The Lenkurt® Demodulator

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Noise is the universal enemy of electrical communication. Therefore, the study of noise and its effects is immensely important to the operators and manufacturers of communications equipment. The widespread interest in the subject is indicated by the unusual popularity of this article, which originally appeared in the DEMODULATOR *in 1960. In response to a number of requests, the article has been brought up to date and is being reprinted here. It presents a basic review of the nature and sources of noise, and reflects the current trends in noise measurement.*

Across a crowded room one may have trouble being understood, even when speaking in a loud voice. When the room is empty, the same voice may seem too loud. What has obscured communication? In both cases the same amount of speech power was present to carry the message. The signal was there, but interference prevented it from being identified by the listener.

In communications, interference is called "noise," even though it may be electrical, rather than auditory in nature. A signal represents a certain degree of order or pattern. During transmission, disorganizing forces constantly damage the signal. If this is allowed to go too far, the signal will eventually become lost in the background noise, thus destroying communication. The signal is always at a disadvantage because it constantly undergoes attenuation, whereas noise is generated afresh at almost every point in the transmission path.

Sources of Noise

The very nature of the universe gives rise to noise. Noise is generated in the flow of electricity through a conductor as electrons collide with some of the molecules of the conducting material. As the temperature of the conductor is increased, noise also increases as more of the electrons collide with the more agitated molecules of the conductor. The amount of noise generated is directly proportional to the temperature of the conductor.

In electron tubes and semiconductors noise is generated by the randomness of electrons or other current carriers. Electrons boil off a cathode irregularly. "Holes" or electrons slide through the lattice of a semiconductor randomly, taking different paths and varying amounts of time to travel from one electrode to another, thus adding to the noise in the circuit. This type of noise also increases as temperature rises. Since electricity consists of individual particles or charges rather than being a perfectly smooth homogeneous fluid, noise is bound to arise in connection with current flow.

Another fundamental source of noise is called "black body radiation," and is of interest primarily in radio transmission. All objects in the universe radiate energy over a broad spectrum. The most perfect radiator of energy would also be the most perfect absorber. Thus, a perfect black body—capable of neither transmission nor reflection—would be the ideal radiator. The hotter an object, the more energy it radiates, and the shorter the wavelength at which most of the energy is radiated. For instance, objects at room temperature radiate some energy at microwave frequencies, but most of the radiation from such objects is at very long infra-red wavelengths. Similarly, most of the sun's energy is radiated as visible light and ultra-violet rays, and most of the energy released during the first flash of a nuclear bomb consists of X rays and gamma rays.

Although the radio-frequency energy emitted by objects at moderate temperatures is very slight, some sensitive microwave receivers can detect a man as he crosses a field of snow by the extra microwave radiation that he emits. All radiation of this kind contributes to the background noise that must be overcome in radio communication.

The various types of noise based on thermal agitation or radiation are sometimes called resistance noise, thermal noise, Johnson noise, or white noise. The term "white noise" refers to the fact that white light has a uniform distribution of energy across the visible spectrum. Similarly, thermal or Johnson noise is uniformly distributed across the spectrum. This uniform distribution is caused by the great variety of noise

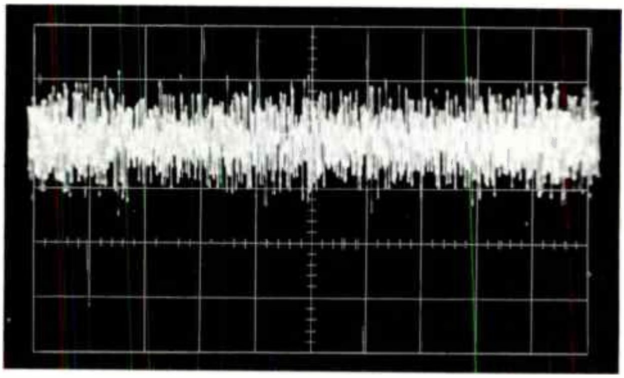


Figure 1. "White" noise as it appears in communication channel. Other names for white noise include "background noise," "random noise," and "fluctuation noise."

sources, and the extremely wide range of energy levels of the electrons and molecules that actually generate the noise.

Effect of Temperature

Johnson noise has been found to be directly proportional to bandwidth and temperature, regardless of the source of the noise. Actual calculations of the noise power to be found in an electrical circuit or detected by a radio receiver follow the relationship

$$noise\ power = kTB\ watts$$

where

k is Boltzmann's constant (1.38×10^{-23} joule per degree),

T is absolute temperature in degrees Kelvin (0°C = 273°K), and

B is the bandwidth in cycles per second.

Since k does not change, the noise power for a *particular bandwidth* depends only on the temperature of the noise source. Thus a thermal noise source at room temperature of 290°K produces noise power of (1.38×10^{-23}) (290) = 4.0×10^{-21} watt per cycle of bandwidth. If heated to twice the temperature (580°K), the same source will produce twice the noise power because the noise is directly proportional to the temperature.

Thus, if a highly directional microwave antenna were connected to a suitable receiver having a bandwidth of 1 megacycle and pointed at an object the temperature of the sun (which has a surface temperature of about 6000°K), noise power of 8.28×10^{-14} watt, or —101 dbm would be received. The same microwave receiver, if pointed at a man (whose body temperature is about 310°K), would receive about 4.28×10^{-15} watt, or —114 dbm of noise power. Radio astronomers are now using this technique to uncover many new facts about other planets and other galaxies, by using very sensitive microwave equipment to measure *noise temperature.*

The concept of noise temperature, however, can be extended to cover many other noise sources. Any device which produces random noise of 4.0 x 10^{-21} watt (−174 dbm) per cycle of bandwidth may be said to have a noise temperature of 290°K—even though that may not be its physical temperature. In other words, the noise temperature of a device is the temperature at which a thermal noise source would have to be operated to produce the same noise power as that produced by the device under consideration.

Assigning a noise temperature to each part of a system considerably simplifies the calculations. The total noise temperature is merely the arithmetical sum of the individual noise temperatures. Suppose the antenna noise temperature in a microwave system is 300°K and the receiver noise temperature is 2000°K. The noise temperature of the combination is then 2300°K.

Noise Figure

The noise contribution of a device can also be expressed in terms of its "noise figure." Noise figure is defined as the input signal-to-noise ratio divided by the output signal-to-noise ratio:

$$F = \frac{(S/N)_i}{(S/N)_o}$$

Both the signal-to-noise ratio and the noise figure can be specified in terms of pure numbers. The more common procedure, however, is to specify these quantities in db. For example, consider a signal-to-noise ratio of 60 db at the input to an amplifier, and an output signal-to-noise ratio of 50 db. Since both ratios are expressed in logarithmic terms, the noise figure in db is simply the difference between the two:

$$\begin{aligned} 10 \log F &= 10 \log (S/N)_i - 10 \log (S/N)_o \\ &= 60\ db - 50\ db \\ &= 10\ db \end{aligned}$$

This 10 db may be considered a figure of merit for the amplifier—an indication of how much noise is introduced by the amplifier.

In microwave receivers, considerable noise is introduced by the first intermediate-frequency amplifier. Other major contributors of noise are diodes used in the mixer, and noise sidebands from the local oscillator. In addition, impedance mismatch between antenna, waveguide, or mixer can distort the signal, resulting in increased noise. Intermodulation or nonlinear distortion also produces noise which tends to obscure the signal.

Although there is little that can be done about noise originating outside the communication system, much progress has been made in reducing noise that originates within the system itself. New technological developments now permit the use of transmission performance standards which would have been beyond reach a few years ago.

Impulse Noise

A type of interference known as impulse noise is becoming increasingly important with the upsurge in digital communications. Unlike thermal noise, impulse noise is sporadic and may occur in bursts, rather than being uniformly distributed. Impulse noise consists of discrete impulses which occur on the circuit as the result of any of several causes. Some types of impulse noise are natural, being caused by lightning, aurora borealis, or other such electrical disturbances. Increasing amounts of impulse noise are man-made. Ignition noises, power lines and their associated switching are strong offenders. In telephone offices, impulse noise may be very great, due to dialing and switching impulses which are induced or otherwise coupled into transmission paths.

Figure 2 compares a speech signal and a typical noise impulse. Both traces are to the same scale; the speech signal level was approximately —20 dbm. Note that the amplitude of the noise impulse is greater than the maximum speech amplitude. These photographs also suggest why impulse noise hardly disturbs speech. A speech sound must be sustained to be understood, since the tone and other qualities of the speech are determined by a succession of waves over a continuing period of time. Noise impulses are too brief to produce a serious disturbance to speech. On the other hand, although noise impulses are usually of very short duration, they may have very great amplitude. Data pulses do not have the redundancy which permits speech to be understood in the presence of large amounts of interference. As a result, a burst of noise which might have little effect on even a single speech syllable could easily make a meaningless jumble of a block of information such as that contained on a punched card.

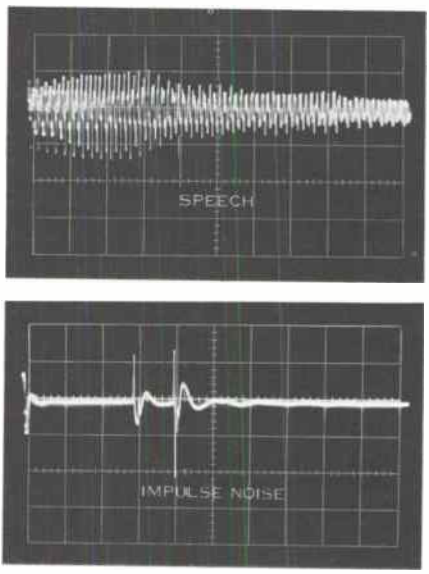
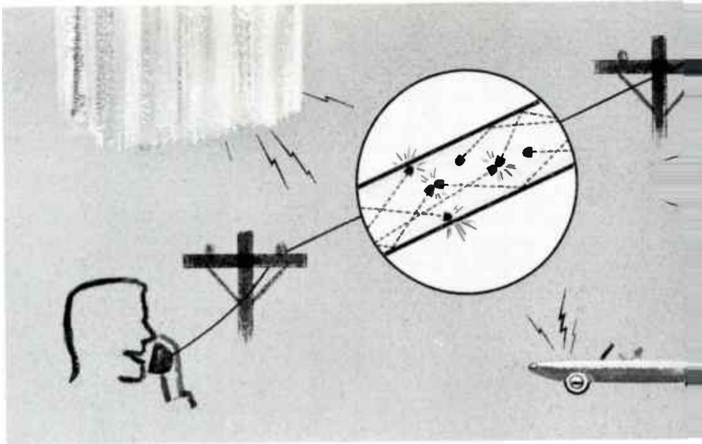


Figure 2. Comparison of speech and impulse noise recorded from actual telephone circuit. Speech sample is the word "two." Note slight ringing following each noise impulse.

The advent of dial-up data-transmission services makes the problem of impulse noise much greater. As data transmission rates increase (in a given bandwidth), the transmission becomes much more vulnerable to impulse noise, mostly because the data pulses are shorter and more nearly like the noise impulses. Even though noise impulses may be very brief, much shorter than the data pulses, they can cause serious interference by causing filters and other tuned elements in a communications channel to "ring." The resulting oscillations may interfere with the signal and cause errors.

Figure 3. Noise originates outside a communication system as well as inside. Sources may include aurora borealis, molecular agitation in conductors, ignition systems, solar radiation, radio interference, atmospheric disturbances, and others.



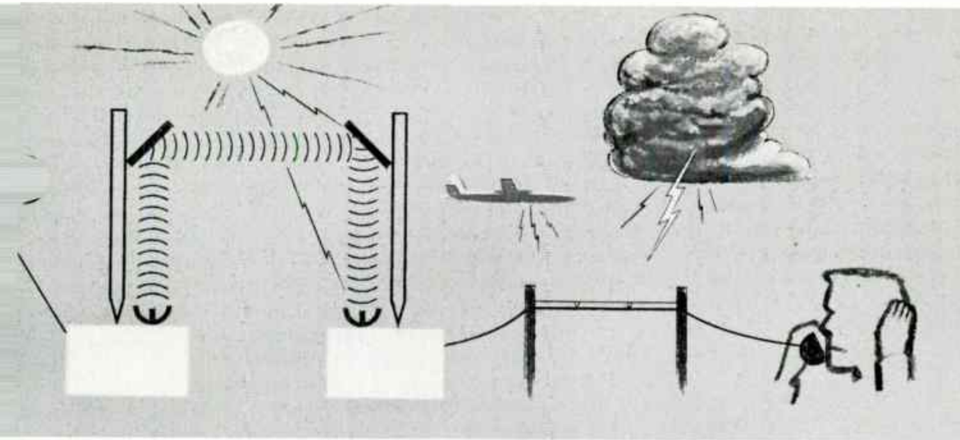
Noise Measurements

In order to establish performance standards for communications systems, it is necessary to be able to measure the interfering effect of noise. This is different from measuring the amplitude or power of the noise, since noise seems to create more interference at some frequencies than at others. Because the "waveshape" of noise is entirely different than that of speech or music, the ear reacts differently to noise than to speech. In telephone circuits, the type of receiver used has an effect on the amount of interference that a given amount of random noise will produce.

In establishing noise measurement standards, the interfering effect of noise was simulated by comparing the interference provided by a 1000-cycle tone at a reference level with other frequencies. The levels of the other frequencies were adjusted until they were estimated to have the same interfering effect as the 1000-cycle tone. In all tests, a carefully prepared recorded conversation was used to test the interference. Weighting curves such as those shown in Figure 4 were obtained. When a filter or weighting network having these characteristics is used in connection with a flat meter, the meter will give a direct measure of the actual interference produced on voice circuits by the noise.

Line weighting should not be used when measuring interference on data circuits, since the weighting is based on human response when using a certain type of instrument.

At the time of the first tests, the Western Electric type 144 handset was the most widely used handset in the United States. The 144 line weighting curve pertained to this instrument. With the advent of the type 302 set, new response curves were obtained by similar tests, resulting in F1A line weighting. With the development of the type 500 set, still another weighting curve, called C-message weighting, was introduced. However, it is important to



note that none of these weighting curves represent the frequency response of the telephone receiver alone. Instead, they combine the effect of the receiver and the listener's subjective reaction to the interference.

Noise Units

In the United States telephone industry, the reference power level for noise measurements was standardized at 10^{-12} watt or 90 db below 1 milliwatt at 1000 cycles per second. At the time this standard was established, the 144 handset was in general use and noise was measured in decibels above the reference power level (using the weighting network). The unit was called "dbrn" (formerly written dbRN) or decibels above reference noise. With the introduction of the 302 handset, which was about 5 db more sensitive than the 144 handset, the reference level was raised to —85 dbm so that established standards would still be meaningful. Measurements made with the F1A line weighting network were in terms of "dba" or decibels adjusted.

When C-message weighting was established in conjunction with the 500 set, the reference level was returned to —90 dbm. Thus, the noise unit again became "dbrn." At 1000 cps, this unit is the equivalent of the original dbrn, but it is not the same at other frequencies because of the different weighting characteristics. Therefore, noise measured with C-message weighting is specified in "dbrnc."

Rarely, if ever, is 144 line weighting used now. However, noise is often specified in dba, which normally implies F1A weighting unless some other weighting characteristic is specified. The trend in North America is toward C-message weighting with noise specified in dbrnc.

European Noise Units

In Europe and many other parts of the world, units established by the CCITT (International Telegraph and

Telephone Consultative Committee) are used to express circuit noise. The principal units of measurement, which are linear rather than logarithmic, are called "psophometric emf" and "psophometric voltage" (from the Greek *psophos*, meaning noise).

The psophometric emf is the electromotive force (or voltage) generated by a source having an internal resistance of 600 ohms and no internal reactance, which, when connected across a standard receiver having 600 ohms resistance and no reactance, produces the same sinusoidal current as an 800-cycle generator of the same impedance.

Psophometric voltage is defined as the voltage which would appear across a 600-ohm resistance connected between any two points in a telephone circuit. This value is one-half the psophometric emf since the latter is essentially the open-circuit potential necessary from a source to produce the psophometric voltage if the source has a 600-ohm internal resistance. Figure 4 illustrates the relationship between psophometric emf (E) and psophometric voltage (V).

Noise is measured by a psophometer —essentially a vacuum-tube voltmeter which includes a psophometric weight-

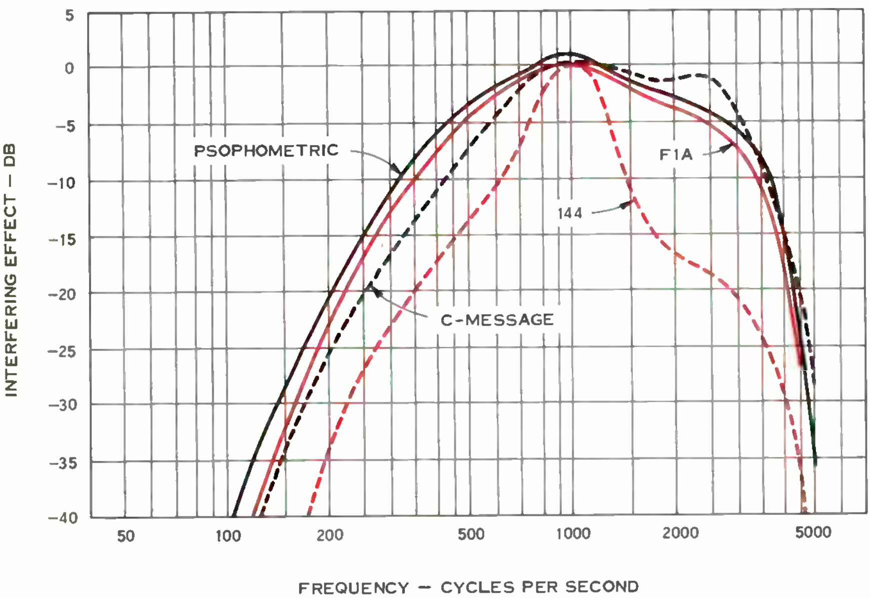
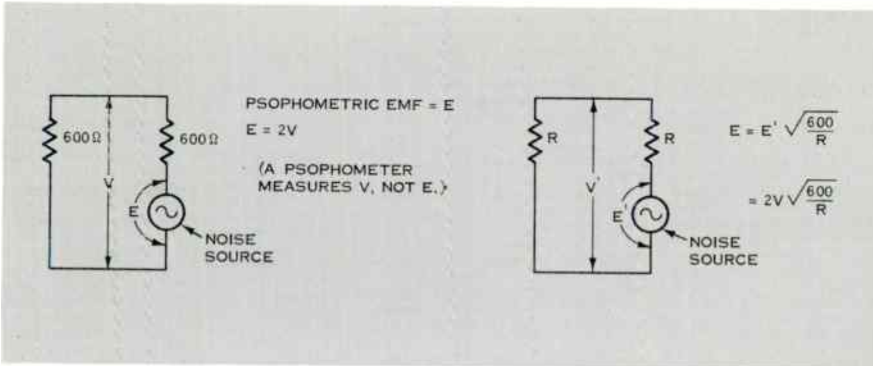


Figure 4. Weighting curves, based on listener response when using a particular type handset, show the relative interfering effect of noise on speech. All curves are referred to 1000 cps except psophometric, which is referred to 800 cps. Although no longer in wide use, 144 line weighting is included for historical interest.



REFERENCE DATA FOR RADIO ENGINEERS

Figure 5. Psophometric noise is measured or calculated in volts (or millivolts) under conditions shown.

ing network. Psophometric weighting is nearly identical to F1A weighting. Minor differences include the fact that psophometric weighting is referenced to 800 cps instead of 1000 cps. The psophometer is calibrated so that an 800-cps tone at 0 dbm in a 600-ohm resistance will produce a meter reading of 0.775 volt, psophometrically weighted.

A common procedure is to specify noise in picowatts, psophometrically weighted (pwp), where

$$\textit{Psophometric power} = \frac{(\textit{psophometric voltage})^2}{600 \textit{ ohms}}$$

The description of noise power in terms of picowatts, rather than logarithmic units, has the advantage of simplifying many calculations. Simple arithmetical addition gives the total noise power contributed by several sources. This is not true of logarithmic units, such as dba and dbrnc. However, many people feel that the use of db units gives a more accurate impression of the interfering effect of the noise. For example, a 3-db increase in noise power increases the interfering effect about the same amount whether the change is from 12 to 15 dbrnc or from 30 to 33 dbrnc. By contrast, a 50-pw change could have a considerable effect on interference at a low level, while it might go unnoticed at a high level.

While exact conversion from one noise unit to another is quite laborious, approximate conversions (accurate enough for most purposes) are as follows:

$$dba = 10 \log pwp - 6$$
$$dbrnc = dba + 6$$
$$dbrnc = 10 \log pwp.$$

Impulse Noise Measurements

Since impulse noise may be quite sporadic, it does not generate a "noise power" in the sense that thermal noise does. Although thermal noise may be measured with conventional instruments such as noise measuring sets and voltmeters, these instruments are unsuitable for measuring impulse noise. One reason is that impulses last too short a time for the instrument to register. Another is that pulse amplitudes at one instant do not necessarily indicate the maximum pulse amplitudes that may be encountered. Because of this uncertainty, most impulse noise figures are estimates of the highest pulse amplitude that will occur. The estimates, in turn, are based on noting the highest amplitude which occurs in a given period of time—the longer the better.

One instrument used for such measurements is known as an impact meter. This device amplifies the impulse and charges a capacitor. The charge on the capacitor is directly proportional to the impulse amplitude. A vacuum tube voltmeter constantly indicates the charge. Thus, the meter reading will indicate the highest amplitude which occurred after the measurement began. Determining the impulse noise characteristics may take on the aspects of a statistical survey.

Trends

As communications users become more sophisticated, they demand "quieter" circuits, which in turn further refine the users' tastes. Thus, noise reduction appears to be a never-ending process. New standards for various types of service are nearly always more stringent than the ones they replace.

A major factor in providing consistently good noise performance is the acceptance of standardized noise measuring and specifying methods. Although F1A weighting is still used, the trend in the United States is toward C-message weighting, with noise specification in dbrnc. In other parts of the world, however, the more common unit is the pwp. Both units are widely recognized, and as international communication ties become stronger it is not uncommon to see noise specified both ways. •

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