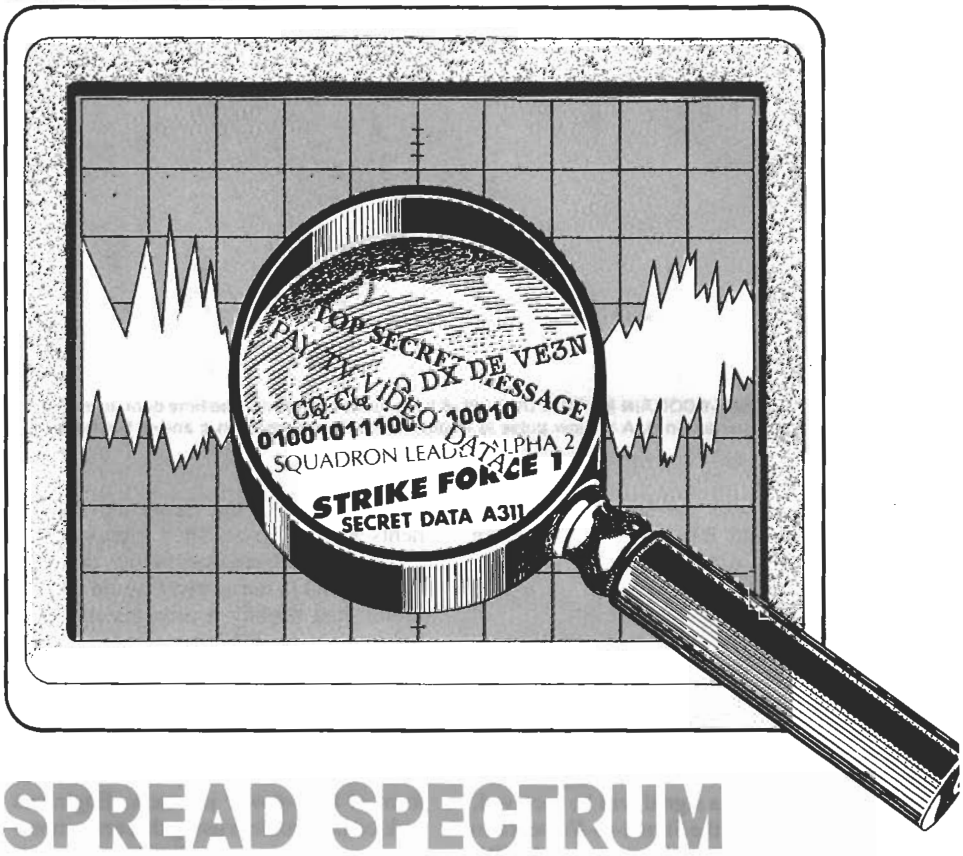
ALL ABOUT SPREAD SPECTRUM COMMUNICATIONS



Learn about the methods used by the government and others to achieve reliable communications under the most difficult conditions.

JAMES E. McDERMOTT

A NOCTURNAL BAT EMITS WEAK ULTRASONIC chirps as it bobs and weaves through a maze of obstacles; a deep-space probe accurately broadcasts its position to an earth-based tracking station; and a military radio link is maintained despite powerful enemy jamming signals. In all of those situations, a modulation technique known as *spread spectrum* is used.

As its name implies, in spread spectrum a communications signal is spread over a wide frequency range. Among the potential advantages offered by spread-spectrum communications are message privacy, signal invisibility, noise rejection, and accurate signal timing.

In this article we will look at some of the various spread-spectrum techniques in use today. Among them are frequency hopping, time hopping, chirping, and direct sequence. But before we can fully understand those techniques and their applications in space, military, and commercial communications, some necessary groundwork must be laid.

Time *vs.* frequency

A signal can be represented in one of two ways. Most often, a signal is represented as a function of time (change in amplitude *vs.* change in time). That is also called a *time-domain* representation. But signals can also be represented as a function of frequency (change in amplitude *vs.* change in frequency). That is called a frequency-domain representation.

In Fig. 1 are two common signals; both are shown in the time and the frequency domain. In Fig. 1-*a* is the time-domain representation of a wide data pulse; the frequency-domain representation of that signal is shown in Fig. 1-*b*. A narrow pulse or spike is shown in the time domain in Fig. 1-*c*; the frequency-domain version of that signal is shown in Fig. 1-*d*.

Any signal can be shown in either the time or the frequency domain. It is also possible to convert a time-domain representation to a frequency-domain representation, and vice versa, using a mathematical operator called a *transform*. The most familiar of those, at least to advanced students of electronics, are the *Fourier* and the *Laplace* transforms. As a meaningful discussion of transforms requires a working knowledge of calculus, we will not go into further depth on that subject here. Consult your local library for more information on the subject.

Bandwidth

The most familiar type of frequency-domain representation shows us the *bandwidth* or spectrum of a signal at an instant of time. Such a representation is called an *instantaneous bandwidth* and can be thought of as a snapshot view of a signal's frequency spectrum. Instantaneous bandwidth is most useful when discussing pulsed signals.

In some spread-spectrum techniques, the bandwidth of a signal changes significantly over time. For instance, in a frequency-hopping system (such systems will be discussed later on in this article) the instantaneous bandwidth may be narrow; but over time, signal components may be present over a wide frequency range. For such signals, the concept of *hopped bandwidth* is useful. Hopped bandwidth is analogous to time-lapse photography and describes the full extent of the frequency spectrum covered by the signal.

A spread-spectrum signal, by definition, occupies a larger bandwidth than necessary to convey information. The minimum bandwidth required to convey the information contained in the signal is called the *information bandwidth*. For example a voice signal requires approximately 2000 Hz of bandwidth to be faithfully reconstructed; a television signal may require 6 MHz. A typical spread-spectrum signal carrying a single voice message may occupy a hopped bandwidth of 100 MHz, or an instantaneous bandwidth of 10 MHz or more.

For a signal-processing technique to be useful it must offer some gain over an unprocessed signal. That gain is called *process gain*. In spread-spectrum systems, the process gain is the ratio of the spread-spectrum bandwidth to the information bandwidth; it can be expressed in decibels by the formula:

$$G_P = 10 \text{ LOG } (BW_{RF}/BW_I)$$

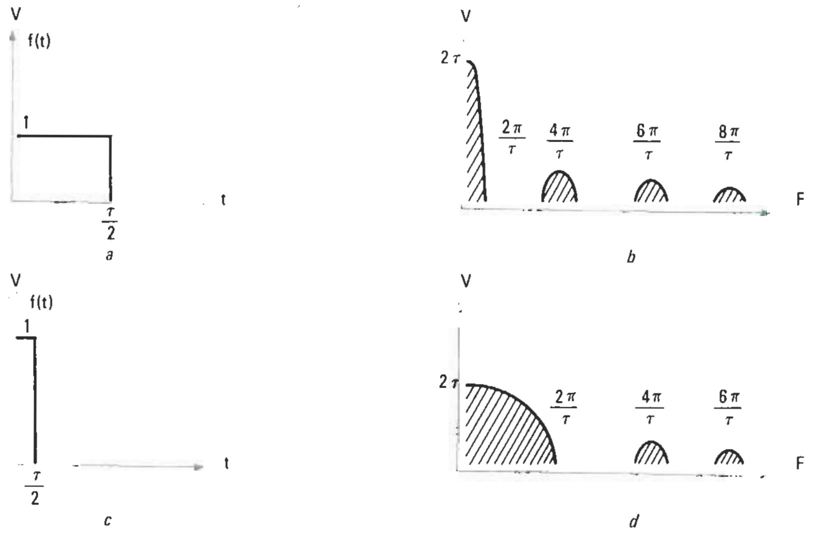


FIG. 1—FREQUENCY DOMAIN *VS.* TIME DOMAIN. A wide pulse is shown in the time domain in *a* and in the frequency domain in *b*. A narrow pulse is shown in the time domain in *c* and in the frequency domain in *d*.

where BW_{RF} is the spread-spectrum bandwidth and BW_I is the information bandwidth.

Noise

Noise can be considered as all RF energy other than the signal of interest; it is the most significant limiting factor for all communications systems. For a signal to be received, its level must be greater than the noise level. A useful quantity in determining whether a signal will be received, and how well, is the *S*ignal-to-*N*oise *R*atio (SNR). The SNR can be expressed in dB's using the following formula:

SNR = 10 LOG (signal-power/noise-power)

In designing a communications system, the goal is to maximize the effective SNR. When increasing the signal strength is either impractical or illegal, the only recourse is to minimize the effects of the noise degrading the signal. Depending on the nature of the signal and the noise, there are various techniques that can be used to achieve that goal.

When faced with white or flat noise, narrowband signals are transmitted so that effective filtering can be done at the receiver. A bonus is that the use of narrow bandwidths allows for greater use of the crowded communications bands.

Willful interference, especially from narrowband, high-power jammers, is quite another story, however. Spread spectrum is a powerful weapon in combating that type of interference.

Some history

As early as the 1920's, engineers proposed using broadband signals, primarily to counteract the effects of fading on communications links. The idea was to spread the signal energy over a wide range of frequencies, then to reconstruct the signal by gathering all the frequency components at the receiver. Then when one part of the band suffered from fading, the combined signal in the receiver would only be diminished slightly. Unfortunately, technology was far behind insight, so those proposed systems remained largely theoretical.

World War II brought an urgent need for secure communications as engineers confronted man-made problems in the form of high-power jammers. Engineers tackled the problem using that era's more-advanced technology. Before the war's end both sides were using sophisticated communications systems, many of which used bandspreading techniques.

By occupying large bandwidths, spread-spectrum signals increase their ability to withstand interference by improving what is referred to as *jamming margin*. For example, if a narrowband signal is marginally readable under a certain level of jamming or interference, and 20 dB of G_P is added by using a spread-spectrum technique, then the signal can withstand 20 dB, or 100 times, more jamming power.

A useful byproduct of the bandwidth spreading process is a proportional reduction in signal density, making the signal virtually undetectable by an uninformed receiver. That has a particular appeal in tactical and strategic systems; today the military is one of the largest users of spread-spectrum systems.

A communications shell game

A frequency hopper is a communications signal in which the carrier frequency is continuously changed to one of a great many frequency *slots*. The resulting signal has a large hopped bandwidth, often in the hundreds of MHz. Figure 2-*a* shows the resulting spectrum for a 10-slot system, although typical systems in use today may have 1000 or more such "hop slots." A noise source, usually a digital *P*seudo*N*oise (PN) sequence generator, is used to determine the current hop slot. A typical hop sequence for a ten-slot system is shown in Fig. 2-*b*. A typical frequency-hopper system is shown in block diagram form in Fig. 3.

Frequency hoppers can be subdivided into fast hoppers, which can change frequency in less than a microsecond, and slow hoppers, which may use each slot frequency for several seconds at a time. Fast hoppers are generally used in tactical military environments where jammers can quickly home in and swamp a slow-hopping signal. Such a system is usually based around expensive state-of-the-art frequency synthesizers. Fast hoppers are limited by the speed at which the synthesizer can be effectively switched, al-

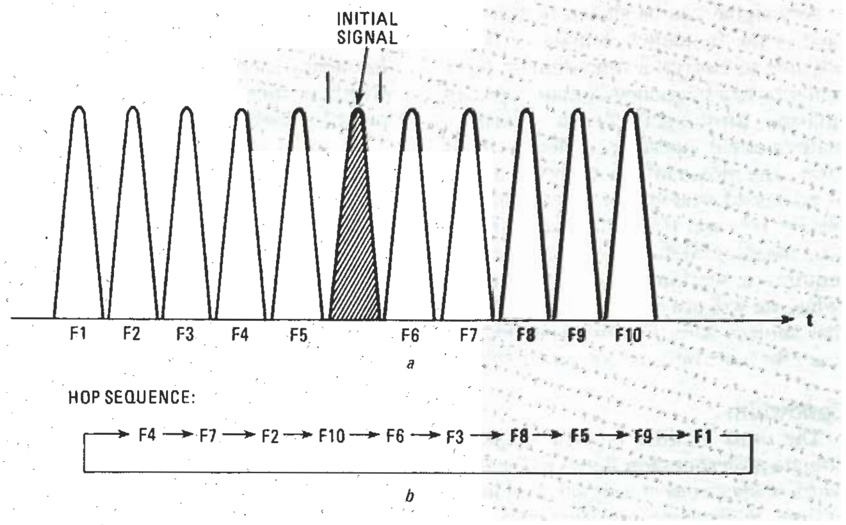


FIG. 2—A FREQUENCY HOPPER will jump from one frequency slot to another over time. The spectrum of a simple 10-slot system is shown in *a*. One possible hop sequence for the system shown in *a* is shown in *b*.

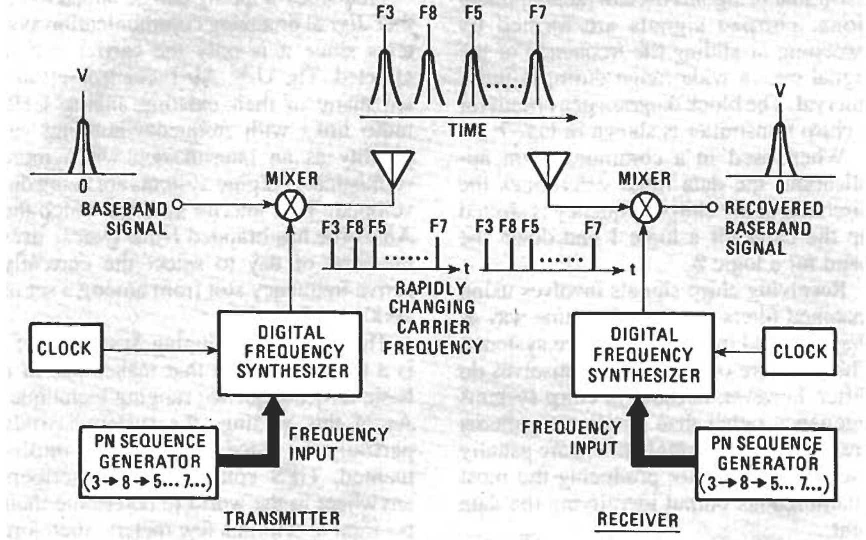


FIG. 3—BLOCK DIAGRAM of a typical frequency-hopper system. The pseudo-random noise-sequence generators at both the transmitter and receiver are set up to output the same sequence.

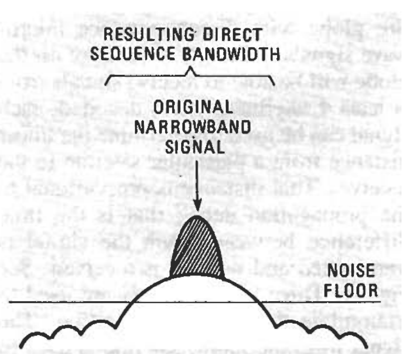


FIG. 4—WHEN AN RF SIGNAL IS MODULATED by a digital pulse, the carrier widens. If that pulse were replaced with a chip sequence, extremely wide bandwidths would result.

though many can hop over a 1-GHz range in less than 1 μs.

Slow hoppers are normally used where low cost is important and where any expected jamming lacks sophistication. Slow hoppers are also used as an inexpensive way to share a band among many users. By carefully selecting the hopping sequences or codes to prevent overlap, several slow-hopped systems can co-exist in the same band and in so doing increase band efficiency. A jammer attempting to interfere with a specific signal is now even less effective since it may be impossible to isolate that signal from the rest of those using the band. (Of course, a jammer could always just knock the entire band out of service.)

Signal shredders

Imagine shredding an important message into a million pieces and then scattering them into a tornado. A thousand miles away someone gathers up all or almost all of the snippets and reconstructs the original message. If you substitute communications signals for the paper you have the essence of the most sophisticated and exciting of the spread-spectrum techniques: direct-sequence spreading.

In the direct-sequence technique, bandspreading is accomplished by exploiting the inherent properties of digital modulation. That is, whenever a pulse stream is mixed with a carrier signal, a slight broadening of the RF carrier occurs. However, if instead of a single bit, a long code sequence, called a *chip sequence*, is sent in the same time interval, large instantaneous bandwidths can be produced, as shown in Fig. 4. The wide bandwidths are a direct consequence of the extremely narrow pulse widths of the bits in the chip sequence.

In the receiver, the RF signal must be *correlated*; that is the signal must undergo a de-spreading or bandwidth-collapsing procedure. First, the signal is converted back to baseband by mixing it with an appropriate carrier signal. The resulting baseband signal contains noise as well as the chip sequence. That noise, which includes willful interference, must be removed. That task can be handled in many ways, but one design makes use of a *matched filter*, a circuit that compares the received chip sequence with a predetermined sequence and looks for a match.

One popular matched-filter design is built around an analog shift register, as shown in Fig. 5. As each bit in the chip sequence is received, it is fed into the input of the register. As the bits are cycled through the register, the contents of each cell are sampled and summed. The output of the filter is a current that is proportional to the degree of the match. The filter shown in Fig. 5 is set up to look for a sequence of 1101101. When the bits in each cell match that sequence exactly, the out-

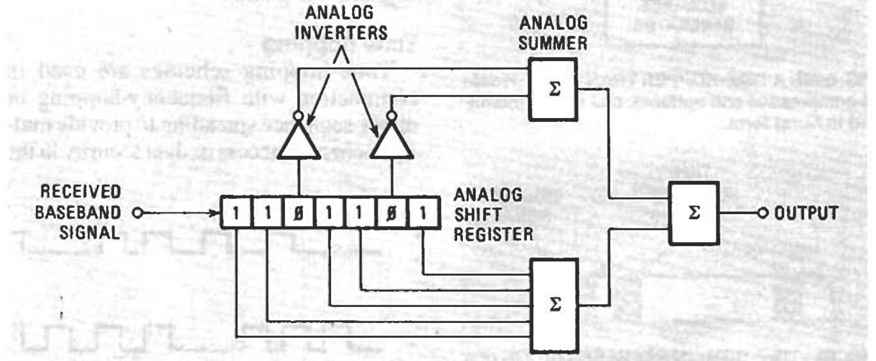


FIG. 5—MATCHED FILTERS are used to search for particular chip sequences. The one shown here, which is built around an analog shift register, searches for the sequence 1101101.

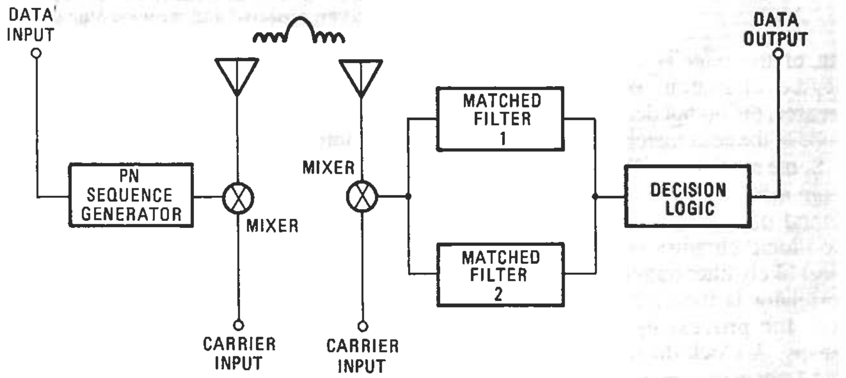


FIG. 6—MULTIPLE MATCHED FILTERS are used in direct-sequence receivers to increase the likelihood of successful correlation. Decision logic is used to select the filter output that is most likely to be correct.

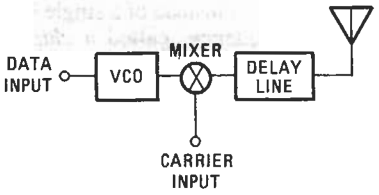


FIG. 7—A CHIRP-SYSTEM transmitter is shown here in block diagram form.

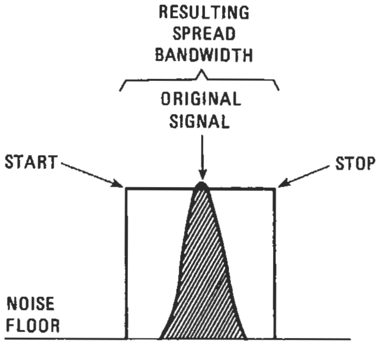


FIG. 8—THE CHIRP SIGNAL'S carrier frequency is continuously swept through part of a band. Intelligence is conveyed by the direction of the sweep.

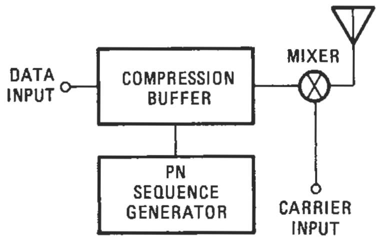


FIG. 9—IN A TIME-HOPPER TRANSMITTER data is compressed and buffered, and then transmitted in burst form.

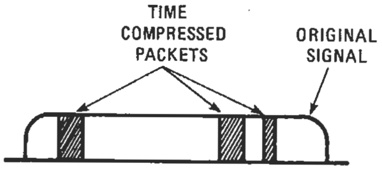


FIG. 10—TIME-DOMAIN REPRESENTATION of a time-hopped signal. In the frequency domain, the resulting spectrum would be similar to that of a direct sequence signal.

put of the filter is a maximum. As the degree of match, or correlation, decreases, the output decreases. If the bits in none of the cells match, the output is zero.

Some receivers will make use of two or more matched filters to increase the likelihood of successful correlation. Decision-logic circuitry is used to select the most likely filter output. The output of the correlator is then fed to a demodulator, etc. for processing by conventional means. A block diagram of a typical direct-sequence system, up to the output of the correlator at the receiver, is shown in Fig. 6.

Chirp systems

Similar to signals used in radar applications, chirped signals are formed by sweeping or sliding the frequency of the signal over a wide range during a pulse interval. The block diagram of a circuit for a chirp transmitter is shown in Fig. 7.

When used in a communication application, the data input determines the direction of the chirp: frequency is shifted up the band for a logic 1 and down the band for a logic 0.

Receiving chirp signals involves using matched filters in much the same way as they are used in direct-sequence systems. The structure of the filters themselves do differ, however, because in chirp systems frequency rather than amplitude patterns are of interest. Multiple filters are usually used, with the filter producing the most unambiguous output identifying the data sent.

Chirp systems usually use a linear frequency sweep instead of a noise source and so in strict terms don't qualify as a spread spectrum signal. However, as you can see in Fig. 8, they do have larger than required bandwidths and so produce processing gain. See Fig. 8.

Although many experimental wartime systems used some form of chirping, it is not often used today for communications—at least not for *human* communications. However, it is believed that dolphins use complex chirp signals for communications; bats use similar signals for ranging and navigation.

Time hopping

Time-hopping schemes are used in conjunction with frequency-hopping or direct-sequence spreading to provide multiple-channel access or data security in the form of "randomly" scheduled transmission times. As shown in Fig. 9, time hopping requires that data be stored or compressed and then transmitted in high-speed bursts during the allotted time slot. See Fig. 10.

The processing gain of time hopping is achieved by virtue of the shorter time taken to transmit the information, since the narrower the pulse in the time domain the larger the bandwidth in the frequency domain. Since scheduling can be derived from a random or pseudo-random source, time-hopping systems are bonafide members of the spread-spectrum family.

Applications

Frequency hopping can be added to either digital or analog communication systems since it is only the carrier that is affected. The U.S. Air Force has retrofitted many of their existing analog UHF radio links with frequency-hopping capability as an interim step while more sophisticated digital systems are being developed. That interim system, which the Air Force has branded *Have Quick,* uses the time of day to select the currently active frequency slot from among a set of 7000 possible slots.

The *G*lobal *P*ositioning *S*ystem (GPS) is a satellite system that makes use of a basic direct-sequence ranging technique. As of this writing, the system is only partially in place. When fully implemented, GPS could allow subscribers anywhere in the world to determine their position to within a few meters, therefore revolutionizing navigation.

The GPS will consist of a fleet of 18 satellites in low-altitude circular orbits that allow contiguous coverage of the entire globe with direct-sequence microwave signals. Virtually every spot on the globe will be able to receive signals from at least 4 satellites. When decoded, each signal can be used to determine the linear distance from a particular satellite to the receiver. That distance is proportional to the propagation delay; that is the time difference between when the signal is transmitted and when it is received. See Fig. 11. Three of the signals are used to triangulate the receiver's position. The signal from the fourth satellite is used to correct clock drift and other error effects.

The *J*oint *T*actical *I*nformation *D*istribution *S*ystem (JTIDS) is designed primarily for military use. Using frequency-hopped, direct-sequence modulation the system provides communication, navigation, and control facilities to air-, land-, and sea-based subscribers. The system uses a 5-MHz wide MSK (*M*imimum *S*hift *K*eying, which is closely related to frequency shift keying) direct-sequence signal. The signal is then frequency hopped over a 52-frequency set, with 3 MHz of separation between hopped frequencies. After a user synchronizes with the system, which is done using special preamble signals, data can be exchanged with any other authorized user within a range of 500 nautical miles. **R-E**

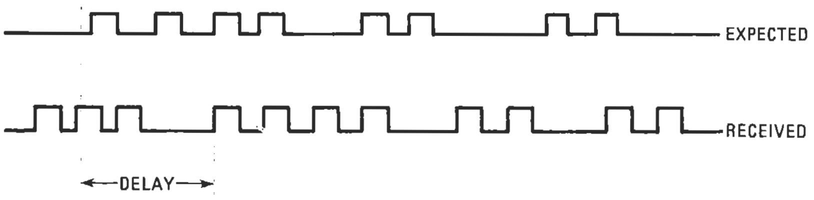


FIG. 11—IN THE GPS RANGING SYSTEM, distance to the transmitter is determined by the time delay between expected and received signals.