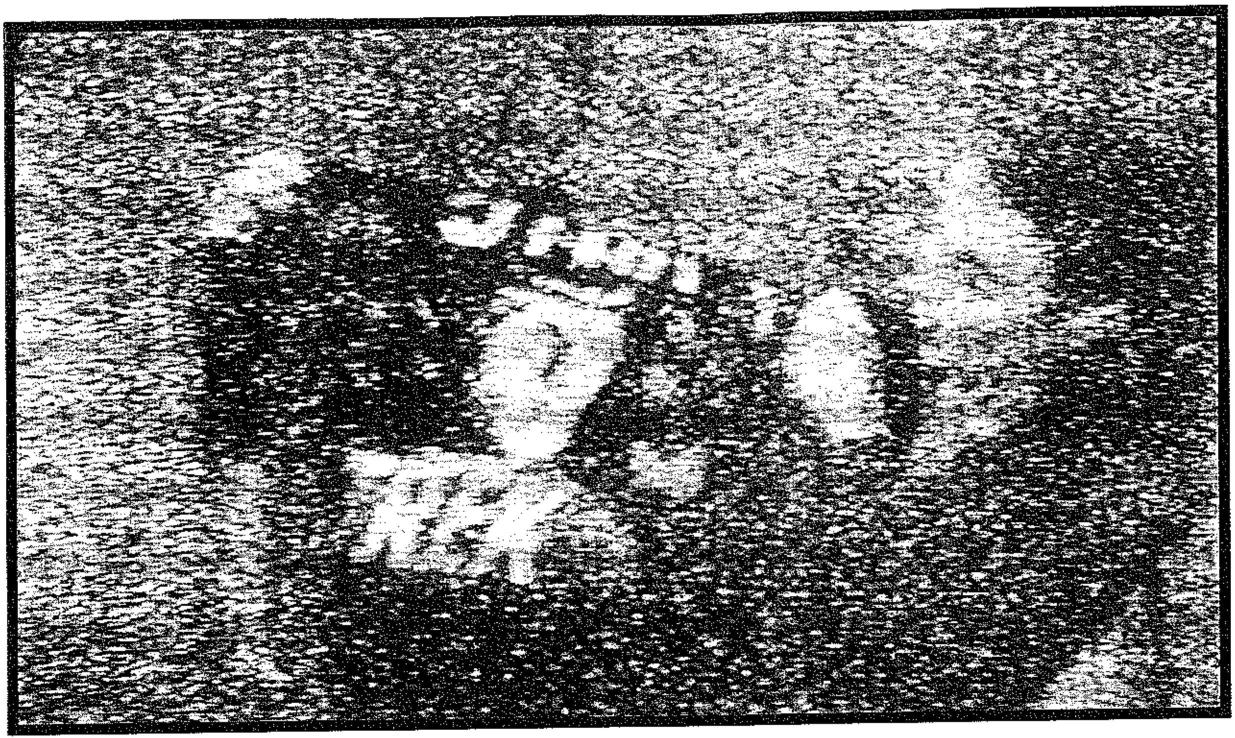

Know noise

Joe Carr looks at noise from the receiver designer's perspective and explains which elements of the receiving system are the biggest contributors to it.

If you are in electronics, and you work with signals, then you will undoubtedly have to deal with noise. A radio receiver for example must detect signals in the presence of noise. Indeed, radio reception – especially at the weak signal level – is essentially a game of signal-to-noise ratio.

The signal-to-noise or s-to-n ratio is the key here because a signal must be above the noise level before it can be successfully detected and used.

Noise affects other electronics systems as well as receivers. In medical electronics, for example, the very low electrical potentials generated by the human brain are displayed by an electroencephalograph, or EEG, machine. Those signals are of the order of 1 to 100µV. Because they exist in a high-impedance source and high 50 or 60Hz electrical mains fields, they are often obscured. But they can also be obscured by noise generated in amplifier circuits.

Noise comes in a number of different guises, but for sake of this discussion we can divide noise sources into two classes: sources external to the receiver or amplifier and internal sources.

There is little you can do about external noise sources. They consist of natural and man-made electromagnetic signals that fall within the passband of the receiver. **Figure 1** shows an approximation of the external noise situation from the middle of the amplitude-modulation broadcast band to the low end of the vhf region. One has to select a receiver that can cope with external noise sources – especially if the noise sources are strong.

Some natural external noise sources are extraterrestrial. These signals that form the basis of radio astronomy. For example, if you aim a beam antenna at the eastern horizon prior to sunrise, a distinct rise of noise level occurs as the Sun slips above the horizon – especially in the vhf region. The reverse occurs in the west at sunset, but less dramatically, probably because atmospheric ionisation decays much slower than it is generated.

During World War II, it is reported that radar operators noted an increase in received noise level any time the Milky Way

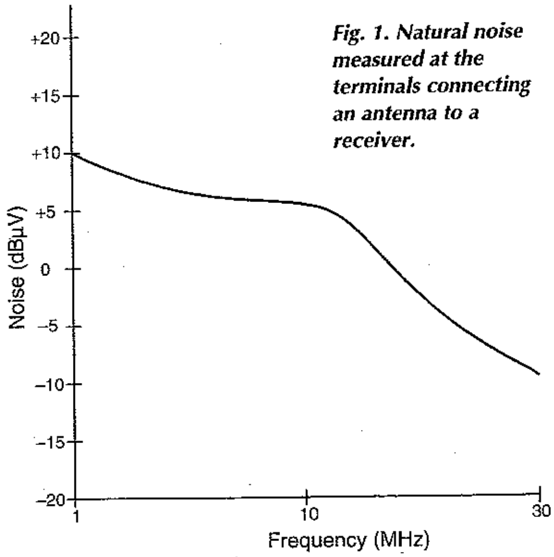

Fig. 1. Natural noise measured at the terminals connecting an antenna to a receiver.

Joseph J. Carr, MSEE

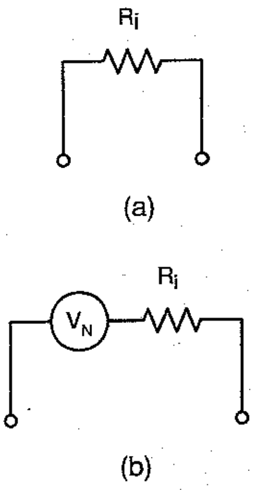

Fig. 2. Model of an ideal resistor, a) and a real resistor – i.e. pure resistance plus a noise source, b).

was above the horizon, decreasing the range at which they could detect in-bound German bombers. Radio astronomy was only then in its infancy, so the effect was apparently not anticipated.

There is also some well-known, easily observed noise from the planet Jupiter in the 18 to 30MHz band.[1]

Internal noise sources

A receiver's internal noise sources are affected by the design of the receiver. Ideal receivers produce no noise of their own, so the output signal from the ideal receiver would contain only the noise that was present at the input along with the radio signal. But real receiver circuits produce a certain level of internal noise of their own.

Even a simple fixed-value resistor is noisy. **Figure 2a)** shows the equivalent circuit for an ideal, noise free resistor, while Fig. **2b)** shows a practical real-world resistor. The noise in the real-world resistor is represented in Fig. 2b) by a noise voltage source, V_n, in series with the ideal, noise free resistance, R_i.

At any temperature above absolute zero – 0K or about –273°C – electrons in any material are in constant random motion. Because of the inherent randomness of that motion, however, there is no detectable current in any one direction.

In other words, electron drift in any single direction is cancelled over even short time periods by equal drift in the opposite direction. Electron motions are therefore statistically decorrelated. There is, however, a continuous series of random current pulses generated in the material, and those pulses are seen by the outside world as noise signals.

If a shielded 50Ω resistor is connected across the antenna input terminals of a radio receiver, the noise level at the receiver output will increase by a predictable amount over the short-circuit noise level. Noise signals of this type are called by several names: thermal agitation noise, thermal noise, or Johnson noise. This type of noise is also called 'white noise' because it has a very broadband – near gaussian – spectral density.

The thermal noise spectrum is dominated by mid-frequencies – 104 to 105Hz – and is essentially flat. The term 'white noise' is a metaphor developed from white light, which is composed of all visible colour frequencies. The expression for such noise is,

$$V_N = \sqrt{4KTBR} \qquad (1)$$

Where Vn is the noise potential in volts, K is Boltzmann's constant (1.38×10–23 J/K), T is the temperature in kelvin, R is the resistance in ohms and B is bandwidth in hertz. Temperature T is normally set to an average room temperature of 290K by convention.

Table 1 and **Fig. 3** show noise values for a 50Ω resistor at various bandwidths out to 10kHz. Because different bandwidths are used for different reception modes, it is common practice to delete the bandwidth factor in equation 1 and write it as,

$$V_N = \sqrt{4KTR}\,\frac{V}{\sqrt{Hz}} \qquad (2)$$

With this equation, you can find the noise voltage for any particular bandwidth by taking its square root and multiplying it by the equation. It is essentially the solution of the previous equation normalised for a 1Hz bandwidth.

Signal-to-noise ratio

Receivers are evaluated for quality on the basis of signal-to-noise ratio, also known as S/N or SNR and sometimes denoted Sn. The goal of the designer is to enhance the s-to-n ratio as much as possible.

Ultimately, the minimum signal level detectable at the output of an amplifier or radio receiver is that level which appears just above the noise floor level – usually measured in dBm. Therefore, the lower the system noise floor, the smaller the minimum allowable signal. Designers of weak signal receivers spend a great deal of effort on suppressing the noise floor as low as possible.

Noise factors, figures and temperatures

The noise performance of a receiver or amplifier can be defined in three different, but related, ways: noise factor, or F_N, noise figure, or NF, and equivalent noise temperature, Te; these properties are definable as a simple ratio, decibel ratio or kelvin temperature, respectively.

Noise factor, F_N. For components such as resistors, the noise factor is the ratio of the noise produced by a real resistor to the simple thermal noise of an ideal resistor.

The noise factor of a radio receiver – or any system – is the ratio of output noise power, P_{no}, to input noise power, P_{ni}:

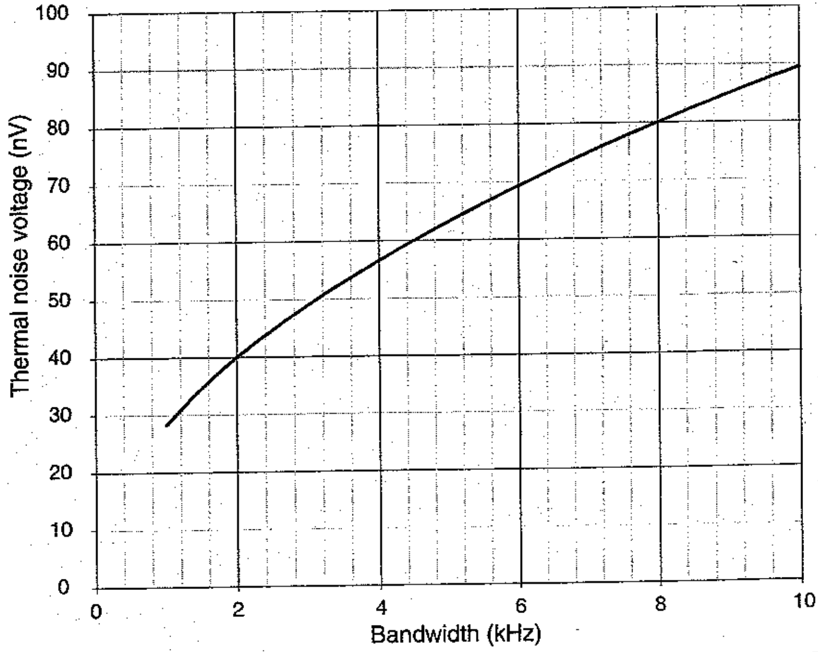

Fig. 3. Noise voltage for bandwidths to 10kHz for a 50Ω resistor.

Table 1. Noise voltage for bandwidths to 10kHz.

Bandwidth (kHz)	Noise×10⁻⁸ (V)
1	2.83
1.5	3.46
2	4.00
2.5	4.47
3	4.9
3.5	5.29
4	5.66
4.5	6.00
5	6.33
5.5	6.63
6	6.93
6.5	7.21
7	7.49
7.5	7.75
8	8.00
8.5	8.25
9	8.49
9.5	8.72
10	8.95

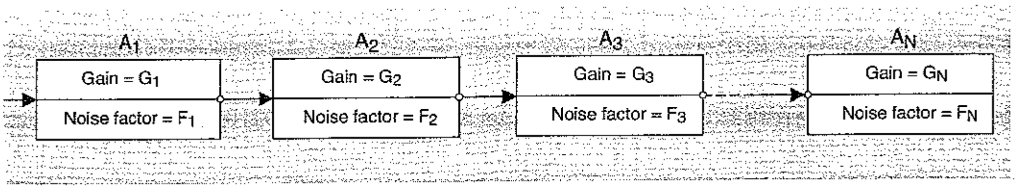

Fig. 4. In a cascaded amplifier chain like this one, each stage not only adds its own noise, but amplifies noise from the preceding stage.

$$F_N = \left[\frac{P_{NO}}{P_{NI}}\right] T = 290K \quad (3)$$

In order to make comparisons easier, the noise factor is usually measured at the standard temperature T_o of 290K, i.e. standardised room temperature; in some countries though, 299 or 300K are commonly used, but the differences are negligible.

It is also possible to define noise factor F_N in terms of the output and input signal-to-noise ratios:

$$F_N = \frac{S_{NI}}{S_{NO}} \quad (4)$$

where S_{NI} is the input signal-to-noise ratio, S_{NO} is the output signal-to-noise ratio.

Noise figure, *NF*. The noise figure is frequently used to measure the receiver's 'goodness,' i.e. its departure from 'idealness.' Thus, it is a figure of merit. The noise figure is the noise factor converted to decibel notation,

$$NF = 10 \log F_N \quad (5)$$

where NF is the noise figure in decibels and F_N is the noise factor. Note that the log here is base 10.

Noise temperature, T_e. The noise 'temperature' is a means for specifying noise in terms of an equivalent temperature. That is, the noise level that would be produced by a resistor at that temperature, expressed in kelvin.

Evaluating the noise equations shows that the noise power is directly proportional to temperature in kelvin, and also that noise power collapses to zero at the temperature of absolute zero (0K).

Note that the equivalent noise temperature T_e is not the physical temperature of the amplifier, but rather a theoretical construct that is an equivalent temperature that produces that amount of noise power in a resistor.

Noise temperature is related to the noise factor by:

$$T_e = (F_N - 1) T_o \quad (6)$$

and to noise figure by

$$T_e = 290\left(10^{NF/10} - 1\right) \quad (7)$$

Noise temperature is often specified for receivers and amplifiers in combination with, or in lieu of the noise figure.

Noise in cascade amplifiers and receivers

A noise signal is seen by any amplifier following the noise source as a valid input signal.

Each stage in the cascade chain, **Fig. 4**, amplifies both the signals and the noise from previous stages. Each stage also contributes some additional noise of its own. Thus, in a cascade amplifier the final stage sees an input signal that consists of the original signal and noise amplified by each successive stage plus the noise contributed by earlier stages.

The overall noise factor for a cascade amplifier can be calculated from Friis' noise equation,

$$F_N = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} ... + \frac{F_N - 1}{G_1 G_2 ... G_{N-1}} \quad (8)$$

where F_N is the overall noise factor of N stages in cascade, F_1 is the noise factor of stage 1, F_2 is the noise factor of stage 2, F_N is the noise factor of the nth stage, G_1 is the gain of stage 1, G_2 is the gain of stage 2 and G_N–1 is the gain of stage n–1.

As you can see from Friis' equation, the noise factor of the entire cascade chain is dominated by the noise contribution of the first stage or two. High-gain, low-noise rf amplifier chains, or receivers, typically use a low-noise amplifier circuits for the first stage or two in the cascade chain.

As an example, you will find a low-noise amplifier at the feedpoint of a satellite receiver's dish antenna, and possibly another one at the input of the receiver module itself. Other amplifiers in the chain might be more modest, although their noise contribution cannot be ignored at radio astronomy signal levels.

Receiver noise floor

The noise floor of the receiver is a statement of the amount of noise produced by the receiver's internal circuitry, and directly affects the sensitivity of the receiver.

The noise floor is typically expressed in dBm. Its specification is evaluated as follows: the more negative the better. The best receivers have noise floor numbers of greater than –130dBm, while some very good receivers offer numbers of –115 dBm to –130 dBm.

The noise floor depends directly on the bandwidth used to make the measurement. Receiver advertisements usually specify the bandwidth, but remember to compare the figure given with the bandwidth that you'll need for the mode of transmission you want to receive. If, for example, you are interested only in weak 6kHz wide amplitude-modulated signals, and the noise floor is specified for a 250Hz cw filter, then the noise floor might be too high for your use.

Receiving-system example

Figure 5 shows a receiving system that is common in the vhf through microwave regions of the spectrum. An antenna is used to obtain the signal, and a low-noise amplifier, A_1 in Fig. 5, is provided to boost the antenna signal.

It is common practice to place the low-noise amplifier at

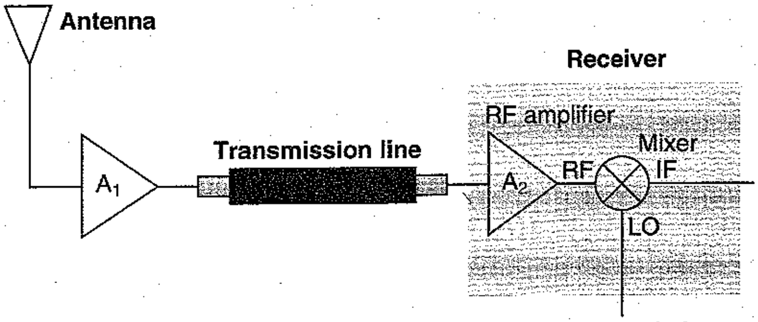

Fig. 5. Typical receiver system front-end. Low-noise amplifier A_1 is put before the transmission line. If it came after, it would have to deal with a signal subjected to more loss.

Noise calculations for a configuration such as Fig. 5, obtained via Excel from gain and noise figure entered into the spreadsheet in decibels.

Stage	Gain/loss (dB)	Gain/loss (lin.)	Noise figure	Noise factor	Noise Temp.
Preamplifier	15	31.62	2.2	1.66	191
Transmission line	–2	0.63	2.00	1.58	170
RF amplifier	10	10.00	3	2.00	289
Mixer	–6	0.25	4.5	2.82	527
Overall	17	50.12	2.398	1.737	214

the antenna terminals so that it does not have to overcome the loss of the transmission line.

The receiver may or may not have an rf amplifier, but in this model one is used, namely A_2. The mixer then converts the rf signal to the intermediate frequency used by the receiver.

Loss in the coaxial cable transmission line can be a significant cause of noise in the system. The cable loss is usually expressed in decibels, and is taken from the manufacturer's data sheets if no actual measurements are available.

Typically, the manufacturer will provide a chart that relates loss in decibels per metre (dB/m) to frequency. Find the loss factor appropriate to the desired frequency, and correct for the actual length of the line.

The noise temperature of the transmission line is:

$$T_{e(line)}=T_L(L-1) \qquad (9)$$

where $T_{e(line)}$ is the noise temperature of the line and L is the loss of the line expressed in linear terms, as a ratio.

Table 1 shows the results of making the noise calculations on a receiving system such as **Fig. 5** when the following specifications are used,

Stage	Gain (dB)	Noise figure (dB)
Preamp	15	2.2
Trans. line	–2	2.0
RF amp	10	3.0
Mixer	–6	4.5

Overall gain for this part of the receiver is the sum of the gains, or 17dB.

The results of the Friis equation shows an overall noise figure of 2.398. If you program a spreadsheet with the noise equations so that you can vary the noise figure parameters, it becomes apparent that the first stage dominates.

Let's do a little *ceterus paribus*† exercise in which one noise figure is changed by 1dB. If the preamplifier noise figure is increased to 3.2dB, then the overall noise figure rises to 3.36dB.

Increasing the transmission line noise figure to 3dB only raises the noise figure to 2.47dB. Increasing the rf amplifier noise figure to 4dB increases the overall noise figure to 2.46dB. This finally increases the mixer noise figure to 2.41dB.

For a 1dB increase in noise figure, the overall noise figure changes to:

Stage	New *NF* (dB)	Change
Low-noise amplifier	3.20	+0.8 dB
Transmission line	2.47	+0.072dB
RF amplifier	2.46	+0.062dB
Mixer	2.41	+0.012dB

Note that the increase in overall noise figure is greatest for the first stage in the chain, and that the change for each succeeding stage is less than for the stage before. The lesson here is to put as much effort as possible into the first stage in order to reduce the noise figure overall. ■

Reference

1. Carr, J., RadioScience Observing, Vol. 1.

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† All else remaining unchanged.