atmosphere may rapidly alter the suitability of a given frequency for transmission between two points. For instance, it may be possible, because of strong solar activity, to transmit 30-mc signals across an ocean. As solar activity abates or as darkness nears, electron concentration may drop to a value which no longer reflects the 30-mc signal back to earth. Alternatively, the signal may not be deflected back to the particular spot where the desired receiver is located, but may instead reach the earth at a greater distance. In either case, transmission fails at 30 mc, but may be possible at some lower frequency.

Improving HF Reliability

It is difficult to overstate the value of reliable communications in either war or commerce. A superior method of communicating was worth untold millions to Lord Rothschild in his stock market dealings during the battle of Waterloo. Over a century later, an urgent message from General George C. Marshall to the commanding officer at Hawaii warning of the possibility of impending attack was blocked by failure of the military HF circuits. The message, which would have been received one-half hour before the Japanese raid on Pearl Harbor, was re-routed over a commercial submarine cable and was delivered about eight hours *after* the attack.

An effective way of minimizing the vagaries of HF propagation is the use of *ionospheric sounding*. In one version an HF transmitter sends a series of pulses which sweep across the entire HF band. At the far end, a synchronized receiver records the reception of each of the transmitted pulses which get through. This technique reveals the presence of multipath distortion at each frequency and shows which frequen-

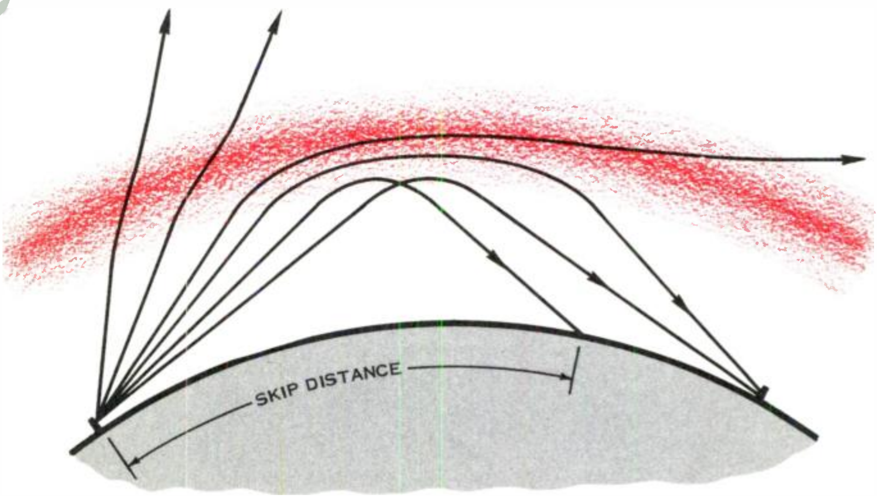
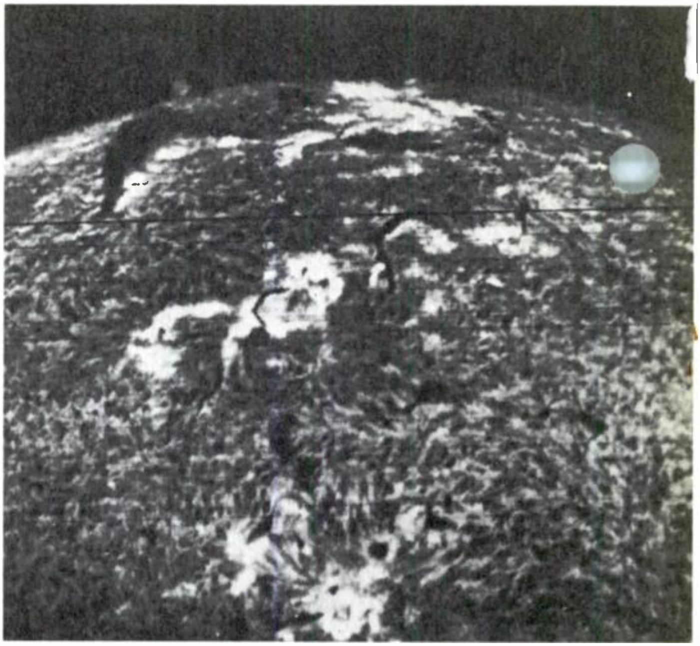


Figure 4. Typical HF propagation. Note that rays which enter ionosphere nearly vertically are only slightly deflected and penetrate the layer. As angle of incidence increases, rays are deflected into layer or refracted back to earth. "Skip distance" is the nearest distance at which radio waves return to earth. At greater distances, signal may arrive by several routes and thus suffer multipath distortion.

Figure 5. Vast solar flares flood space with high-energy particles and intense radiation, causing earthly auroras and magnetic storms. These have an important effect on almost all terrestrial long-distance communications. Solar activity follows an 11-year cycle, reaching a minimum next year (1964).



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cies are most suitable for transmission. Reception characteristics can be displayed on a tube or printed on a strip of paper.

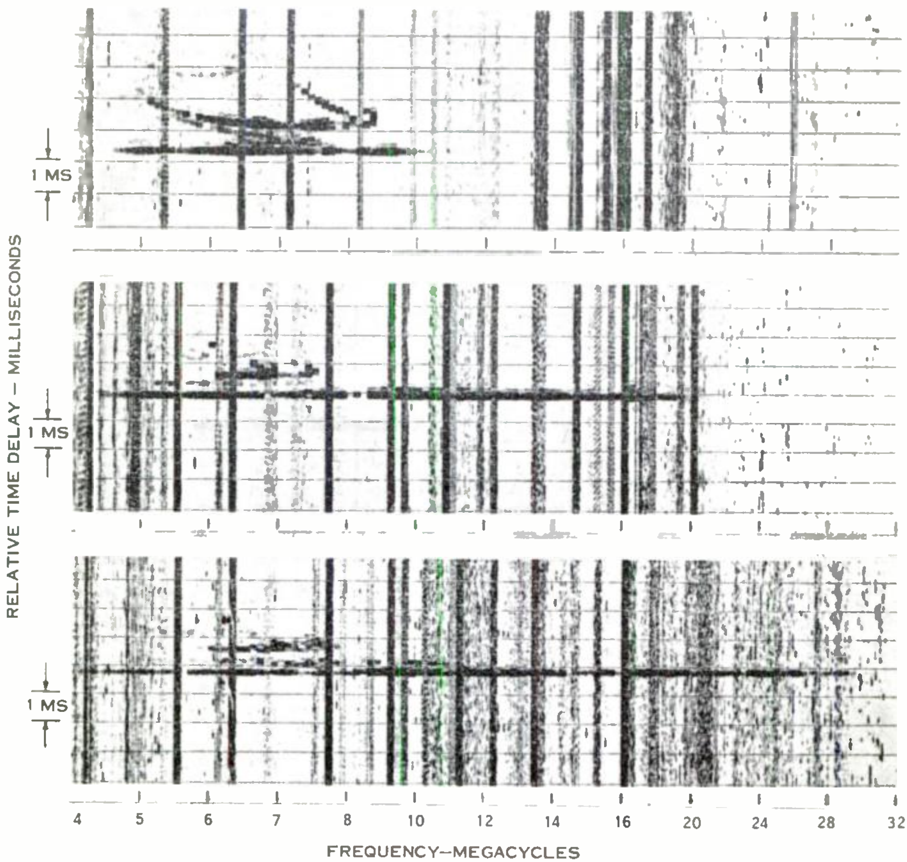
Figure 6 shows a series of ionographs made in this fashion. The horizontal marks in each of the three transmissions represent reception at Palo Alto, California of a signal transmitted from Hawaii. Note that in the first trace the maximum usable frequency on this particular path was approximately 10 mc. At another hour (shown in the second trace) maximum usable frequency had risen to 20 mc. In the last trace adequate signals were received at 28 mc. These ionograms also reveal multipath reception in the lower frequency portions of the band. Obviously, such a technique may occasionally reveal that *no* assigned frequencies are suitable. However, trends in propagation characteristics can be revealed so that communications may be resumed as soon as possible when a usable frequency appears.

A similar technique called "backscatter sounding" may be thought of as a sort of HF "radar." In this technique only a single station is required. As in synchronized sounding, pulses are transmitted at many frequencies across the band. Where they come to earth some of the energy is scattered or reflected back over the transmission path. By recording the time required for each frequency to return, it is possible to calculate the distance traveled and therefore the location of distant points at which reception is possible. Where multiple reflections are involved each will tend to return a signal, thus revealing the number of skips.

Figure 7 shows a typical recording of a backscatter sounding. Between 16 and 32 mc it is possible to transmit more than 4500 kilometers using two low-angle hops. Note that although each frequency appears to be limited to certain specific distances, this is for *optimum* communication. Successful transmission is usually possible at frequencies lower than those indicated in the display. By using backscatter sounding it becomes possible to select the optimum frequency for a particular destination. Had such a technique been available on "Pearl Harbor Day," the loss of eight battleships, hundreds of aircraft and thousands of lives might have been avoided.

Transmission of Digital Signals

More and more communications are transmitted in the form of digital sig-



IONOGRAMS COURTESY OF GRANGER ASSOCIATES

Figure 6. Typical ionograms obtained by oblique ionospheric sounding between Hawaii and California. The vertical streaks are radio transmissions. Horizontal lines represent 1 millisecond relative time. Note multipath reception between 4 and 7 mc. Maximum usable frequency increased from about 10 mc (top) to about 30 mc in the bottom record. Periodic soundings reveal propagation trends, permit optimum use of transmitting time.

nals. The digital signal form of information can be handled and transmitted more efficiently than such other forms as speech. It can be recorded in the form of punched tape or cards for transmission at any rate which the handling equipment and transmission medium will allow. For one reason or another, it is often desirable to transmit even speech in digital form. In the telephone network, pulse code modulation affords the possibility of improving signal quality when transmitting over great distances, and provides compatibility with electronic switching techniques which will probably dominate future telephone networks.

Another approach for transmitting digital speech has the advantage of reducing bandwidth considerably. So called "Vocoders" analyze speech sounds and generate digital code signals which represent the average energy level in various portions of the sound spectrum. At the receiving end a synthesizer interprets the codes and regenerates the speech. In this way it has been possible to reduce the bandwidth required for intelligible speech from about 3000 cycles to about 300 cycles while maintaining a surprisingly high degree of intelligibility and quality.

This technique lends itself admirably to the transmission of "secure" speech, that is, voice transmissions which cannot be understood if intercepted. This is useful in military and government operations where privacy of communication is essential. This type of security can be obtained by taking the digital signals from a Vocoder and scrambling them into an unpredictable code pattern

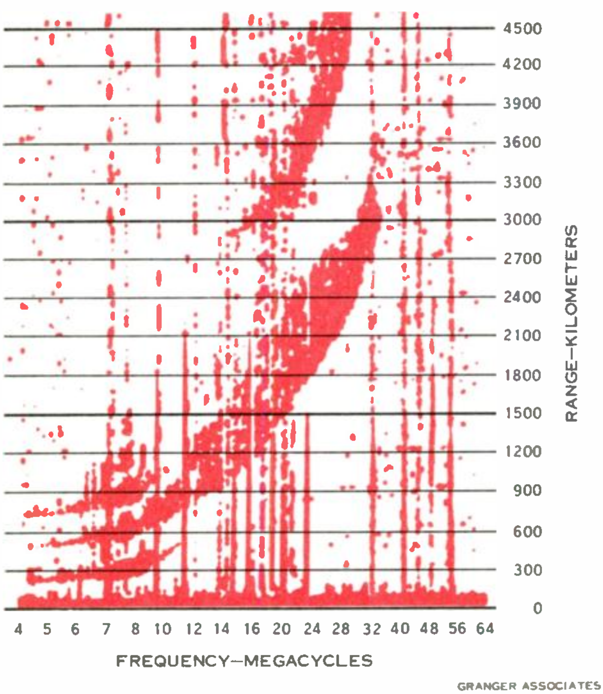


Figure 7. Backscatter sounding is made from a single location, reveals distances at which reception is optimum. Gain of receiver is set to reveal best transmission, usually at or near maximum usable frequency. Good reception is also usually possible at frequencies lower than those shown in ionogram.

which only the intended receiver can interpret correctly.

Although digital transmission is efficient and useful, it encounters a number of problems when going through HF circuits. HF circuits are crowded, noisy and erratic. Although these characteristics have little effect on voice or other analog signals, they tend to cause transmission errors in digital signals. This can be very serious because of the inherent lack of redundant information in most digital signals. Noise bursts which produce only "static" in a voice transmission could destroy or alter digital characters or the larger blocks of information contained on a punched card. Although the error rate can be reduced by using more transmission bandwidth, this is generally impracticable in HF radio due to spectrum crowding.

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Figure 8. Typical receiver for ionospheric sounder. Heart of device is a precision time standard to sweep receiving frequency across band in precise step with transmitter.

Most approaches for obtaining better transmission have been based on improving the modulation technique. The earliest systems used on-off keying of the radio carrier. This was disadvantageous on two counts: average transmitted power was only half the average capability of the transmitter, since energy was radiated only during "marks." Thus, at the receiver a space was indicated only by background noise. If the circuit were marginal or if the carrier frequency suffered a momentary fade, communication would almost certainly be lost.

To overcome this, *frequency-shift-keying* (FSK) was introduced. Two adjacent alternate frequencies represent either mark or space. Since the transmitter is sending either the mark or the space frequency at all times, the full average power rating of the transmitter is attained. Furthermore, FSK provides greater protection against fading, since the receiver detector can respond to signals that are almost lost in the background noise. By contrast, the envelope detector used in the on-off keyed transmission required that the signal clearly exceed a higher arbitrary power threshold.

Although FSK transmission greatly improves the reliability of digital transmission over HF channels, it is considered to be wasteful of bandwidth; the two sidebands seem to cost too much transmitter power and frequency spectrum. In a further effort to reduce the bandwidth required for digital transmission over HF channels, various methods of *phase*-shift-keying (PSK) have been introduced within the last decade. In this method, a single carrier frequency is transmitted. At appropriate instants, the carrier is shifted 180° in phase to signify mark or space for binary transmission. Higher information rates can be transmitted by shifting the carrier between 0°, +90°, −90°, and 180°, which is the equivalent of a quaternary or four-level system. PSK reduces the bandwidth requirements for transmission and thus provides a theoretical improvement in the vulnerability to noise, since the receiver bandwidth can also be reduced.

Since all the information transmitted in this fashion is conveyed by the phase shift of the carrier, it is important that the carrier be extremely stable. Successful operation requires that the transmitter and receiver not depart from perfect synchronization more than a very few degrees of phase. Because of the stringency of this requirement, PSK transmission may be very difficult over HF radio.

The main difficulty stems from the inherent phase instability of HF radio. Random phase variations of the signal occur in transmission. The receiver can only interpret phase shifts as information bearing signals. It would appear, therefore, that such transmission channels would be unsuitable for PSK modulation. This is not quite true, since the rate of the phase change is usually not very great. One system takes advantage of this to establish a phase reference at the receiver, based on comparison of each received signal pulse with the preceding pulse. In effect, phase shifts introduced by the transmission medium are "averaged out." For such a "differentially coherent" PSK system to be successful, the bit rate must be substantially faster than the random phase variations introduced in the channel. This approach is, in fact, a compromise between an ideal phase coher-

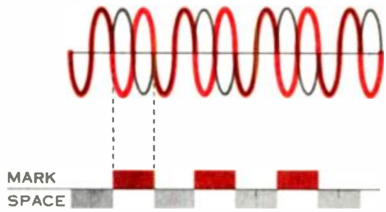

Figure 9. Phase shift keying (PSK) alters the phase of a stable carrier ±180° to achieve binary transmission. Use of four phases doubles information rate but also increases errors caused by phase changes in HF medium.

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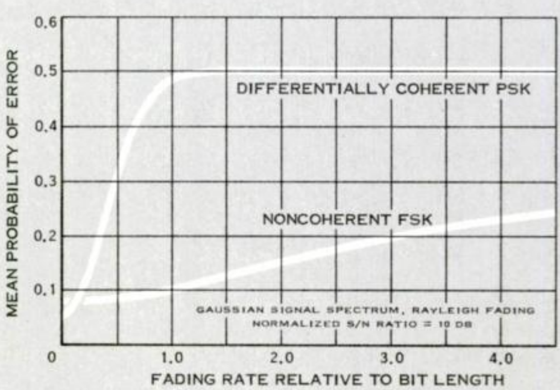

Figure 10. PSK signals are very vulnerable to fading and phase shifts in transmission medium. PSK systems have lower probability of error than FSK systems only when fading rate is very slow. As the fading rate increases, PSK error probability becomes many times that of FSK signals.

ent system and FSK systems, which are essentially phase insensitive but require nearly twice the bandwidth of PSK for a given information capacity. Even under the most favorable conditions, the averaging technique degrades performance enough that twice as much signal power is needed than would be the case with an *ideal* PSK system. Averaging of pulses over longer periods (in an attempt to obtain a more stable phase reference) tends to degrade system performance even more. Actually, the primary advantage of PSK systems has been in the conservation of bandwidth. Although this leads to improved performance under very noisy conditions, PSK systems are particularly vulnerable to fading, whereas FSK systems are the least vulnerable to fading and to phase discontinuities, as shown in Figure 9. Furthermore, PSK transmission shows less improvement in error rate when transmission is very good and the signal-to-noise ratio becomes large.

Coding to the Rescue

The bandwidth conservation that PSK provides can be likened to single-sideband transmission, and this is its principal advantage. FSK suffers the disadvantage of inherently requiring more bandwidth than PSK, but is less vulnerable to transmission disturbances.

Lenkurt's recently discovered Duobinary Coding technique (described in the February 1963 DEMODULATOR) has tipped the balance definitely in favor of FSK transmission by doubling the information capacity of the channel for a given signal bandwidth. In effect, this is the same as reducing the bandwidth required by FSK systems without giving up any of the advantages.

This new performance capability has been implemented in Lenkurt's Type 27A Data Transmission System which permits 2400 bits per second to be sent over a 3-kc voice channel. Future development will permit the operation of thirty-two 100-words-per-minute channels over the 16 basic 150-baud channels. Because of the inherent simplicity of the Duobinary Coding technique, the 27A system is far less complex than a differentially coherent PSK system of the same capacity, while providing far better performance over HF radio channels.

Although new types of submarine cable are being laid which have much greater channel capacity than the old, and communications satellite experiments are very successful, HF radio will have to continue bearing the major burden of global communications for many years. By effectively doubling the capacity of these circuits, the Duobinary Coding technique has, in effect, doubled the availabe frequency spectrum. •

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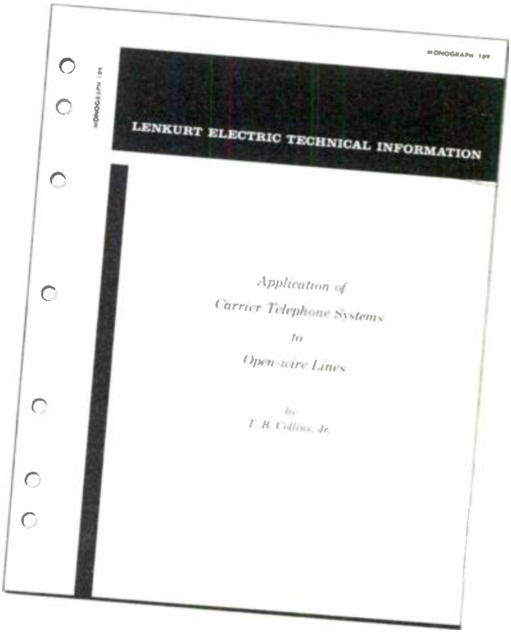

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