NOISE: Measurement and Generation

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Introduction

As anyone who has listened to a receiver suspects, everything in the universe generates noise. In communications, the goal is to maximize the desired signal in relation to the undesired noise we hear. In order to accomplish this goal, it would be helpful to understand where noise originates, how much our own receiver adds to the noise we hear, and how to minimize it.

It is difficult to improve something unless we are able to measure it. Measurement of noise in receivers does not seem to be clearly understood by many amateurs, so I will attempt to explain the concepts and clarify the techniques, and to descrive the standard "measure of merit" for receiver noise performance: "noise figure." Most important, I will describe how to build your own noise generator for noise figure measurements.

A number of equations are included, but only a few need be used to perform noise figure measurements. The rest are included to as an aid to understanding, with, I hope, enough explanatory text for everyone.

Noise

The most pervasive source of noise is thermal noise, due to the motion of thermally agitated free electrons in a conductor. Since everything in the universe is at some temperature above absolute zero, every conductor must generate noise.

Every resistor (and all conductors have resistance) generates an *rms* noise voltage:

$$e = \sqrt{4kTRB}$$

where R is the resistance, T is the absolute temperature in degrees **K**, B is the bandwidth in Hertz, and k is Boltzmann's constant, 1.38×10^{-23} joules / **K.**

Converting to power, e^2/R , and adjusting for the Gaussian distribution of noise voltage, the noise power generated by the resistor is:

$$P_n = kTB \quad \text{(watts)}$$

which is independent of the resistance. Thus, all resistors at the same temperature generate the same noise power. The noise is white noise, meaning that the power density does not vary with frequency, but always has a power density of kT watts/Hz. More important is that the noise power is directly proportional to absolute temperature T, since k is a constant. At the nominal ambient temperature of 290 **K,** we can calculate this power; converted to dBm, we get the familiar -174 dBm/Hz. Just multiply by the bandwidth in Hertz to get the available noise power at ambient temperature. The choice of 290 **K** for ambient might seem a bit cool, since the equivalent 17° C or 62° F would be a rather cool room temperature, but 290 makes all the calculations come out to even numbers.

The *instantaneous* noise voltage has a Gaussian distribution around the *rms* value. The gaussian distribution has no limit on the peak amplitude, so at any instant the noise voltage may have any value from -infinity to +infinity. For design purposes, we can use a value that will not be exceeded more than 0.01% of the time. This voltage is 4 times the *rms* value, or 12 dB higher, so our system must be able to handle peak powers 12 dB higher than the average noise power [1] to if we are to measure noise without errors.

Signal to Noise Ratio

Now that we know the noise power in a given bandwidth, we can easily calculate how much signal is required to achieve a desired signal to noise ratio, S/N. For SSB, perhaps 10 dB S/N is required for good communications; since ambient thermal noise in a 2.5 KHz bandwidth is -140 dBm, calculated as follows:

$$P_n = kTB = 1.38 \times 10^{-23} \times 290 \times 2500 = 1.0 \times 10^{-17} \quad \text{watts}$$

$$\text{dBm} = 10\log(P_n \times 1000) \quad \text{[multiplying the power by 1000 to get milliwatts]}$$

The signal power must be 10 dB larger, so minimum signal level of -130 dBm is required for a 10 dB S/N. This represents the noise and signal power levels at the antenna. We are then faced with the task of amplifying the signal without degrading the signal to noise ratio.

Noise Temperature

Any amplifier will add additional noise. The input noise N_i per unit bandwidth is kT_g is amplified by gain G to produce an output noise of kT_gG. The additional noise, kT_n is added to produce a total noise output power N_o:

$$N_o = kT_gG + kT_n$$

To simplify future calculations, we pretend that the amplifier is noise-free but has an additional noise generating resistor of temperature T_e at the input, so that all sources of noise are inputs to the amplifier. Then the output noise is:

$$N_o = kG\,(T_g + T_e)$$

and T_e is the Noise Temperature of the excess noise contributed by the amplifier. The noise added by an amplifier is then kGT_e, which is the fictitious noise source at the input amplified by the amplifier gain.

Cascaded Amplifiers

If several amplifiers are cascaded, the output noise N_o of each becomes the input noise T_g to the next stage, we can create a large equation for the total. After removing the original input noise term, we are left with the added noise:

$$N_{added} = (k\,T_{e1}G_1G_2\ldots G_N) + (kT_{e2}G_2\ldots G_N) + \ldots + (kT_{eN}G_N)$$

Substituting in the total gain $G_T = (G_1G_2\ldots G_N)$ results in the total excess noise:

$$T_{eT} = T_{e1} + T_{e2}/G_1 + T_{e2}/G_1G_2 + \ldots + T_{eN}/(G_1G_2\ldots G_{N-1})$$

with the noise of each succeeding stage reduced by the gain of all preceeding stages. Clearly, if the gain of the first stage, G_1, is large, then the noise contributions of the succeeding stages are not significant. This is why we concentrate our efforts on improving the first amplifier or preamplifier.

Noise Figure

The noise figure of an amplifier is the logarithm of the ratio (so we can express it in dB) of the total noise output of an amplifier with an input T_g of 290 **K** to the noise output of an equivalent noise-free amplifier. A more useful definition is to calculate it from the excess temperature T_e:

$$\mathbf{NF} = 10\log(1 + T_e/T_0) \qquad \text{(dB)} \qquad @ \qquad T_0 = 290\ \mathbf{K}$$

If the **NF** is known, then T_e may be calculated after converting the **NF** to a ratio, **F:**

$$T_e = (\mathbf{F} - 1)\, T_0$$

Typically, T_e is specified for very low noise amplifiers, where the **NF** would be fraction of a dB, and **NF** is used when it seems a more manageable number than thousands of **K**.

Losses

We know that any loss or attenuation in a system reduces the signal level. If attenuation also reduced the noise level, then we could suppress thermal noise by adding attenuation. We know intuitively that this can't be true. The answer is that the attenuator or any lossy element has a physical temperature, T_x, which contributes noise to the system while the input noise is being attenuated. The output noise after a loss **L** (ratio) is:

$$T_{g'} = T_g / \mathbf{L} + [(\mathbf{L}-1)/\mathbf{L}]\, T_x$$

If the source temperature T_g is higher than the attenuator temperature T_x, then the noise contribution is the familiar result found by simply adding the loss in dB to the **NF.** However, for low source temperatures the degradation can be much more dramatic. If we do a calculation for the affect of 1 dB of loss (**L =** 1.26) on a T_g of 25 **K:**

$$T_{g'} = 25/1.26 + (0.26/1.26) \mathbf{x}\, 290 = 80\ \mathbf{K}$$

The resultant $T_{g'}$ is 80 **K,** <u>a 5 dB increase in noise power</u> (or 5 dB degradation of signal to noise ratio). Since noise power = kT and k is a constant, the increase is the ratio of the two temperatures 80/25, or in dB, 10*log*(80/25) = 5 dB.

Antenna Temperature

How can we have a source temperature much lower than ambient? If an antenna, assumed to be lossless, is receiving signals from space, rather than the warm earth, then the background noise is much lower. The background temperature of the universe has been measured as about 3.2 **K.** An empirical number[2] for a 10 GHz antenna pointing into clear sky is about 6 **K,** since we must always look through attenuation and temperature of the atmosphere. The figure will vary with frequency, but a good EME antenna might have a T_g of around 20 **K** at UHF and higher frequencies.

A couple of examples of actual antennas[3] might bring all of this together.

1. A 30 inch conventional dish at 10 GHz, with measured gain of 36.4 dBi and efficiency of 64%. The estimated spillover efficiency is 87% for a 10 dB illumination taper. With the dish pointing at a high elevation as shown in **Figure 1**, perhaps half of the spillover is illuminating earth at 290 **K,** which adds an estimated 19 **K** to the 6 **K** of sky noise, for a total of 25 **K**. In a 500 Hz bandwidth, the noise output is -157.6 dBm.

2. An 18 inch DSS offset-fed dish at 10 GHz, with measured gain of 32.0 dB and efficiency of 63%. The spillover efficiency should be comparable, but with the offset dish pointing at a high elevation as shown in **Figure 2**, far less of the spillover is

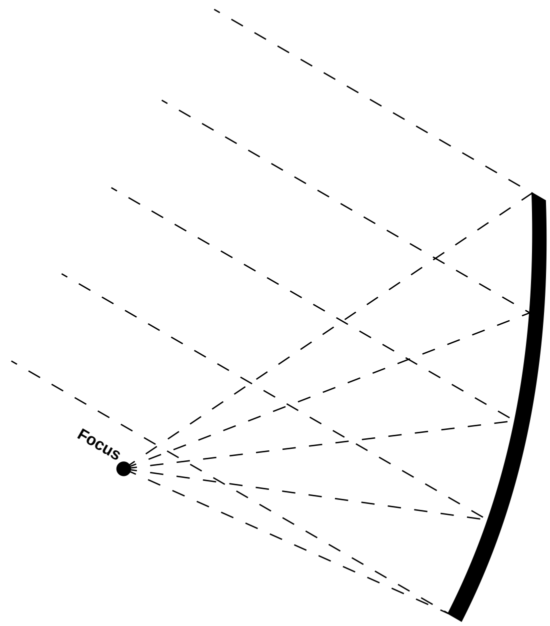


Figure 2. Offset Parabolic Dish Antenna Aimed at Satellite

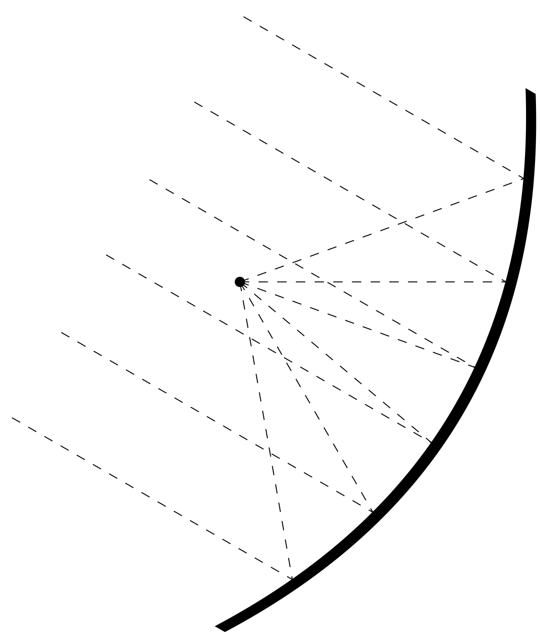


Figure 1. Parabolic Dish Antenna Aimed at Satellite

illuminating warm earth. If we estimate 20%, then 8 **K** is added to the 6 **K** of sky noise, for a total of 14 **K**. In a 500 Hz bandwidth, the noise output is -160 dBm.

The larger conventional dish has 2.4 dB higher noise output, but 4.4 dB higher gain, so it should have 2.0 dB better signal to noise ratio than the smaller offset dish when both are pointing at high elevations.

However, the while the offset dish is easy to feed with low loss, it is convenient to feed the conventional dish through a cable with 1 dB of loss. Referring back to our loss example above, the noise temperature after this cable loss is 80 **K.** In a 500 Hz bandwidth, the noise output is now -152.6 dBm, 7.4 dB worse than the offset dish. The convenience of the cable reduces the signal to noise ratio by 5 dB, making the larger conventional dish 3 dB worse than the smaller offset dish. Is it any wonder that the DSS dishes sprouting on rooftops everywhere are offset-fed?

If the dishes are pointed on the horizon for terrestrial operation, then the situation is much different. At least half of each antenna pattern is illuminating warm earth, so we should expect the noise temperature to be at least half of 290 **K,** or about 150 **K.** Adding 1 dB of loss increases the noise temperature to 179 **K**, a 1 dB increase.   At the higher noise temperatures, losses do not have a dramatic effect on signal to noise ratio. In practice, the antenna temperature on the horizon may be even higher, since the upper half of the pattern must take a much longer path through the warm atmosphere, which adds noise just like any other loss.

Image Response

Most receiving systems use at least one frequency converting mixer which has two responses, the desired frequency and an image frequency on the other side of the local oscillator.   If the image response is not filtered out, it will add additional noise to the mixer output. Since most preamps are broadband enough to have significant gain (and thus, noise output) at the image frequency, the filter must be placed between the preamp and the mixer. The total **NF** including image response is calculated:

$$\mathbf{NF} = 10 \log[\,(1 + T_e / T_0)(1 + G_{image}/G_{desired})\,]$$

assuming equal noise bandwidth for desired and image responses. Without any filtering, $G_{image} = G_{desired}$ so $G_{image}/G_{desired} = 1$, doubling the noise figure which is the same as adding 3 dB. Thus, without any image rejection, the overall noise figure is at least 3 dB <u>regardless of the **NF** of the preamp.</u> For the image to add less than 0.1 dB to the overall **NF**, a quick calculation shows that the gain at the image frequency must be at least 16 dB lower than at the operating frequency.

Noise Figure Measurement

So far we have dixcussed the sources of noise, and a figure of for evaluating the a receiving system's response to noise. How can we measure an actual receiver?

The noise figure of a receiver is determined by measuring its output with two different noise levels, $\mathbf{T}_{hot}$ and $\mathbf{T}_{cold}$, applied at the input. The ratio of the two output levels is referred to as the "**Y-factor".** Usually, the ratio is determined from the difference in dB between the two output levels, $\mathbf{Y}_{db}$:

$$\mathbf{Y}_{(ratio)} = log^{-1}(\mathbf{Y}_{db} / 10)$$

Then the receiver T_e may be calculated using $\mathbf{Y}_{(ratio)}$:

$$T_e = (\mathbf{T}_{hot} - \mathbf{YT}_{cold}) / (\mathbf{Y}\text{-}1)$$

and converted to noise figure:

$$\mathbf{NF} = 10log(1 + T_e /T_0) \qquad \text{(dB)} \qquad \text{where } T_0 = 290\ \mathbf{K}$$

The two different noise levels may be generated separately, for instance by connecting resistors at two different temperatures. Alternatively, we could use a device that can generate a calibrated amount of noise when it is turned on. When such a device is turned off, it still generates noise from its internal resistance at $\mathbf{T}_{cold}$, the ambient temperature (290 **K**); usually this resistance is 50 ohms, to properly terminate the transmission line which connects it to the receiver. When the noise generator is turned on, it produces excess noise equivalent to a resistor at some higher temperature at $\mathbf{T}_{hot}$. The noise produced by a noise source may be specified as the Excess Noise Ratio ($\mathbf{ENR}_{dB}$), the dB difference between the cold and the equivalent hot temperature, or as the equivalent temperature of the excess noise, $\mathbf{T}_{ex}$, which is used in place of $\mathbf{T}_{hot}$ in the previous equation. If the **ENR** is specified, then the calculation is:

$$\mathbf{NF}_{dB} = \mathbf{ENR}_{dB} - 10log(\mathbf{Y}_{(ratio)} -1)$$

The terms $\mathbf{T}_{ex}$ and **ENR** are used rather loosely; assume that a noise source specified in dB refers to $\mathbf{ENR}_{dB}$, while a specification in degrees or **K** refers to $\mathbf{T}_{ex}$.

An automatic noise figure meter, sometimes called a PANFI (for Precision Automatic Noise Figure Meter), turns the noise source on and off at a rate of about 400 Hz and performs the above calculation electronically[4]. A wide bandwidth is required to detect enough noise to operate at this rate; a manual measurement using a narrowband communications receiver would require the switching rate to be less than one Hz, with some kind of electronic integration to properly average the gaussian noise.

Noise figure meters seem to be fairly common surplus items. The only one in current production, the HP 8970, measures both noise figure and gain, but commands a stiff price.

AIL (later AILTECH or Eaton) made several models; the model 2075 measures both NF and gain, while other models are NF only. The model 75 (a whole series whose model numbers start with 75) shows up frequently for anywhere from $7 to $400, typically $25 to $50 and performs well. Every VHFer I know has one, with most of them waiting for a noise source to be usable. Earlier tube models, like the AIL 74 and the HP 340 and 342, have problems with drift and heat, but they can also do the job.

Another alternative is to build a noise figure meter[5].

Using the Noise Figure Meter

I'll describe the basic procedure using the Model 75; others are similar, but the more complex instruments will require studying the instruction manual.

Input to almost all noise figure meters is at 30 MHz, so a frequency converter is required (some instruments have internal frequency converters; except for the HP 8970, I'd avoid using this feature). Most ham converters with a 28 MHz IF work fine, unless the preamp being measured is so narrowband that a MHz or two changes the NF. The input is fairly broadband, so LO leakage or any other stray signals can upset the measurement — this has been a source of frustration for many users. There are two solutions: a filter (30 MHz low-pass TVI filters are often sufficient) or a tuned amplifier at 30 MHz. Since a fair amount of gain is required in front of the noise figure meter, an amplifier is usually required anyway.

A noise source (which we will discuss in detail later) is connected to the rear of the instrument: a BNC connector marked "DIODE GATE" provides +28 volts for a solid-state noise source, and high voltage leads for a gas tube noise source are also available on many versions. The noise figure meter switches the noise source on and off. The noise output coax connector of the noise source is connected to the receiver input.

The model 75 has four function pushbuttons: *OFF*, *ON*, *AUTO*, and *CAL*. The *OFF* and *ON* positions are for manual measurements: *OFF* displays the detector output with the noise source turned off, and *ON* displays the detector output with the noise source turned on. If all is working, there should be more output in the *ON* position, and a step attenuator in the IF line may be used to determine the change in output, or **Y-factor,** to sanity-check our results. The knob marked "GAIN" is used to get the meter reading to a desirable part of the scale in the *OFF* and *ON* positions only; it has no effect on automatic measurements.

The *AUTO* position causes the instrument to turn the noise source on and off at about a 400 Hz rate and to calculate the NF from the detected change in noise. The model 75 has a large green light near the meter which indicates that the input level is high enough for proper operation — add gain until the light comes on. Then the meter should indicate a noise figure, but not a meaningful one, since we must first set the $\mathbf{ENR}_{dB}$ using the *CAL* position. The lower scale on the meter is marked for from 14.5 to 16.5 dB of **ENR**; adjust the "CAL ADJ" knob until the reading in the *CAL* position matches the **ENR** of the noise source.

If the **ENR** of your noise source is outside the marked range, read the section below on homebrew noise sources.

Now that we have calibrated the meter for the **ENR** of the noise source, we may read the noise figure directly in the *AUTO* position. Before we believe it, a few sanity checks are in order:

1. Manual **Y-factor** measurement and calculation.
2. Insert a known attenuator between the noise source and preamp — the NF should increase by exactly the attenuation added.
3. Measure something with a known noise figure (known means measured elsewhere; a manufacturers claim is not necessarily enough).

Finally, too much gain in the system may also cause trouble, if the total noise power exceeds the level that an amplifier stage can handle without gain compression. Gain compression will be greater in the on state, so the detected **Y-factor** will be reduced, resulting in erroneously high indicated NF. The Gaussian distribution of the noise means that an amplifier must be able to handle 12 dB more than the average noise level without compression. One case where this is a problem is with a microwave transverter to a VHF or UHF IF followed by another converter to the 30 MHz noise figure meter, for too much total gain. I always place a step attenuator between the transverter and the converter which adjust until I can both add and subtract attenuation without changing the indicated noise figure.

One final precaution: noise figure meters have a very slow time constant, as long as 10 seconds for some of the older models, to smooth out the random nature of noise. If you are using the noise figure meter to "tweak" a receiver, *tune very slowly!*

Sky Noise Measurement

Another way to measure noise figure at microwave frequencies is by measurement of sky noise and ground noise[3,6]. Sky noise is very low, around 6 K at 10 GHz, for instance, and ground noise is due to the ground temperature, around 290 K, so the difference is nearly 290 K. At microwave frequencies we can use a manageable antenna that is sharp enough that almost no ground noise is received, even in sidelobes, when the antenna is pointed at a high elevation. A long horn would be a good antenna choice.

The antenna is pointed alternately at clear sky overhead, away from the sun or any obstruction, and at the ground. The difference in noise output is the **Y-factor**; since we know both noise temperatures, the receiver noise temperature is calculated using the $\mathbf{Y}_{(\text{ratio})}$:

$$T_e = (\mathbf{T}_{\text{hot}} - \mathbf{YT}_{\text{cold}}) / (\mathbf{Y}\text{-}1)$$

The latest version of my microwave antenna program[3], **HDLANT21,** will make this calculation. Since the measured **Y-factor** will be relatively small, this measurement will only be accurate for relatively low noise figures. On the other hand, they are the most difficult to measure accurately using other techniques.

A system for measuring sun noise was described by Charlie, G3WDG[7], which also works well for measuring noise figure from sky noise. He built a 144 MHz amplifier with moderate bandwidth using MMICs and helical filters which amplifies the transverter output to drive a surplus RF power meter. The newer solid-state power meters are stable enough to detect and display small changes in noise level, and the response is slow enough to smooth out flicker. Since my 10 GHz system has an IF output at 432 MHz, duplicating Charlie's amplifier would not work. In the junk box I found some surplus broadband amplifiers and a couple of interdigital filters, and combined these to provide high gain with a few MHz bandwidth, arranged as shown in **Figure 3**. I found that roughly 60 dB of gain after the transverter was required to get a reasonable level on the power meter, while the G3WDG system has somewhat narrower bandwidth so more gain is required.

Several precautions are necessary:

1. Peak noise power must not exceed the level that any amplifier stage can handle without gain compression. Amplifiers with broadband noise output suffer gain compression at levels lower than found with signals, so be sure the amplifier compression point is at least 12 dB higher than the indicated average noise power.
2. Make sure no stray signals appear within the filter passband.
3. Foliage and other obstructions add thermal noise which obscure the cold sky reading.
4. Low noise amplifiers are typically very sensitive to input mismatch, so the antenna must present a low VSWR to the preamp.

A noise figure meter could also be used as the indicator for the sky noise measurement, but a calibrated attenuator would be needed to determine the **Y-factor**. Using different equipment gives us an independent check of noise figure, so that we may have more confidence in our measurements.

W2IMU[8] suggested that the same technique could be used for a large dish at lower frequencies. With the dish pointing at clear sky, the feedhorn is pointing at the reflector which shields it from the ground noise so it only sees the sky noise. If the feedhorn is then removed and pointed at the ground, it will then see the ground noise.

Noise figure meters are convenient, but if you don't have one, the equipment for measuring sun and sky noise could also be used indoors with a noise source. The only

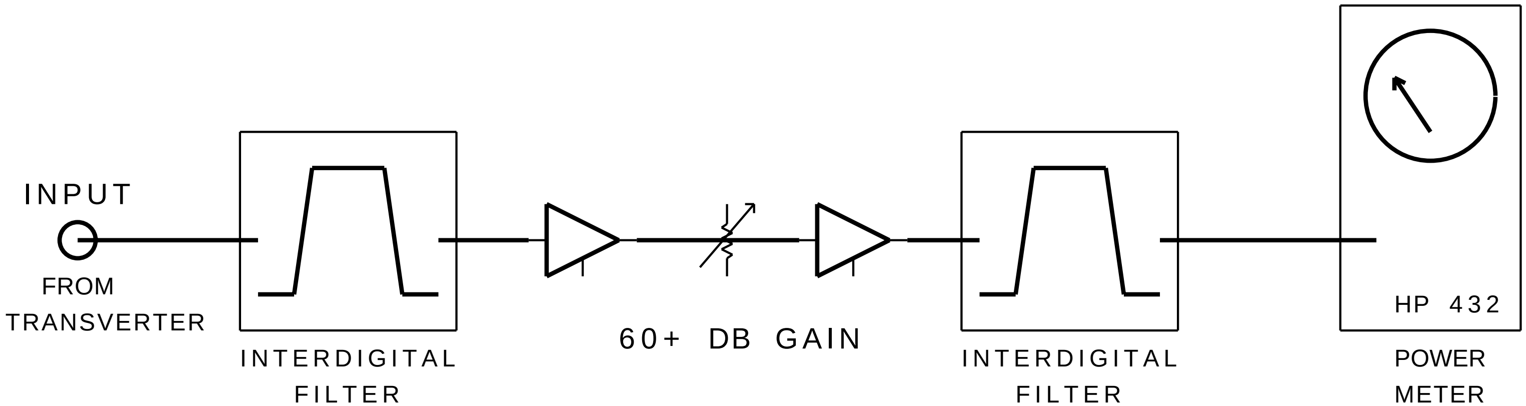


FIGURE 3. INDICATOR FOR SUN NOISE

complication is that the **Y-factor** could be much larger, pushing the limits of amplifier and power meter dynamic range.

Noise Sources

The simplest noise source is simply a heated resistor — if we know the temperature of the resistor, we can calculate exactly how much noise it is generating. If we then change the temperature, the noise output will change by a known amount. This would work if we could find a resistor with good RF properties whose value does not change with temperature, an unlikely combination. There are commercial units, called Hot-Cold Noise Sources, with two calibrated resistors at different temperatures with low VSWR. Typically, one resistor is cooled by liquid nitrogen to 77.3 **K** (the boiling point of nitrogen), while the other is heated by boiling water to 100°C, or 373.2 **K**. The preamp is connected to first one resistor, then the other; the difference in noise in noise output is the **Y-factor.** Using the $\mathbf{Y}_{(ratio)}$, the preamp noise temperature is calculated:

$$T_e = (\mathbf{T}_{hot} - \mathbf{Y}\mathbf{T}_{cold}) / (\mathbf{Y}-1)$$

Since the boiling point of pure liquids is accurately known, this type of noise generator can provide very accurate measurements. However, they are inconvenient to use, since the receiver must be connected directly to alternate resistors (the loss in an RF switch would significantly reduce the noise output and accuracy). Also, few amateurs have a convenient source of liquid nitrogen.

Three types of noise sources are commonly available and convenient to use:

1. Temperature-limited vacuum tube diode. The noise output is controlled by the diode current, but is only accurate up to around 300 MHz due to limitations of the vacuum tube. These units generate around 5 dB of excess noise.

2. Gas tube sources. The noise is generated by an ionized gas in the tube, similar to a fluorescent light — homebrew units have been built using small fluorescent tubes. The noise tubes use a pure gas, typically argon, to control the noise level. These units typically generate about 15 dB of excess noise.

Coaxial gas tube sources work up to around 2.5 GHz, and waveguide units to much higher frequencies. One problem using these is that a high voltage pulse is used to start the ionization (like the starter in a fluorescent light) which is coupled to the output in the coaxial units and is large enough to damage low-noise transistors. Since a noise figure meter turns the noise source on and off continuously, pulses are generated at the same rate.

Since waveguide acts as a high-pass filter, the starting pulses are not propagated to the output, so waveguide gas-tube noise sources are safe to use, though bulky and inconvenient. However, they could be used to calibrate a solid-state noise source.

Another problem with all gas tubes is that the VSWR of the noise source changes between the on and off states. If the source VSWR changes the noise figure of an amplifier, as is almost always the case, then the accuracy of the measurement is reduced.

3. Solid-state noise sources. Reverse breadown of a silicon diode PN junction in causes an avalanche of current in the junction which would rise to destructively high levels if not limited by an external resistance. Since current is “electrons in motion,” a large amount of noise is generated. If the current density of the diode is constant, then the average noise output should also be constant; the instantaneous current is still random with a gaussian distribution, so the generated noise is identical to thermal noise at a high temperature. Commercial units use special diodes designed for avalanche operation with very small capacitance for high frequency operation, but it is possible to make a very good noise source using the emitter-base junction of a small microwave transistor.

Typical noise output from an avalanche noise diode is 25 dB or more, so the output must be reduced to a usable level, frequently 15 dB of excess noise to be compatible with gas tubes or 5 dB of excess noise for more modern equipment. If the noise level is reduced by a good RF attenuator of 10 dB or more, then the source VSWR (seen by the receiver) is dominated by the attenuator, since the minimum return loss is twice the attenuation. Thus, the change in VSWR as the noise diode is turned on and off is minuscule. Commercial noise sources consist of a noise diode assembly and a selected coaxial attenuator permanently joined in a metal housing, calibrated as a single unit.

Homebrew Noise Sources

There are three components of a noise source: a noise generator, an attenuator, and the calibration data of **ENR** at each frequency. The most critical one is the attenuator; it is very important that the noise source present a very low VSWR to the preamp or whatever is being measured, since low-noise amplifiers are sensitive to input impedance, and even more important that the VSWR does not change when the noise source is turned on and off, since a change causes error in the measurement. Because an attenuator provides twice as many dB of isolation as loss (reflections pass through a second time), 10 dB or more of attenuation will reduce any change in VSWR to a very small value.

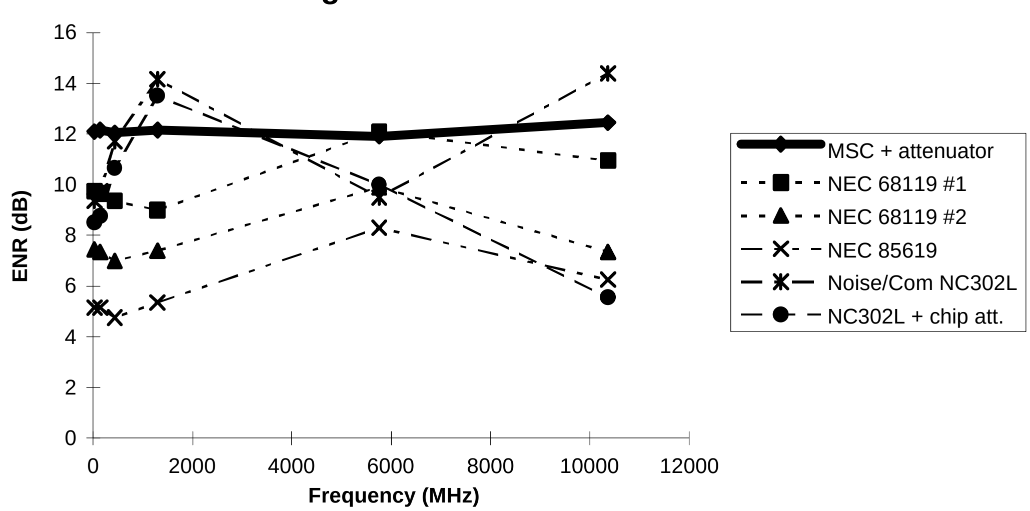
Commercial solid-state noise sources occasionally appear in surplus sources, usually at high prices but occasionally very cheap if no one knows what it is. I have found two of the latter, and one of them works! It produces about 25 dB of excess noise, which is too much to be usable. I went through my box of hamfest attenuators and found one which has excellent VSWR up to 10 GHz and 13 dB of attenuation. Mated with the noise source, the combination produces about 12 dB of excess noise — a very usable amount.

Finally, I calibrated it against a calibrated noise source for all ham bands between 50 MHz and 10 GHz; not exactly NTIS traceable, but pretty good for amateur work.

While noise sources are hard to locate, noise figure meters are frequent finds. If we could come up with some noise sources, all the VHFers who have one gathering dust could be measuring and optimizing their noise figure.

Several articles[9,10,11] have described construction of homebrew noise sources, which work well at VHF and UHF, but not as well at 10 GHz. All of them have the diode in a shunt configuration, with one end of the diode grounded. When I disassembled my defective commercial noise source (even the attenuator was bad), I found a bare chip diode in a series configuration — diode current flows into the output attenuator. Obviously I could not repair a chip diode, but I could try the series diode configuration. I found the smallest packaged microwave transistor available, some small chip resistors and capacitors, and soldered them directly on the gold-plated flange of an SMA connector with zero lead length, as shown in the photograph, **Figure 4**. We've all soldered components directly together in "dead-bug" construction; this is more like "fly-speck" construction. The schematic is shown in **Figure 5,** and it works at 10 GHz! I built several versions to evaluate reproducibility, and measured them at several ham bands from 30 MHz to 10 GHz, with results shown in **Figure 6**. All units were measured with the same 14 dB attenuator, so the diode noise generator output is 14 dB higher.

Figure 6. Noise Source ENR



(Later I found that the MIT Radiation Laboratory had described[12] a noise source with a series diode 50 years ago, so we aren't giving away anyone's trade secrets.)

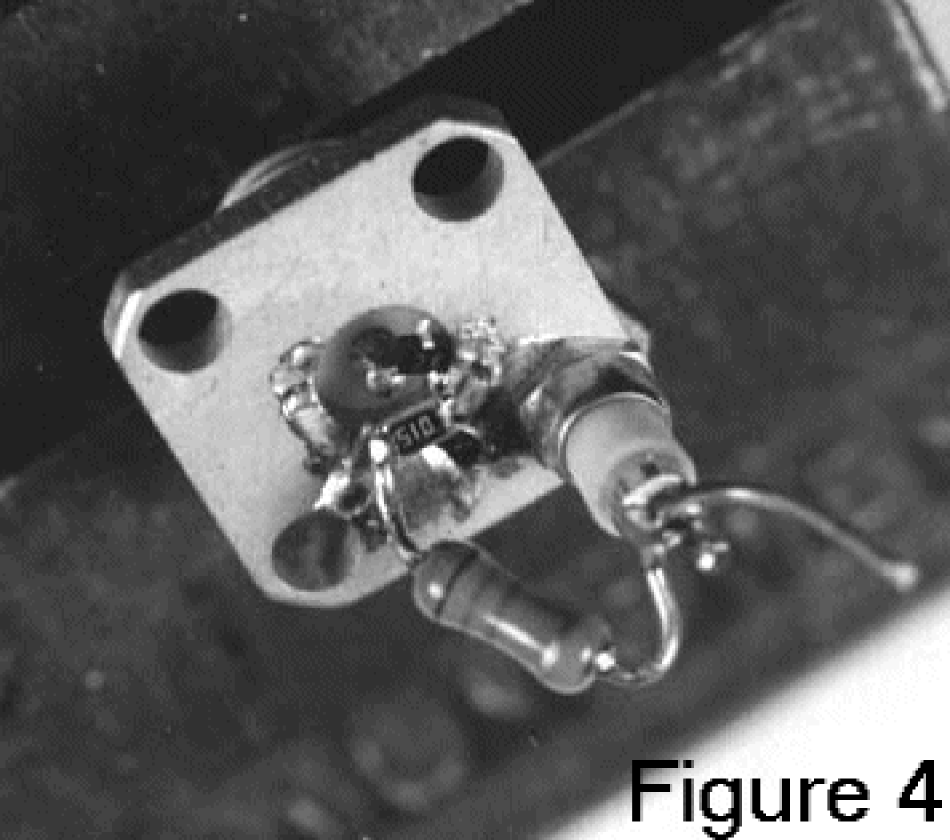
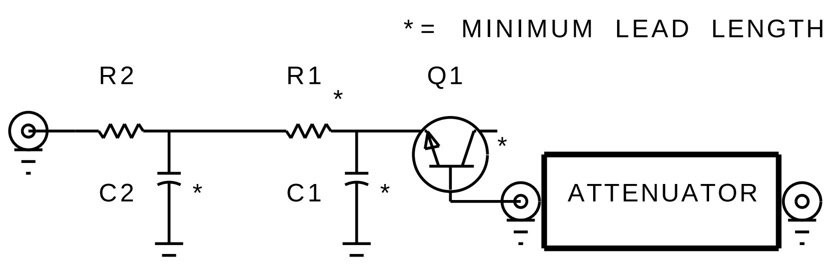


Figure 4



PARTS LIST

ATTENUATOR - MICROWAVE COAXIAL

C1 - CHIP 1.0 pF ATC
C2 - CHIP 1000 pF or more

Q1 - NPN, Tiny Silicon RF like NEC 68119
Alternate: NC302L Noise Diode

R1 - 51 OHM CHIP
R2 - Sets Current, Minimum 1K 1/4 Watt

FIGURE 5. NOISE SOURCE

I then remembered that I had a commercial noise diode, a Noise/Com NC302L, which was used in a noise source described in QST[11], with the diode in the shunt configuration. The diode is rated as working to 3 GHz, so, in the amateur tradition, I wanted to see if I could push it higher, using the series configuration. Since I didn't expect to reach 10 GHz, I increased the value of the bypass capacitor, but otherwise, it looks like the units in **Figure 5**. When I measured this unit, it not only worked at 10 GHz, but had more excess noise output than at lower frequencies, probably due to an unexpected resonance. The performance is shown in **Figure 6** along with the other units.

Also shown in **Figure 6** is the output of my pseudo-commercial noise source; even with the external attenuator, the excess noise output is pretty flat with frequency. Commercial units are typically specified at + or - 0.5 dB flatness. In **Figure 6**, none of the homebrew ones are that flat, but there is no need for it; as long as we know the excess noise output for a particular ham band, it is perfectly usable for that band.

All the above noise sources relied on a coaxial microwave attenuator to control the VSWR of the noise source. Attenuators are fairly frequent hamfest finds, but ones that themselves have good VSWR to 10 GHz are less common, and it's hard to tell how good they are without test equipment. An alternative might be to build an attenuator from small chip resistors. I used my **PAD.EXE** program[13] to review possible resistor values, and found that I could make a 15.3 dB π attenuator using only 140 ohm resistors if the shunt lugs were formed by two resistors in parallel, a good idea to reduce stray inductance. I ordered some "0402" size (truly tiny) chip resistors from DigiKey, more NC302L diodes from Noise/Com, and built the noise source shown in **Figure 7** on a bit of Teflon PC board, cutting out the 50 ohm transmission line with an X-Acto knife.
The schematic of the complete noise source is shown in **Figure 8.**

The chip resistor attenuator works nearly as well as an expensive coaxial one. The measured VSWR of two noise sources, one with the chip attenuator and the other with a coaxial attenuator, is shown in **Figure 9.** Curves are shown in both the off and on states, showing how little the VSWR changes. The VSWR of the chip attenuator unit is 1.42 at 10 GHz, slightly over the 1.35 maximum specified for commercial noise sources, but still fine for amateur use.

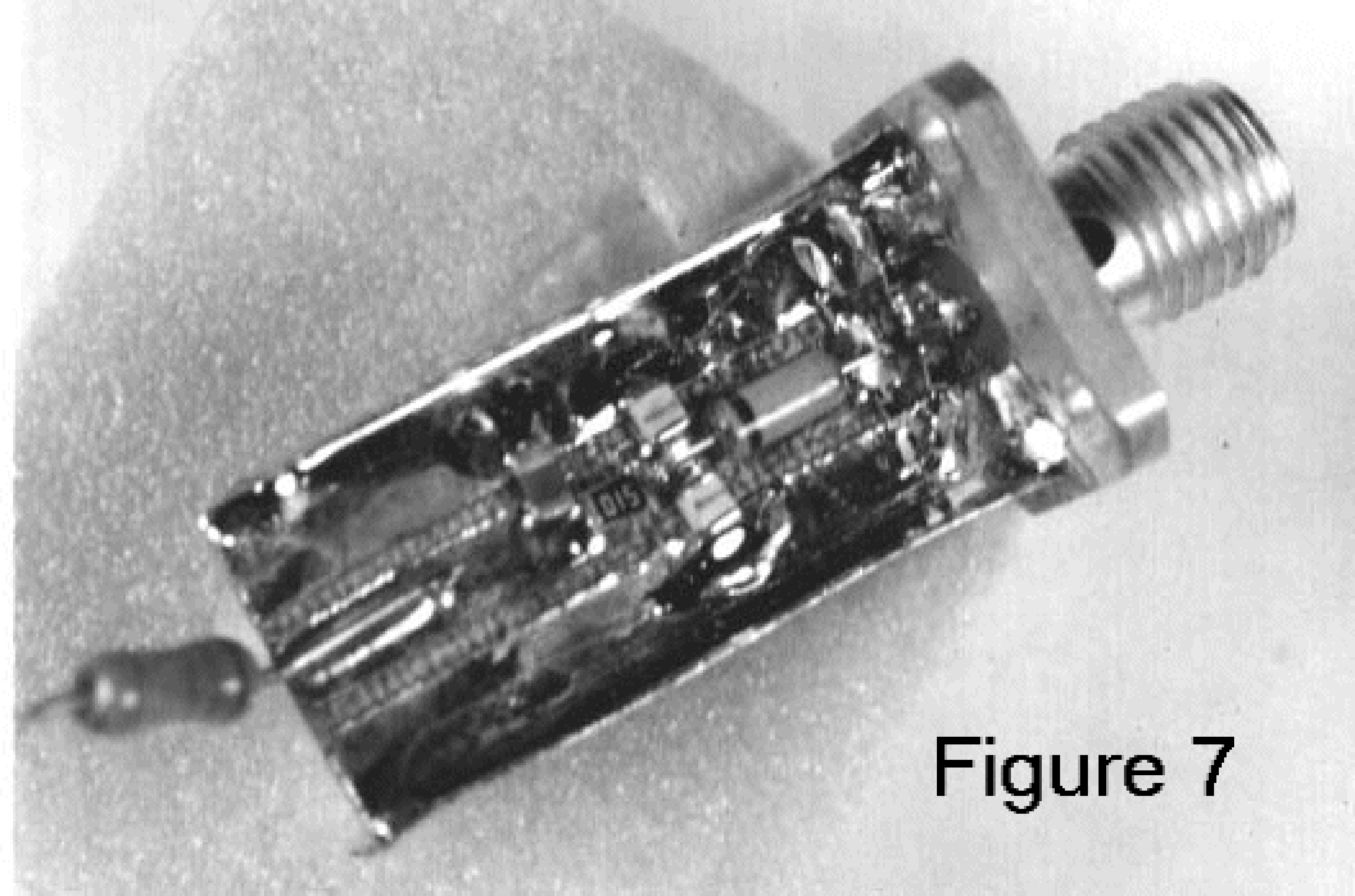
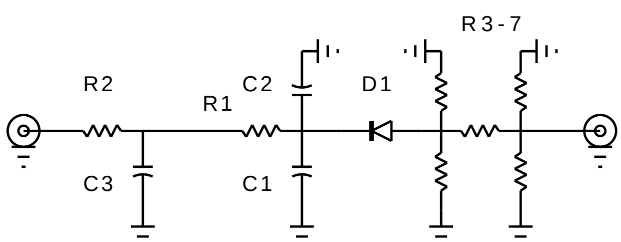


Figure 7



PARTS LIST

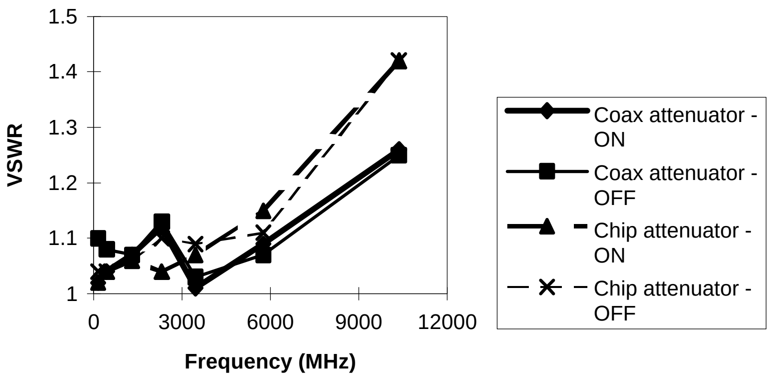
C1 - CHIP 1.0 pF ATC
C2 - CHIP 8.2 pF ATC
C2 - CHIP 1000 pF or more

D1 - NC302L Noise Diode

R1 - 51 OHM CHIP
R2 - Sets Current, Minimum 1K 1/4 Watt
R3-7 - 140 OHM CHIP, 0402 SIZE

NOISE SOURCE WITH CHIP ATTENUATOR
FIGURE 8.

Figure 9. VSWR of Homebrew Noise Sources



Noise Source Alignment

The only alignment requirement for a solid-state noise source is to set the diode current; the current is always set at the highest frequency of interest. A noise figure meter must be set up with converters, etc., for the highest frequency at which the noise source might be used, and set to display the detector output (*OFF* position on a model 75). Then voltage from a variable DC power supply is applied to the noise diode through the 1K current-limiting resistor. The detector output should increase as the voltage (diode current) increases, reach a peak, then decrease slightly. The optimum current is the one that produces peak output at the highest frequency (I set mine at 10 GHz). Then additional resistance must be added in series with the current-limiting resistor so that the peak output occurs with 28 volts applied, so that the noise source may be driven by the noise figure meter. Once the proper resistor is determined and added, the DC end of the noise source is connected to the diode output of the noise figure meter, and the meter function set to *ON*. This should produce the same detector output as the power supply.
Then the meter function is set to *AUTO*, and the meter should produce some noise figure indication, but not a calibrated one yet. However, it is good enough to tune up preamps — a lower noise figure is always better, even if you don't know how low it is.

Noise Source Calibration

Much of the high price of commercial noise sources pays for the NTIS-traceable calibration. Building a noise source only solves part of the problem — now we need to calibrate it.

The basic calibration technique is to measure something with a known noise figure using the new noise source, then calculate what **ENR** would produce the indicated noise figure. Fortunately, the calculation is a simple one involving only addition and subtraction; no fancy computer program required. Simply subtract the indicated noise figure, $\mathbf{NF}_{indicated}$, from the known noise figure, $\mathbf{NF}_{actual}$, and add the difference to the **ENR** for which the meter was calibrated, $\mathbf{ENR}_{cal}$:

$$\mathbf{ENR}\ \textit{(noise source)} = \mathbf{ENR}_{cal} + (\mathbf{NF}_{actual} - \mathbf{NF}_{indicated})$$

This procedure must be repeated at each frequency of interest; at least once for each ham band should be fine for amateur use.

The known noise figure is best found by making the measurement with a calibrated noise source, then substituting the new noise source so there is little opportunity for anything to change. Next best would be a sky noise measurement on a preamp. Least accurate would be to measure a preamp at a VHF conference or other remote location, then bring it home and measure it, hoping that nothing rattled loose on the way. If you can't borrow a calibrated noise source, it would be better to take your noise source elsewhere and calibrate it. Perhaps we could measure noise sources as well as preamps at some of these events.

Using the noise source

Now that the **ENR** of the noise source has been calibrated, the noise figure calibration must be adjusted to match. However, the model 75 in the *CAL* position has only two dB of adjustment range marked on the meter scale. Older instruments have no adjustment at all. However, we can just turn around the equation we used to calculate the **ENR** and calculate the **NF** instead:

$$\mathbf{NF}_{actual} = \mathbf{NF}_{indicated} + (\mathbf{ENR}\ \textit{(noise source)} - \mathbf{ENR}_{cal})$$

There is a short cut. My noise source has an **ENR** around 12 dB, so I set the "CAL ADJ" in the *CAL* position as if the **ENR** were exactly 3 dB higher, then subtract 3 dB from the reading. Even easier, the meter has a *+3dB* position on the "ADD TO NOISE FIGURE" switch. Using that position, I can read the meter starting at 0 dB. Any **ENR** difference from 15 dB that matches one of the meter scales would also work — rather than an involved explanation, I'd urge you to do the noise figure calculations, then try the switch positions and see what works best for quick readout.

Reminder: noise figure meters have a very slow time constant, as long as 10 seconds for some of the older models, to smooth out the random nature of noise. *Tune slowly!*

Don't despair if the **ENR** of your noise source is much less than 15 dB. The optimum[1] **ENR** is about 1.5 dB higher than the noise figure being measured. The fact that today's solid state noise noise sources have an **ENR** around 5 dB rather than the 15 dB of 20 years ago shows how much receivers have improved.

Conclusion

The value of noise figure measurement capability is to help us all to hear better. A good noise source is an essential part of this capability. Accurate calibration is not necessary, but helps us to know whether our receivers are as good as they could be.

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