NOISE FIGURE MEASUREMENTS
— HF to Microwave
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A look at noise figure, noise sources, and noise figure measurements for amateur radio communications, and from a radio astronomy and science point of view.

Receiving systems, whether amateur radio or radio telescope receivers, must process very weak signals. Noise added by the system degrades the signal-to-noise ratio, reduces the sensitivity of the system, and obscures very weak signals. Signal-to-noise and noise figure are measured parameters that define the sensitivity of the receiver.

Sensitivity is the smallest signal that a system can reliably detect. In ham radio, this is often called the Minimum Detectable Signal (MDS).

SIGNAL-TO-NOISE RATIO

Figure 1 illustrates the concepts of input and output signal-to-noise. The input signal could be the input to a receiver from the antenna – the signal applied to the first amplifier in the receiver, which serves as the “low noise amplifier” (LNA). There are two signals at the receiver input, one a very weak DX station, and another fairly strong signal (labeled W1AW) a few kHz away.

The noise floor of this receiver input is –100dBm; the signal power of W1AW is –60dBm. The input SNR is 40dB, simply the power difference of the signal to the noise floor (100–60dBm=40dB). The SNR of the weak DX station is only about 10dB (probably the station you are interested in).

These signals are amplified by a 20dB RF amplifier. The –60dBm input signal is amplified by 20dB to –40dBm. If this were a perfect amplifier, the –100 dBm noise floor is also amplified 20dB to –80 dBm to preserve the 40dB SNR. However, in the real world, the amplifier will add some noise. In the example, the 20dB amplifier adds 10dB of noise, which raises the noise floor from the ideal –80dBm to –70dBm.

Thus the noise figure (NF) of the 20dB amplifier is 10dB (admittedly, a rather poor NF), which reduces the output SNR by 10dB to only 30dB.

Perhaps just as important is this 10dB NF raised the noise floor to above the signal level of the weak DX station you are trying to work. That rare DX is now below the noise floor not to be heard.

Important Points:
• SNR will degrade through each stage in the receiver (never better than the input SNR)
• NF reduces both SNR and sensitivity of the receiver – regardless of gain

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LOW NOISE AMPLIFIER (LNA)

The first stage in a receiver (RF amplifier or mixer) dictates the overall NF of the receiver. Therefore, it is important that the first amplifier be a low-noise amplifier. Especially at VHF and above.

An LNA should have the following characteristics:
• High gain (20-30 dB)
• Low noise figure (<1.5dB VHF and above)
• Good input-output impedance match (low reflected power)
• High P1dB for high dynamic range
• Stable biasing

Many HF receivers do not have an RF amplifier, or LNA, before the first mixer. This is because the noise power from the antenna – the “sky power” noise (discussed shortly) is far greater than the noise contributed by the receiver.

VHF, UHF, and microwave receivers must have an LNA to ensure the NF of the receiver is lower than the sky noise power.

NOISE FIGURE IN CASCADED STAGES

Every stage in your receiver contributes some noise to the signal, and thus each stage has its own NF. As stated above, the first stage in the receiver, whether an RF amplifier, LNA, or mixer, dictates the overall NF of the receiver. Subsequent stages have a diminishing effect on NF.

The overall NF of a system is determined by the gain (G) and NF of each stage, and calculated using the **Friist equation**:

\[
F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \frac{F_4 - 1}{G_1G_2G_3} \ldots
\]

where,

- \(F\) = noise factor (unitless)
- \(G\) = gain, linear (not dB)
- \(F_1\) = NF of 1st stage  
- \(F_2\) = NF of 2nd stage
- \(G_1\) = gain of 1st stage
- \(G_2\) = gain of 2nd stage

A spreadsheet can be devised to convert the input quantities of G(dB) and NF(dB) of each stage into linear units, calculate the overall F, then convert F to NF(dB) = 10logF.

There are also numerous NF cascade calculators online, such as: minicircuits.com/applications/mcl_nf_calc.html

To save a bunch of calculations, the following examples demonstrate the effects of NF in cascaded stages (and the importance of the first receiver stage).

**Fig. 2** shows the first two stages of a typical HF receiver with the first stage a passive mixer. On the first stage, some value of input loss is usually added. This would be the losses in the antenna feedline, receiver preselector filters, etc. 2dB is a typical value. A passive mixer usually has a conversion gain of −6dB, which equates to a 6dB noise figure, or NF=−8dB adding the 2dB input loss. Followed by −a 20dB amplifier with a 6dB NF yields a total NF=8.2dB, clearly indicating the overall NF is dictated by the first stage.

![Fig. 2 – HF receiver NF with mixer first stage](image)

**Fig. 3** is a typical HF receiver “front end” using the ubiquitous NE602 active mixer with a conversion gain of 17dB and 5dB NF. It is followed by the same IF amplifier above with 20dB gain and NF=6dB. This scheme yields an overall NF of 7.1 dB, again dictated by the NE602 mixer stage.

![Fig. 3 – HF receiver NF with NE602 active mixer](image)

**Fig. 4** is the HF receiver scheme using an RF amplifier (LNA) prior to a passive mixer. Again, the overall NF of the cascaded stages is dictated by the NF of the 1st stage, the RF amplifier.

![Fig. 4 – HF receiver NF with LNA first stage](image)
**HF receiver** NF is not highly important, except to keep front end losses fairly low <10–12dB. This is because the sky and atmospheric noises on the HF bands is higher than even a very lousy receiver. Though a decent NF receiver will improve sensitivity.

**VHF frequencies** and above is a far different story where sky and atmospheric noise is fairly low. This is obvious by the noise level you hear on 2M vs. 40M! The objective is to maintain a NF at the higher frequencies that is below the input noise level. For this reason, an overall NF of <5–6dB is desired for VHF/UHF.

**Fig. 5** is a VHF receiver using the same HF scheme of a passive mixer for the first stage (not recommended >50 MHz). This yields an overall NF of 8.2dB, which may be above the input noise level of the antenna.

**Fig. 6** illustrates a more sensical scheme of using a good LNA prior to the mixer. A 1.5 NF LNA is now more common than a few years ago. This yields an overall NF of 3.9dB, which is about the “sky noise” at 220 Mhz.

Note, however, that the 2dB input loss is now more than the 1.5dB NF of the LNA, and the dominant source of NF of the network. This is why at the higher frequencies, having an efficient antenna, low-loss feed line, and a short-as-possible length of feed line between antenna and the VHF/UHF receiver is very important. Reducing feed line and other input losses with a good LNA will yield a low NFVHF/UHF receiver.

**Important Points:**

- The receiver first stage NF dictates the NF for the rest of the system.
- NF for a passive device is equal to its loss.
- On HF, the overall NF of the receiver is not highly important.
- On VHF, the NF of the first stage is very important to establish good sensitivity.
- On VHF, low-loss and short feed lines are a larger contributor to NF than HF systems.

**NOISE TEMPERATURE**

Noise temperature is another means of expressing signal-to-noise degradation and noise figure. It is commonly used in radio astronomy, satellite communications, and the sciences. It is becoming more accepted in VHF and microwave amateur work. Noise temperature, T, is expressed in degrees Kelvin (°K) and defined as:

\[
T = 290K \times (F-1)
\]

where,

- \( T = \) noise temperature, °K
- \( F = \) noise factor

Converted from NF(dB) by

\[
F = 10^{\frac{NF(dB)}{10}}
\]

290K = reference (room) temperature, about 65°F

**Fig. 7** shows the relationship between NF in dB vs. noise temperature in °K. Using the VHF NF example in Fig. 6, the 3.9dB NF would be equivalent to about 400°K. Noise temperature is often estimated by the Rule of Thumb shown below, or devising a simple spreadsheet converter.

**Rule of Thumb for VHF/UHF:**

- For noise figures <1 dB
  \( T = 70°K \) per dB (ex. NF 0.8dB =~56K)
- For noise figures 1-2 dB
  \( T = 80°K \) per dB (ex. NF 1.5dB =~120K)
- For noise figures 2–4 dB
  \( T = 100°K \) per dB (ex. NF 3.5dB =~350K)

**Fig. 7 – Noise Figure vs. Noise Temperature**
Other advantages of using noise temperature measurements at VHF through microwave frequencies are powers and noise figures are usually a fraction of a dB and very difficult to measure.

Secondly, the noise power illuminating a VHF or microwave antenna due to sky and atmospheric noise is widely available in degrees K. Various radio observatories have measured the background sky power, called Tsky, in °K. By knowing the noise temperature of your receiver, you immediately know whether your noise floor is above or below Tsky.

**SOURCES OF NOISE**

Most literature describes how noise in a receiver is caused by thermal noise, shot noise, flicker noise, impedance mismatches, and the like. These are *internally* generated noise sources, and indeed are factors that determine the NF and sensitivity.

In the real world, the overall noise that is experienced is when the receiver system is connected to an antenna (which most hams try to do!). When the antenna is connected, there is a noted increase in the noise (and hopefully some signals). This increase in noise is caused by external noise source. The most dominant sources of external noise, especially at HF, are:

- Sky noise and atmospheric noise
- Human noise (ignition, motors, PCs, etc.)
- Thunderstorms; geomagnetic storms
- Solar storms
- SIDs – Sudden Ionospheric Disturbances

Sky noise and atmospheric noise are by far the most dominant, and lumped together to form a background noise temperature called Tsky. The power from space, millions of celestial radio sources, our galactic center and our sun delivers a surprising amount of power to planet earth, and to our antenna systems. This is the majority of noise, or “hiss,” one hears on HF through UHF.

**Fig. 8** shows the temperature of Tsky from 40–400 MHz with the approximate level in dBm added. This is the “Cane Model,” developed by the Naval Research Laboratory (NRL), and used for calibrating the “cold sky” on low frequency radio telescopes. This is a lot of power, with about –100dBm (100°K) at 220 MHz and –80dBm (10,000°K) of noise power, or worse, in the HF bands below 30 Mhz.

**Figure 9** is another representation of noise temperature vs. frequency, also compiled by the NRL. The angles shown are different elevation angles of a radio telescope dish antenna … which would also represent the angle of the main lobe, or take-off angle, of an amateur radio antenna. Looking straight up (0°) at the sky, obviously you would “see” the maximum amount of Tsky; looking at the horizon (0°) would be minimum Tsky and the various take-off angles in between.

**Figure 10** (next page) is an adaption of the various solar and celestial powers, and their magnitude, as measured on the VLA low-band system (50–500 MHz). It would be similar to the powers present on an amateur radio installation.
There are a few items that may be of interest.

1. The power from the quiet sun begins to diminish around 300 MHz (except during solar flares). Below about 100 MHz, Cassiopeia A (Cas A) becomes the brightest radio source in the sky. Cas A is the remnant of a massive supernova in the year 1056 and so strong and stable, it is used as a standard calibrator for both professional and amateur radio telescopes. If you can’t detect Cas A, you won’t hear anything.

2. The noise power generated by solar flares, and the associated Type II and IV solar noise storms, is shown. Note that it takes an X-class flare or stronger to cause GPS disturbances.

3. Astronomers use “Janskys” (Jy) as a unit of measure for source powers. 1 Jy = $10^{-26}$ watts, or $10^{-23}$ mW. The sensitivity of the VLA is in the order of a few milli-Jy (depending upon frequency). Now that is QRP!

4. Our galactic background, about $-120$ to $-90$ dBm, is strongest near our galactic center, near Sagittarius and Scorpio in our southern sky.

5. The background radiation from the big bang is about $3^\circ$K (about $-170$dBm) and takes something like the VLA to detect it.
MEASURING NOISE FIGURE

There are different ways to measure the noise figure of any 2-port device (amplifier, mixer, etc.) or a receiver system, though are all somewhat involved and/or requiring proper test equipment.

Two methods often used by the amateur is the Gain Method using a signal generator and the Y–method using a noise source. Both of these methods are described on the internet and in the ARRL VHF handbooks.

The most accurate method is known as the hot-cold load test. This method is used for accurately measuring very low noise figures and noise temperatures typical in cryogenically cooled radio astronomy receivers, satellite systems, or about anything in the microwave region.

This is the NF measurements method that will be demonstrated at New Mexico Tech Fest.

HOT/COLD LOAD TEST

This method involves measuring the output system noise power of the device under test (DUT) with the input terminated by a resistor, usually 50 ohms for most RF systems. The DUT can be an amplifier, mixer, or a receiver system. The noise power (Pn) of the input resistor is:

\[ P_n(\text{watts}) = kTB \]

where,
\[ k = \text{Boltzman's constant} = 1.38 \times 10^{-23} \text{ joules/}^\circ\text{K} \]
\[ T = \text{Temperature in} \ ^\circ\text{K} \]
\[ B = \text{bandwidth in Hz} \]

This is illustrated in Figure 11.

\[ P_n(\text{watts}) = kTB \]
\[ V_n = -\sqrt{4kTR} \]

\[ \text{Fig. 11 - Terminating resistor producing } P_n \]

Pn will be a certain power at room temperature, 290°C. If the resistor is heated above 290K, Pn will be higher; if the resistor is cooled below 290K, Pn will be lower. The difference between the HOT and COLD values of Pn is the Y–factor.

Typically, PH is measured at 290K, room temperature. For best results (a good Y factor), TC is usually measured with the resistor immersed in liquid nitrogen (LN2). This cools the resistor to a known 77K (–321°F).

The basic test setup for hot/cold test is shown in Figure 12.

A power meter or spectrum analyzer is used for measuring PH and PC in dBm. However, most power meter heads are only sensitive down to about –60 to –70 dBm and most spectrum analyzers have a noise floor around –80dBm. An external amplifier on the DUT output to elevate the power for the measuring device will be needed.

Some newer high sensitivity spectrum analyzers have a noise floor around –100dBm, which can be used directly. For best power measurement, the DUT output should be band limited with a narrow bandpass filter.

An RBW of 1MHz works well with the filter, and is a convenient measure of dBm/MHz. This can be converted to dBm/Hz if needed by deducting 60dB(10log1kHz).

Video filtering should be 0.3–1.0 of the RBW. Like the power meter method, some averaging should also be applied for a stable power measurement.

The final test setup for hot/cold load tests are shown in Figure 13 (next page). The procedure is actually fairly simple. Measure PH with the load resistor at 290K room temperature. Then immerse the load into the LN2 to cool to 77K. The displayed power should drop until it stabilizes, which is the PC noise power. Equations are used to convert PH and PC into noise temperature (°K) and noise figure (dB).
A REAL WORLD EXAMPLE

The noise figure will be measured of an LNA from Radio Astronomy Supply (RAS), a WD5AGO design. These are sold to amateur radio astronomers and UHF hams. Several were built for the VLA years ago for a prototype system centered on 327 MHz. Thus, a 327 ±20 MHz filter was used before the spectrum analyzer.

PH was measured at –80.0 dBm at TH=290°K room temperature. See Fig. 14.

The 50Ω terminating load was then immersed into the LN2 and allowed to stabilize (about 1 min.). The noise power on the spectrum analyzer was observed to slowly decrease.

PC was measured at –75.9 dBm at TC=77°K, the temperature of liquid nitrogen. See Fig. 15.

The Y factor is:

\[
Y = TH - TC = (-80.0) - (-75.9) = 4.1
\]

These values are inserted into a spreadsheet that calculates the noise temperature \( \text{Trx} \) and noise Figure using the equation:

\[
\text{Trx} = \frac{TH - (10^{\frac{Y}{10}} \times TC)}{10^{\frac{Y}{10}} - 1} = \frac{290K - (10^{4.1} \times 77K)}{10^{4.1} - 1}
\]

\[
= \frac{290K - (197.9K)}{2.57 - 1} = \frac{92.1}{.57} = 58.7K
\]

Ball park conversion to NF(db):

\[
\text{NF} = \text{Trx} / 70dB = 58.7K / 70dB = 0.83 \text{ dB}
\]