The Lenkurt® Demodulator

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NOISE PERFORMANCE in Industrial Microwave Systems

Part One

The performance of a communications system should be evaluated by how well it meets the requirements of the user. This sounds simple, but often there is confusion about how to establish performance criteria, and then about how to measure the actual performance. This article discusses noise performance of FM microwave systems using single-sideband, suppressed-carrier multiplex equipment. Sources of noise in such systems are discussed in terms of their effect on signal-to-noise ratios in the derived voice channels. Methods of calculating and measuring noise are considered and specific noise-performance recommendations are made.

Fundamentally, the purpose of a communications system is to transfer some form of intelligence, or "signal," from one point to another. An ideal system would deliver at the receiving end a signal identical in every detail to the signal applied at the transmitting end — with nothing altered and nothing added.

In a real communications system, this ideal performance is never completely achieved. In such a system every characteristic of the signal is altered to some degree, and there is always something

EDITOR'S NOTE

This is the first part of a two-part article written by Robert F. White, Lenkurt Transmission Engineer, in an effort to establish some guidelines for calculating and measuring noise in industrial microwave systems. Because of the exceptional clarity of the discussion, and because most of the article applies to all classes of microwave users, it is being reprinted here for the benefit of all DEMODULATOR *readers. The second part will appear next month.*

added along the way. Thus, the received signal is always a somewhat less than faithful reproduction of the signal applied at the transmitting end, plus some other elements which are mostly unrelated to the original signal and which may be present even when the signal is completely absent.

Performance of a communications system is measured by how closely the received signal resembles the transmitted signal and by how free it is of these other elements. The definition and measurement of the performance thus falls into two natural categories. In the first category there would be considered technical characteristics which define accuracy or fidelity of the reproduced signal: amplitude-frequency response, level stability, phase response, delay distortion, etc. These characteristics are, more or less, under the control of the equipment designer and may be held to almost any desired value.

In the second category there would be considered all the extraneous elements appearing at the channel output which were not a part of the input signal. It is these elements, usually lumped together in a single category called "noise," with which this article deals. The discussion is in terms of the noise as it appears in the derived voice channels. There are good reasons for taking noise in a voice channel as a criterion, even though present day systems usually carry telegraph and data as well as voice. The basic voice channel is familiar to all, is reasonably well standardized, and there is a large body of experience to draw on. Furthermore, the majority of equipments used for modern telegraph and data service are designed to operate over such a carrier-derived voice channel, or some fraction or multiple of it, and it is not difficult to evaluate the effect on a data system of a particular level of noise in the 3-kc band.

Noise Sources

The noise which appears in a voice channel of a microwave system comes from a number of different sources, some of which vary in a rather complex manner. It is useful to consider three general types of noise, classified in accordance with how they vary.

One is the thermal noise generated in the antenna and in the "front-end" circuits of the receiver: this noise in an FM system varies in inverse relation to the strength of the RF level at the receiver input, and is therefore affected by fading. It is not affected by system loading.

A second type of noise, also thermal in nature, is that developed in the electronic circuitry of the transmitter and in certain portions of the receiver. This type of noise, often called "idle" or "intrinsic" noise, is not affected by the RF input level, nor is it affected by system loading.

The third type of noise consists of spurious signals created by intermodulation between the various frequency components of the total composite signal. Such intermodulation is produced by every non-linearity through which the signal passes. The spurious products include the sums and differences of every frequency and its harmonics present in the modulating signal and all of the other frequencies and their harmonics.

Since the baseband spectrum of a multichannel system is extraordinarily complex, the number of intermodulation products produced in such a system ap-

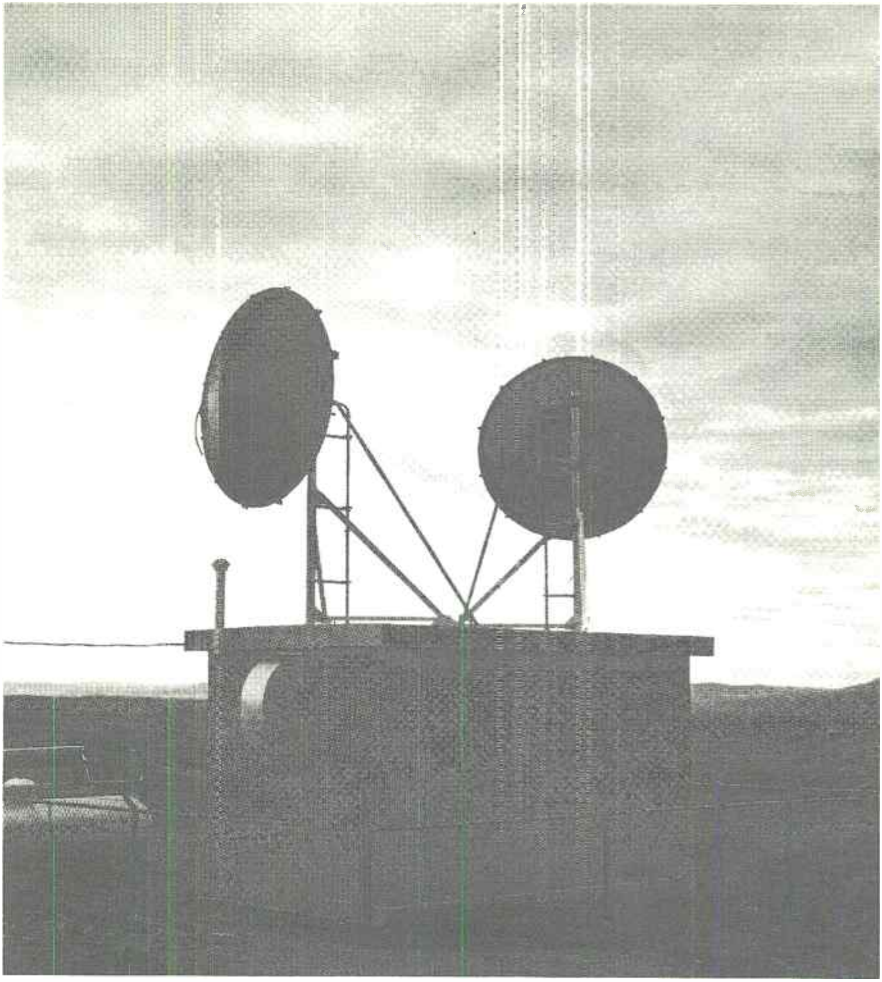

Figure 1. Thermal noise in the receiver adds to the earth noise temperature seen by the antenna.

proaches infinity. Statistically this noise becomes very similar to the thermal and idle noise. Intermodulation noise is affected by system loading, increasing as the loading increases, but it is not directly affected by the RF input level.

Each of the three kinds of noise described above affects system operation in a different way, as can be shown from Figure 2. This graph shows noise performance for one hop of a high-quality microwave system, and is a plot of typical per-channel noise as a function of receiver input level and system loading. Noise is shown at the left as unweighted signal-to-noise ratio in a 3-kc voice channel, and at the right in dba, F1A weighted, at a 0 transmission level point. The curve is typical for the top channel (in which noise is usually greatest) of a 300-channel system using CCIR deviation and CCIR busy-hour loading. A small allowance for antenna distortion is included.

The effect of the receiver front-end noise on the channel signal-to-noise ratio is shown by the long line starting at the lower left-hand corner and running to the upper right-hand corner. It is evident that this noise is controlling when the RF input is lower than about −40 dbm. The noise at threshold is almost entirely of this type.

At high receiver input levels idle noise becomes controlling and limits the signal-to-noise ratio available, as shown by the bend in the upper line at the upper right-hand corner. This noise sets an upper limit to the channel signal-to-noise ratio when the system is in an idle or unloaded condition.

The effect of intermodulation noise is shown by the lower branch line. This noise sets the limit to the channel signal-

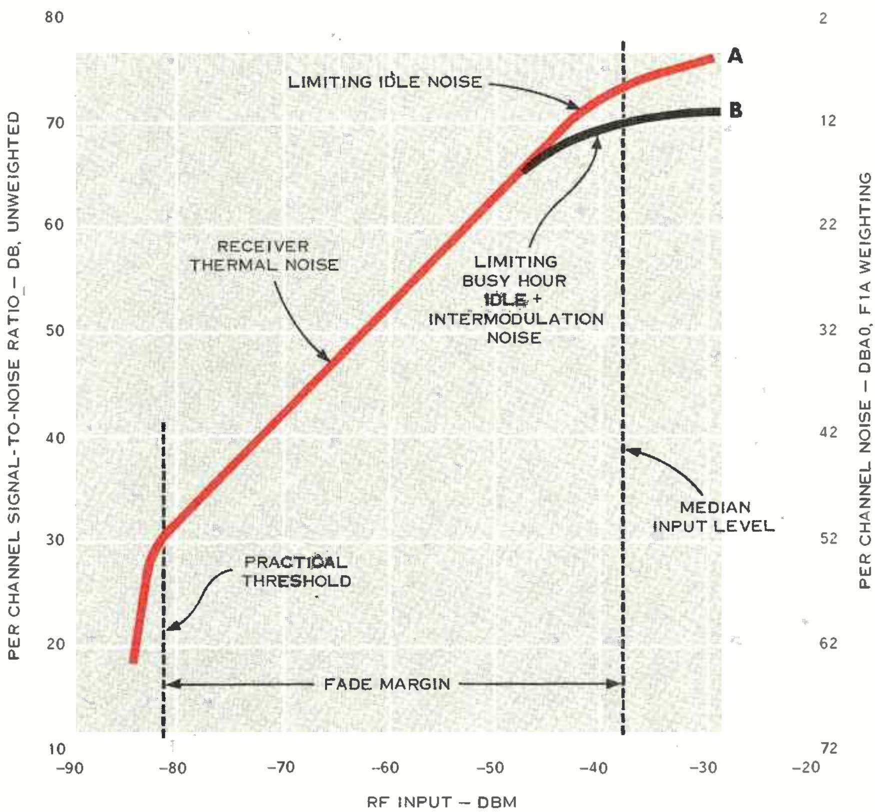

Figure 2. Noise performance of one hop of a high-quality microwave system is shown in this example of typical worst-channel noise plotted as a function of receiver input level and system loading.

to-noise ratio when the system is loaded to simulate busy hour conditions.

A noise characteristic curve such as Figure 2 is a good aid to understanding microwave noise performance, since it includes essentially all of the noise effects and shows them under all conditions of operation. The three most significant bits of information to be derived from the curve are the noise level at the practical threshold point, the noise level at the point of normal RF receiver input level under busy-hour loading conditions, and the fade margin.

A microwave system of the type specified by Figure 2 is usually engineered to have a median RF input level which is somewhere between −30 and −40 dbm. Such a level makes it possible to have very high signal-to-noise ratios during periods of no fading or very little fading, a condition which exists for all but a very small percentage of the time, and to have a fade margin which permits the RF input level to drop by at least 40 db (about one ten-thousandth of normal) before the signal-to-noise ratio becomes objectionable.

With a typical median input level of about −37 dbm, as shown in Figure 2, the signal-to-noise ratio for this system during non-fading periods will be very high, approaching Curve A during periods of light loading and dropping a few db towards Curve B during the heavy loading periods of the busy hour. Only after the input signal has faded several db does the signal-to-noise ratio begin to drop significantly as the receiver thermal noise begins to exceed the other noises. Over the straight line portion of the curve the signal-to-noise ratio varies db for db with the receiver input level and is determined only by the noise figure of the receiver and the deviation ratio used for the particular channel. Over this portion of the curve the unweighted signal-to-noise ratio in db in the derived 3-kc voice channel can be calculated as:

$$S/N \ (in\ db) = C + 136 - NF + 20 \log D$$

where

C = *receiver input level in dbm,*

NF = *receiver noise figure in db,*

and

D = *deviation ratio, or peak deviation for the channel divided by the carrier frequency of the channel.*

Signal-to-thermal noise ratio can be improved in three ways: by increasing the input level with higher transmitting power or bigger antennas, lowering the noise figure of the receiver, or increasing the deviation ratio. In practice, equipment and system designers raise the effective power and lower the receiver noise as far as is economically practicable. The effect of increasing the deviation ratio is not so simple; it improves the signal-to-noise ratio for the thermal and idle noise but degrades it for intermodulation noise. For this reason the equipment designer must choose a deviation ratio which provides an optimum balance between the different types of noise.

It is worth noting that the IF bandwidth of the microwave system does not affect the signal-to-thermal noise ratio as long as the receiver input level is above threshold. It does affect the "noise performance" in two ways: it determines the point at which the "knee" of the noise characteristic occurs, often called the FM improvement threshold, and it has a significant effect on the intermodulation characteristics.

The FM Improvement Threshold in dbm for a microwave receiver can be calculated as:

$$T_{FMI} = -104 + NF + 10 \log B_{mi}$$

where

NF = receiver noise figure in db,

and

B_{mi} = receiver IF bandwidth at the 3-db points.

Changing the deviation ratio does not change the point at which threshold occurs, but it does change the value of signal-to-noise ratio at that point. Increasing the IF bandwidth raises the threshold point by admitting more noise into the system, thus reducing the available fade margin, but it makes possible a reduction in the intermodulation noise. Again, the equipment designer must attempt to achieve an optimum balance between these two conflicting factors. His choices are further affected by the fact that there are legal restrictions on the total bandwidth and deviation which can be used for a microwave channel. The FCC applies somewhat tighter restrictions to industrial users than it does to the common carrier users.

Although the FM Improvement Threshold represents the practical working threshold for a microwave system, there are other definitions of threshold which do not. This has caused a certain amount of confusion among microwave engineers. In order to avoid this confusion, it is now a common practice to specify threshold as the RF input level which will produce a specific minimum acceptable signal-to-noise ratio in the worst voice channel. Since threshold is based on an arbitrary channel signal-to-noise ratio, it may be different from commonly accepted values for either noise threshold or FM improvement threshold. An unweighted signal-to-noise ratio of 30 db is widely used as the minimum acceptable both by telephone and industrial users.

When the receiver input signal becomes very high, a point is reached where the signal-to-thermal noise ratio is no longer directly dependent on the receiver input level. This effect is indicated by the bend in the upper right branch of the curve. Here the thermal noise produced in the transmitter circuits and in those portions of the receiver circuits which are not affected by the automatic gain controls provides an upper limit to the signal-to-noise ratio under non-loaded conditions. This portion of the curve, though of some interest, is not really significant from an operational point of view since the signal-to-noise ratio makes little difference if the system is not being used.

In this area of high receiver input level, the lower branch is the *significant* operational curve. This gives the signal-to-total-noise ratio since it includes thermal noise, idle noise, and intermodulation noise under loaded conditions.

Intermodulation noise is produced in many different ways in a microwave system; reducing it to the extremely low levels required to meet present day noise standards imposes stiff requirements on many areas of equipment design. The FM modulation and demodulation processes, the passbands of the filters, and the characteristics of the baseband amplifiers must be highly linear, both in amplitude and phase, over a wide dynamic range. Impedance mismatches in

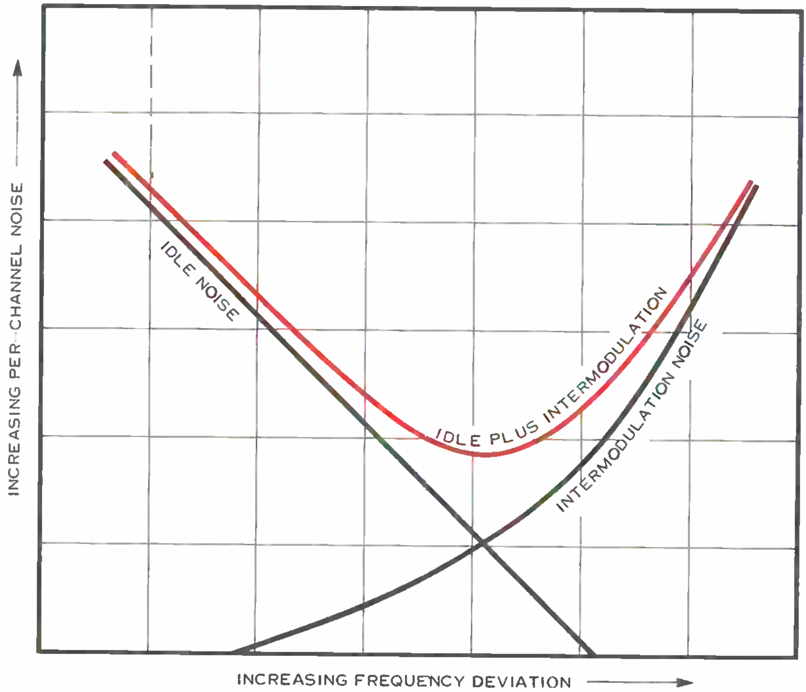

Figure 3. "Front end" idle noise is reduced in direct proportion to increase in frequency deviation due to signal level or system load. However, beyond "break point" of equipment, increasing intermodulation noise rapidly overcomes and reverses this advantage. The level at which intermodulation noise becomes dominant varies from equipment to equipment.

the equipment, and also in the associated waveguide and antenna systems, must be kept as low as possible in order to reduce intermodulation effects caused by reflections.

Multihop Performance

A noise performance curve such as the one shown in Figure 2 applies only on one hop of a microwave system, and it does *not* include the noise contribution of the associated multiplex equipment. The multiplex noise must be added to the microwave noise to get the system signal-to-noise ratio. The multiplex noise under loaded conditions usually runs about 20 to 23 dba0 for a pair of carrier terminals; this is considerably higher than the noise shown for the single microwave hop, and for a one or two hop system the over-all noise is mainly that of the multiplex. But for a long microwave system, in which the multiplex noise appears only once and the per-hop microwave noise many times, the latter becomes controlling.

The curve of Figure 2 shows what the noise performance will be as a function of RF input level, but it does not give any information as to the time distribution of this input level, except by the circumstance that the input will equal or exceed the median level for 50% of the time. For the purposes of this article, it is sufficient to state that the period of time during which a microwave hop will experience a fade of the order of 40 db is extremely small, and the probability that more than one hop of even a very long microwave system will be at or near the threshold level at a given moment is negligible. This means that the noise level at the threshold point on a microwave system does not increase as more hops are added.

When one hop fades down near threshold, the noise contributed by that hop becomes so much greater than the combined noise of all the other hops that the full system signal-to-noise ratio is essentially that of the one faded hop. For systems with high fade margins, then, it is seen that the threshold noise level is the same regardless of the number of hops in the system. Increasing the number of hops does not change the noise level at threshold, but it does increase the amount of time during which the system will reach threshold and, hence, directly reduces system propagation reliability, since the reliability is defined in terms of the percentage of time during which every hop of the complete system is at or above threshold.

Although the threshold noise level does not change as more hops are added to a microwave system, the noise level during average or non-faded conditions does change. To a first approximation, the multihop noise under these conditions is the sum of all the individual hop noises added together on a power basis.

This is strictly true for thermal and idle noise and even-order intermodulation noise products, which are fully incoherent even on tandem hops. But certain odd-order intermodulation products, even though they are essentially random in a single hop, have some coherency on tandem hops and may, therefore, add on a *voltage* rather than a *power* basis. In this case the system noise power can be greater than the sum of all the per-hop noise powers. Odd-order intermodulation products are normally considerably lower than even-order products, so this effect does not significantly affect the noise addition until the system becomes fairly long. For the longer systems it is important that the equipment design be such as to give special attention to the reduction of odd-order intermodulation effects. If this is done, the noise on even long systems has a summation pattern very close to that of power addition.

Noise Specifying Methods

So far in this discussion channel noise has been considered in terms of signal-to-noise ratio, expressed in db, with the "signal" being understood to be a 1,000-cycle test tone with a power of 0 dbm at a 0 transmission level point, and the "noise" being the unweighted noise in a 3-kc bandwidth. Without belaboring the point, the "signal" in signal-to-noise ratio really means "standard signal," which must be taken as test tone level. This way of defining noise, which has been adopted as a standard by the E.I.A., is perhaps the most meaningful for the industrial user.

Although conceptually, signal-to-noise ratio is the significant end result, it is considerably more convenient for purposes of calculation to have the channel noise expressed in some absolute form. One such way, developed by the Bell System and widely used for many years in this country, is in terms of a unit identified as *dba, F1A-weighted*. The reference level, or 0 dba, is equivalent to a 1,000-cycle tone with a power of −85 dbm or of a 3-kc white-noise band with a power of −82 dbm.

(Bell System has recently introduced a new weighting characteristic and a new unit, the dbrnc. The reference level, or 0 dbrnc, is the equivalent of a 1,000-cycle tone with a power of −90 dbm, or of a 3-kc band of white noise with a power of −88.5 dbm, usually rounded off to −88 dbm.)

A second way of expressing noise, developed by CCITT and CCIR, is in terms of picowatts, psophometrically weighted. The reference level, 1 pw_p, is the equivalent of an 800-cycle tone with a power of −90 dbm, a 1,000-cycle tone with a power of −91 dbm, or a 3-kc band of white noise with a power of approximately −88 dbm. The shapes of the F1A weighting curve and the psophometric curve are essentially identical, and dba can be converted to picowatts, or vice versa, by the formula

$$dba = -6 + 10 \log_{10} pw_p.$$

Since the dba and the picowatt are both absolute units, it is necessary to associate them with some specific transmission level before they have any real significance. In recent years it has become quite common to do this by adding a zero to the unit to indicate that it is

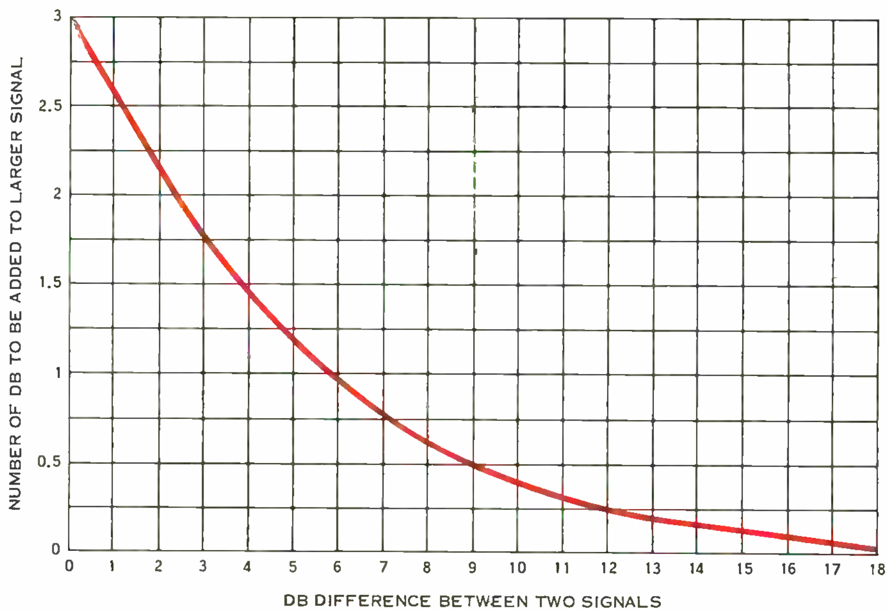

Figure 4. Addition of powers expressed in logarithmic units is simplified by the use of curve.

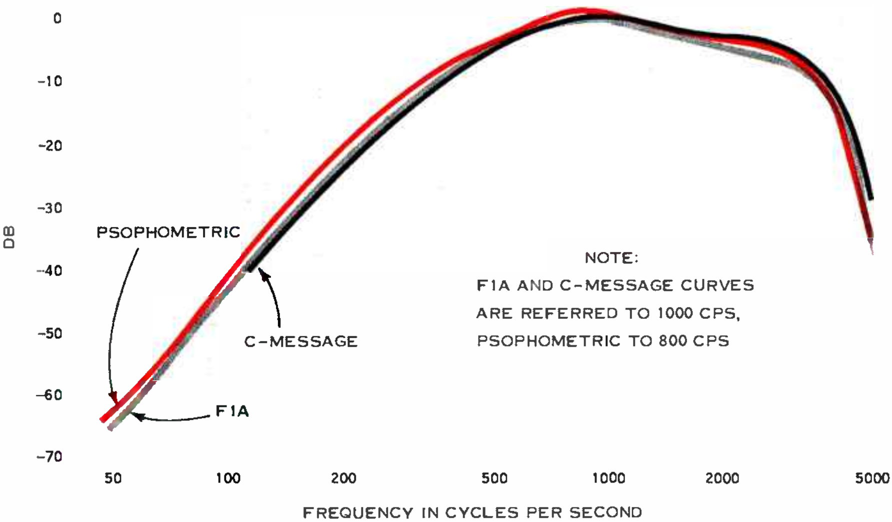

Figure 5. Weighting curves in common use indicate how noise at the band edges affects unweighted measurements out of proportion to its actual interfering effect.

referred to a 0 transmission level point. The resulting units, written as dba0 and pw_p0, can be converted to signal-to-noise ratios as defined earlier by the formulas

$$S/N = 82 - dba0$$

$$S/N = 88 - 10 \log_{10} pw_p 0.$$

These relations are correct only if the noise is essentially white noise. The noise produced in multichannel microwave systems is almost entirely of this type, so the correlations are valid for microwave noise.

The dba and the psophometric picowatt are equally valid absolute noise units, but differ somewhat in application because the one is logarithmic and the other linear. The linear unit, the picowatt, has the advantage that addition of noise powers becomes a matter of simple arithmetical addition of the picowatts. Addition of powers expressed in logarithmic units such as the dba is not quite so simple but can be done relatively easily by the use of a chart such as Figure 4.

Many people feel that the mathematical convenience of the picowatt is more than offset by the fact that the effects being measured are essentially logarithmic themselves and, consequently, a logarithmic unit is much more meaningful than a linear unit. A change of 1 db in signal-to-noise ratio has essentially the same meaning regardless of where it occurs, but a change of 100 picowatts might mean a change of 20 db or more if it occurs at a very low level; or it might mean no detectable change at all if it occurs at a high level.

Weighted or Unweighted?

When only the noise generated in the microwave system itself is considered, along with its measurement at the radio baseband output point, it really makes little difference whether weighting is used. For noise of this kind the effect of weighting is simply to reduce the noise by a fixed, known amount (3 db in the case of F1A weighting, approximately 2 db in the case of psophometric weighting). Using weighting simply changes the numerical value of a noise reading by that fixed amount. It is equivalent to changing the noise unit itself. A noise level giving a flat signal-to-noise ratio of 50 db will give an F1A weighted ratio of 53 db; this sounds better, but the noise is just the same.

But when noise in the complete system and its measurement at the output of the voice channels themselves is considered, with all of the multiplex equipment and drop equipment connected and functioning, weighting is far more significant. In this case there may be substantial amounts of noise which are not random in nature. Much of this noise may be at very low or very high frequencies where the effect on measurements of noise power is far out of proportion to the effect on actual transmission quality. For this reason telephone practice is invariably to use weighted noise units. Even though the weighting is based strictly on voice transmission, it is quite possible that for data transmission systems designed to operate over a voice channel, a weighted measurement may be as good a criterion as an unweighted one or perhaps even better.

Because of phase effects near the band edges, such data circuits are usually located in the interior part of the band — an area where the weighting characteristic introduces the least change. The C-message weighting, for example, is reasonably flat over most of the portion of the band which is usable for data.

The most important thing about noise units is not so much whether they are weighted or unweighted. Rather, it is that they be precisely defined so that the meaning is unmistakably clear. •

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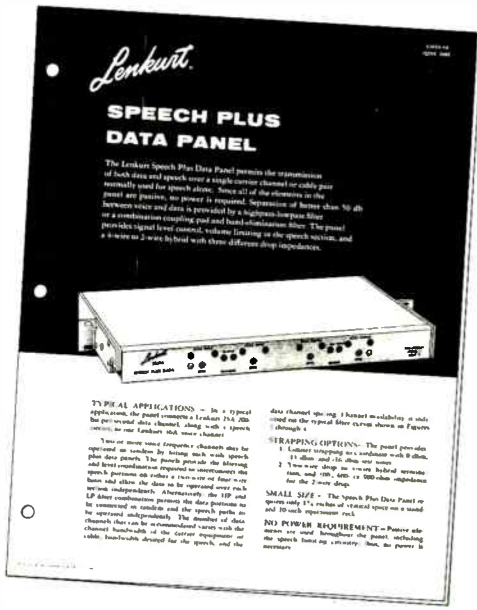

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