Calibration of Noise Sources

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Optimization of an RX system for best NF (Noise Figure) is very important for ham radio activity, especially on the microwave bands. Many QSOs are only made possible with low noise receiving systems. The difficulties of finding the best NF conditions have forced many hams to get an NF meter and noise source 'at home' in order to optimize the entire RX chain for the minimum NF. But when it comes to *measuring* that optimized value, the most important part of the measuring system is an accurately calibrated noise source.

At the beginning, more than 20 years ago, many of us began to venture into this field with home made equipment. This was good for trimming an LNA to minimum NF, but without the possibility to know the actual value of the NF. We also learned that the same LNA measured with professional equipment at different national meetings showed different results. Later on the improved knowledge in this field [1] and the growing availability of surplus test gear helped to achieve better and more consistent results.

This article gives a brief overview of the problems of NF measurement, focused on the problems of noise source calibration. The key parameter that must be accurately known is the Excess Noise Ratio (ENR). The authors have made progressive improvements in calibration of noise sources, until we reached a satisfying accuracy with our automatic measurement system.

NF and ENR – magnitudes involved in the measurement

Accurate measurement of the NF of Low Noise Amplifier (LNA) requires the measurement of extremely low signal levels (around -130 dBm) with an accuracy in the order of 0.1 dB, regardless of all other issues including external interference and other environmental factors. These are noise signals, so all measurements include unavoidable issues of statistics, bandwidth and integration time. So all parts involved in the measurement must guarantee this accuracy, which is not easy to achieve. In particular, any uncertainty in the ENR calibration of the noise source will add directly to the overall uncertainty of the final NF measurement [2, 3, 4].

Calibration of an 'Unknown' noise source requires its noise output power to be compared directly against a 'Reference' noise source that has already been calibrated by some other means. Manufacturers do this by comparing against 'Production Standard' at the factory, which itself has been calibrated against a 'Company Standard', and that in turn had been calibrated by a major international Standards Laboratory such as NPL in Britain or NIST in the USA. The Standards Laboratories use 'hot/cold' substitution techniques that are traceable to international physical standards including temperature and power.

What we made in the past

For years we tried calibrations comparing our noise sources against other sources belonging to newer professional equipment found at meetings or labs. We always used manual methods, which can be valid but can also include user errors.

Another way was to measure some LNAs (one each ham band) at the meetings, then back at home measure the same units with our own equipment, working backward to calculate the ENR of our own noise source. This was a poor method because of the many uncontrollable circuit and environmental conditions that were completely different between the two measurements. So amateur measurements of NF and ENR for a long time were always discordant, with poor agreement between measurements at different times and locations. There was some improvement as older professional test gear became available on the surplus market at more affordable prices, but there was still much more to do.

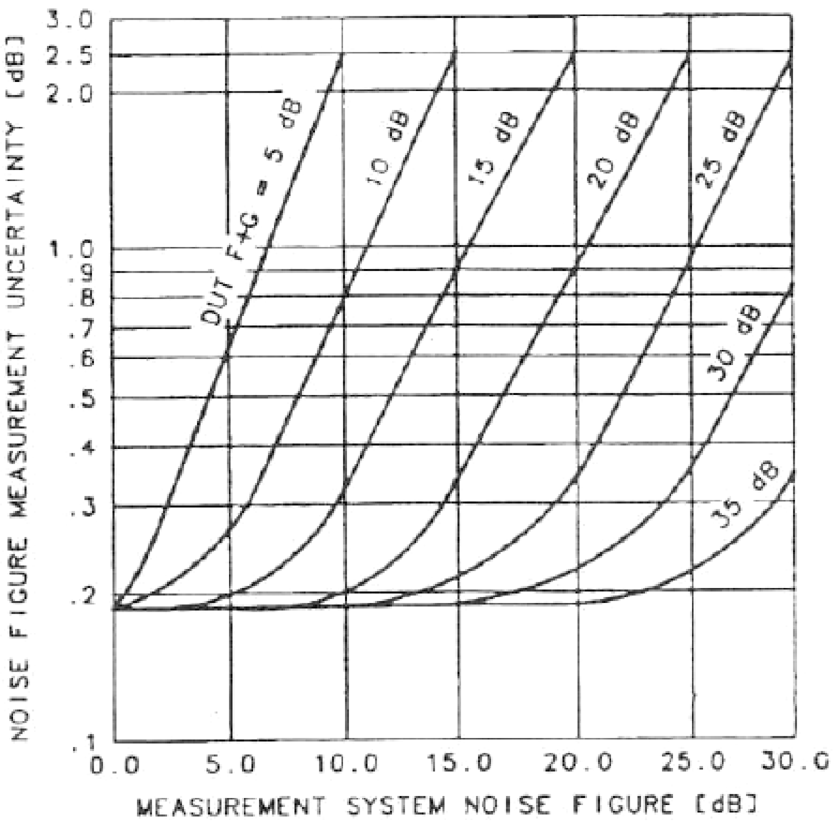
Problems of noise sources accessible to amateur radio

Noise sources accessible to radio amateurs have included:

1. Home made sources, which by definition are not calibrated
2. "Low-end" professional sources from the surplus market. Although these were manufactured by leading companies like Ailtech, MSC, Eaton, NoiseCom etc, they do not command high prices because they are very old and either have no ENR value marked on the body, or maybe have values at only a few frequency points. Due to their age, even the marked ENR values could not be depended on. The ENR of these types of sources is typically about 15 to 30dB, and although they will often work beyond their marked frequency range, they are not calibrated. Also an external attenuator needs to be added in order to lower the ENR to a more convenient value for use with modern LNAs, and once again this requires calibration.

3. "High end" professional sources manufactured by brand name companies, commanding high prices even on the surplus market. The typical ENR value may again be around 15dB, but now it is flat over broadband frequency and the ENR table is printed on the body. The higher price is partly due to the calibration table, but even these sources may be 20-30 years old and not in perfect condition, so the calibration table has doubtful validity.

4. And since prices on the surplus market are so high, we always wonder if it would be worthwhile to spend even more money to buy a new source with modern design and up-to-date calibration.



Noise Figure Measurement Uncertainty versus Measurement System Noise Figure

This is a graph of overall noise figure measurement uncertainty versus measurement system noise figure. "DUT F+G" is the device under test noise figure plus gain in dB. The curves are based on typical values of noise figure instrumentation uncertainty (0.1 dB), gain instrumentation uncertainty (0.15 dB), noise source ENR uncertainty (0.1 dB), measurement system SWR (1.7), noise source SWR (1.15), DUT input SWR (1.5) and DUT output SWR (1.9).

Fig. 1: From the HP8970B User Manual

Figure 1 is taken from the User Manual for the HP8970B Noise Figure Meter, and it shows how the overall measurement uncertainty depends critically on the (NF + Gain) of the Device Under Test (DUT). Both the diagram and the instrument itself are now quite old, and both have been replaced in more recent years, but it does prove that the fundamental issues have been understood for a long time. Modern ham radio LNAs exhibit very low values of NF, often less than 1dB, and often have a high gain as well, so even small errors in the gain measurement can create large errors in the NF. Accurate measurements require a noise source with a low ENR – around 5dB is recommended.

Since low ENR sources are much less common than those with about 15dB ENR, it is quite normal to reduce the ENR by adding an external attenuator. The final ENR value is not a simple subtraction of values in dB, but needs to be calculated with accuracy using the full vector S-parameters of both devices. Because of this complication, it may prove easier to connect the noise source and the attenuator permanently together and then look for a way to make a direct ENR calibration of the whole unit. This is the approach that we have followed.

Adding an extra attenuator shows another advantage: lowering the difference between Zon and Zoff values of the source, which is another cause of errors in LNAs with a high input reflection coefficient, like many older-style GaAsFET preamps [1, 4]. The ENR of the noise diode itself is about 25-30dB so all modern commercial sources include a built-in attenuator. We found that most of the attenuators in the 15dB ENR sources are around 12 dB (HP sources even less) but often this value is too low to mask the impedance changes. Commercial low-ENR sources are variants of a high-ENR source with an additional attenuator built in, and the increase in attenuation of about 10 dB helps to reduce the difference between Zon and Zoff. However, that is the limit of what can be done by adding attenuation; the only way to mask impedance changes even further is by using an isolator.

In conclusion, checking the ENR of a noise source is an absolute need, and when an extra attenuator or isolator is added, a further calibration of some kind is always necessary.

Our basic measurement system

After we got a HP8971C 10MHz to 26.5GHz Noise Figure Test Set to extend the frequency range of the HP8970B, we were encouraged to put together a complete measurement system as proposed by HP. This system works stand-alone as an NF meter – just select the desired frequency from the HP8970B keypad and you can measure the NF of an amplifier across the extended frequency range. If you want to perform multi-frequency measurements with manual recording of the values, this can be a little uncomfortable. Driving the system by means of software running on a PC is much better, because it makes measurements and collects data automatically. Used with care, the HP8970B-HP8971C combination can give comparable results to the newer generation of meters such as an Agilent N975A although the latter is much more convenient to use, being a single instrument which is more compact, faster, more programmable and with a powerful human-machine interface thanks to the large graphic display. However, both generations of instruments show a relatively high NF and poor Return Loss (RL) at the input. Also, both generations of instruments were primarily designed to measure amplifiers and not for the calibration of noise sources.

Frequency	Noise Figure	Input Ret. Loss.
10 – 30 MHz	< 18 dB	< 9 dB
30 – 100 MHz	< 13 dB	< 9 dB
0.1 – 12 GHz	< 10 dB	< 7 dB
12 – 18 GHz	< 11 dB	< 7 dB
18 – 26 GHz	< 14 dB	< 7 dB

Fig. 2: Input return loss of HP8971C frequency converter covering 10MHz to 26.5GHz

How do these systems behave when we measure a noise source?

As you can see from the table in Figure 2, the input RL of the HP8971C is not very good (in the lower bands that are also covered by the HP8970B, the HP8971C is actually worse). The input RL is not a major problem when measuring active devices like an amplifier because the forward gain and reverse isolation tend to reduce the errors, but the input RL does become important for the direct calibration of noise sources because the source is not operating into its correct impedance of 50 ohms.
Agilent recently introduced the N2002A Noise Source Test Set as an addition to the N975A meter which made the measurement of noise sources more convenient and more accurate. We were inspired by this to build our own home-made system.
Improvements required were:
1. Input RL: Inside the N2002A are a number of switches and insulators that ensure proper 50 ohm terminations to both the DUT and the Reference Noise Source.
2. Input NF of the measurement system. To reduce the Input NF requires a separate preamplifier for each band. To stay within the region of better uncertainty as shown in Figure 1 requires each preamplifier to have the lowest possible NF and no more gain than is necessary. This is mandatory when we have low ENR sources to measure.
3. Increasing the number of measuring cycles and discarding any data errors caused by disturbances. This was the task of the software on the PC.

Our 'ENR Front-end Box'

So the task of our home made unit was:

- Switching the Reference Noise Source and the DUT Noise Source automatically (avoiding errors due to a manual operation from different connections).
- Lowering the system NF to <5 dB with RL > 20 dB in order to minimize the uncertainties, by using a combination of LNAs and isolators.

Figure 3 shows the block diagram of the unit and Figure 4 shows the interior layout. The input switch toggles between the two noise sources, one being the Reference Source whose calibration is known and the other the DUT that is to be calibrated. Following the switch is a pair of multi-way switches that insert an isolator and LNA for each band. The unit also includes a digital thermometer with an external probe which has to be applied to the noise heads to detect their physical operating temperature.

Figure 5 shows the block diagram of the whole system and Figure 6 shows a calibration in progress. Our Reference Sources are either a HP346C or a HP346A with a recent calibration.

A few words about the components used. RF switches, isolators cables and connectors are high quality components, which we got from the surplus market. Amplifiers... are a long story. We spent much time to find the final solution – more details below. Then finally the software running on the PC drives all the test gear, processes the measurements and generates tables of results in Excel format and also as graphs.

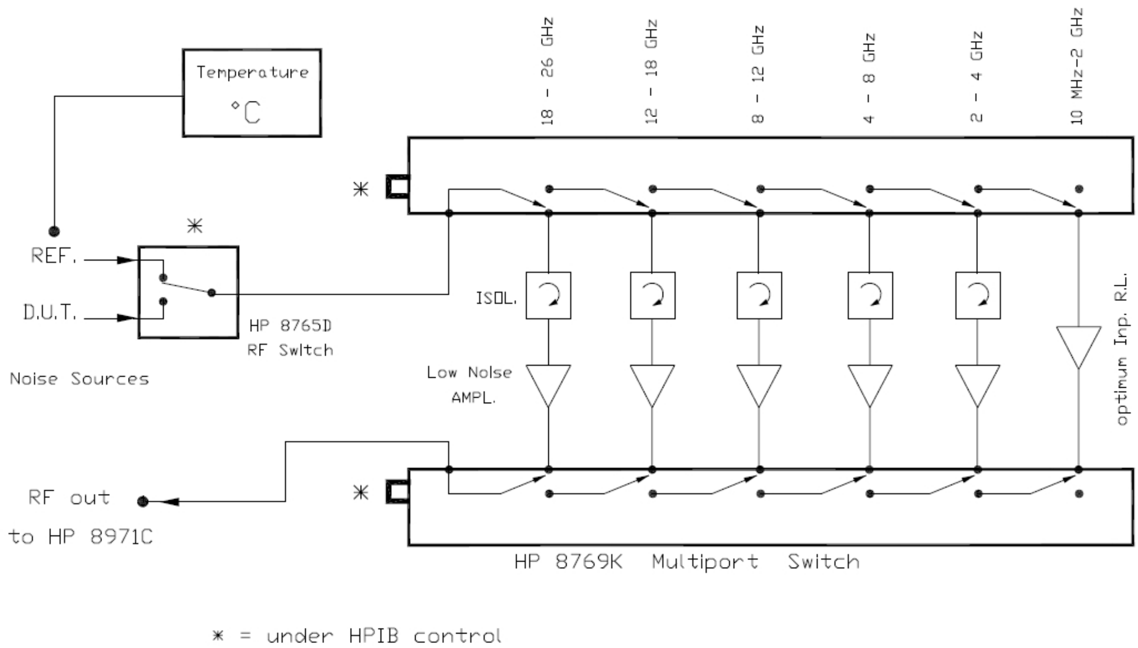


Fig. 3: Block diagram of 'ENR Front-end Box'

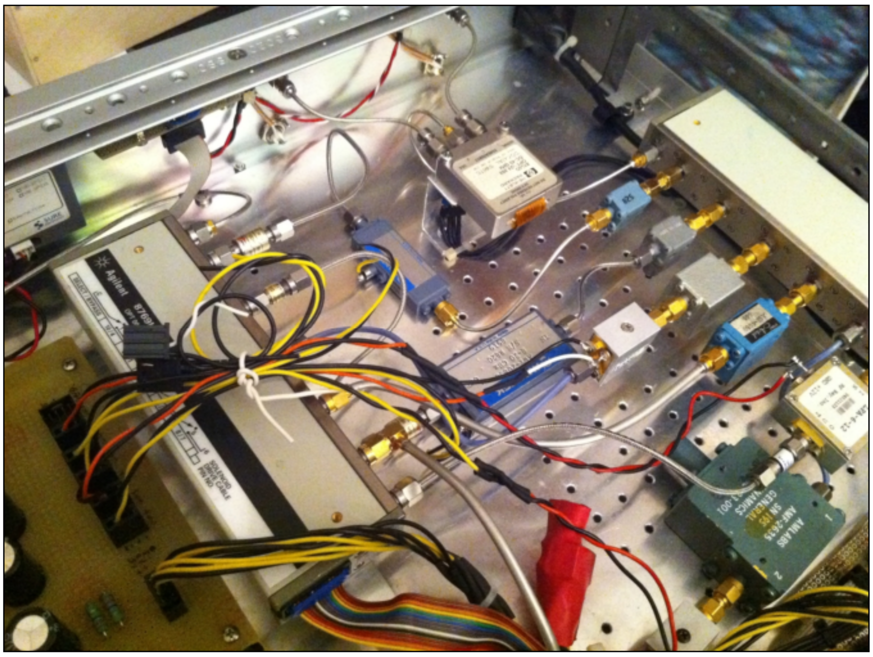


Fig. 4: Interior of 'ENR Front-end Box'

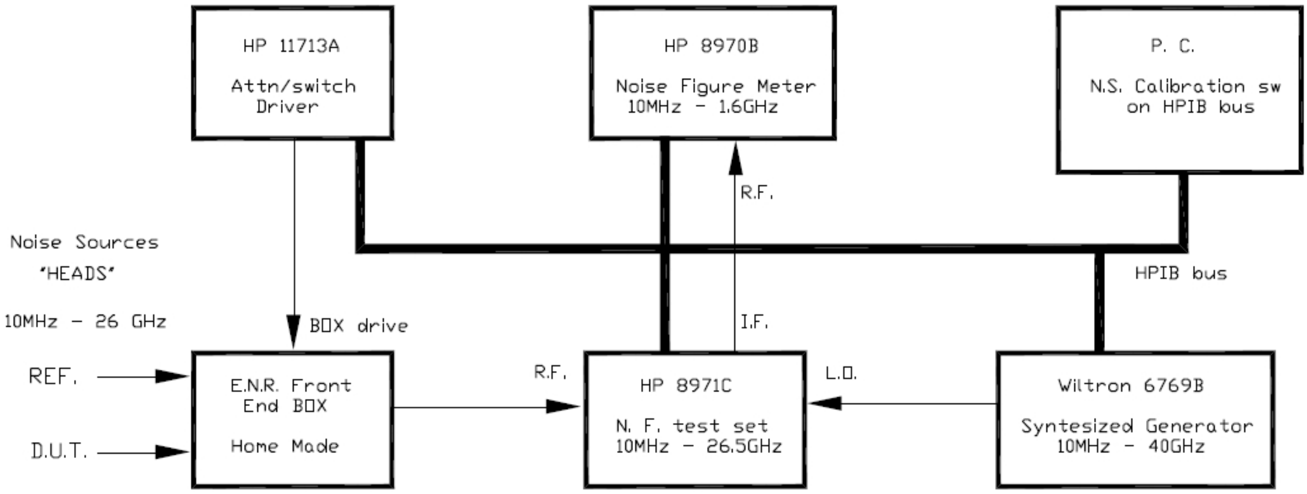


Fig. 5: System block diagram.

Fig. 6: Calibration in progress. Bottom to top: HP8970B, HP8971C and the home made unit with Reference and DUT noise sources.

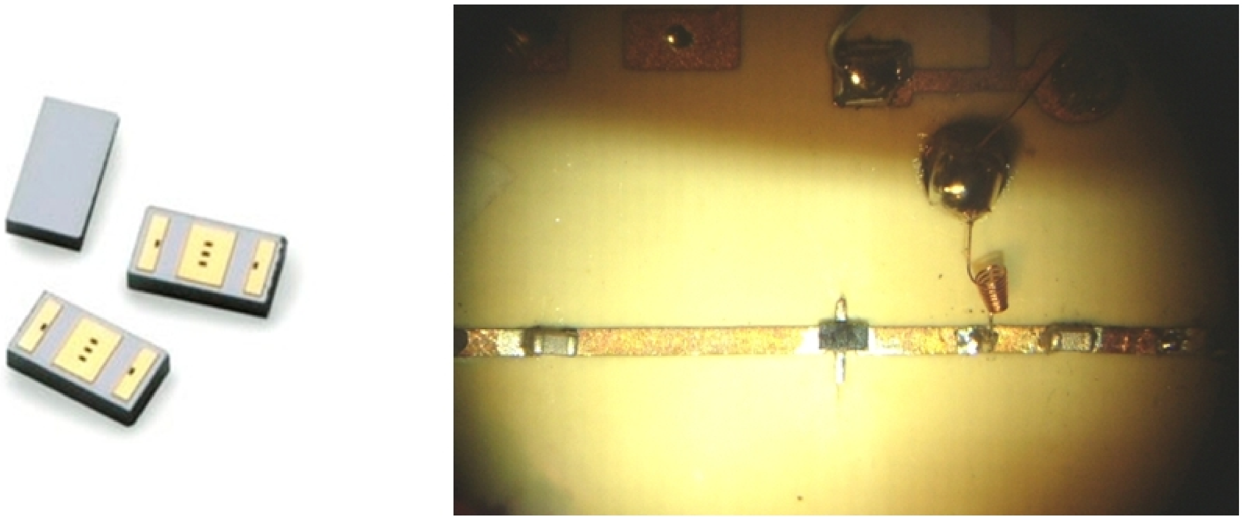
The LNA amplifiers used

A full explanation of the Low Noise Amplifiers would require a whole separate article. The target for each band was an LNA with typical NF <3dB and 15dB of gain, flat over the entire operating band. At first we tried something from the surplus market, an ultra-broadband amplifier intended for fiber optic systems, but results were poor because the NF always was out of specs. So MMIC devices of the new generation were the only way, in separate home made units. See final results in the table of Figure 7 and the picture of a typical example in Figure 8.

One more problem is that in the low range from 10MHz to 2GHz there do not exist isolators that cover the entire band, so the job of guaranteeing a good 50 ohm input has to be provided by the amplifier itself... yet another critical requirement. At the end, the MMIC ERA2+ gave us the best result.

Freq. GHz	Device	G dB	NF dB	In RL dB
0.01 - 2	ERA2 Minicircuits	15	3.3	23
1 – 11	VMMK 2203 Avago	16	2.1	isol.
7 – 21	AMMP 6222 Avago	24	2.3	isol.
17 - 27	HMC 751 Hittite	25	2.2	isol.

Fig. 7: LNA performance



MMIC VMMK-2203 Avago smd 1x0.5mm !! (0402)

Fig. 8: Typical LNA construction

Testing the Test Set

We tested our system at our national microwave meetings in the last two years with 45 noise sources measured and calibrated. This activity allowed us to improve the system to the level reported here. The fundamental requirements about noise averaging time mean that it can never be quick to perform a complete measurement cycle – up to 1.5 hours is required per source, if one wants a significant number of points to be calibrated. However, we must remark that only a few people requested a low ENR calibration of their sources, so there is still not enough 'awareness' in the ham radio world about the use of low ENR sources!

Final questions

At the end, many of you will probably will ask: Is all this stuff necessary to perform a reliable calibration? The answer of course is NO. For a few points you can easily do calibration with only a NF meter one good source as a reference, operating in manual mode and with simple ham converters for upper frequency bands. But the following rules are important:

1. Ensure a good input RL and NF to the system (adding an isolator and a LNA if needed).
2. Take care of all the RF interconnections, including cleaning the connectors.
3. Ensure that the environment is free of RF or noise.
4. Perform a large number of measurements both on the DUT and REF sources, discarding anomalous deviations and then take the average (which is not equivalent to increasing the 'smoothing' function in the NF meter – that is something different).
5. When calibrating at more than one frequency point, proceed as follows: AT EACH FREQUENCY STEP, calibrate the system with the reference and then measure the unknown noise source. Then go to the next step frequency and repeat. DO NOT perform all calibrations first and all unknown measurements later.
6. MEASURE the actual temperature of the noise sources and include this in the calculations – do not assume 290K!

Before starting the measurements it is good practice to have an idea about the value of the attenuator inside the source and the RL for the on / off state (if not good, we suggest to put an attenuator or isolator on the source, and leave them dedicated to the source 'forever').

Conclusions

In this article we have intentionally jumped over many of the theoretical aspects, but it is highly recommended that everybody reads about them. There is a lot of information around! First of all, the HP / Agilent Application Notes are a reference point [2, 3]. Then, we recommend a recent article, which focuses over all the views related to the world of amateur radio, *Noise Figure Measurement - A Reality Check* from GM4ZNX and GM3SEK [4]. Also see the website of SM5BSZ for follow-ups from a different viewpoint [5]. Then, specifically about noise sources, see Reference [6]: *Noise Sources Comparison Around the Europe: Final Report* by S. Mariotti.

At the end, we would like to thank Davide I1DDS for his valuable contribution about the software running on the PC.

Questions? Please email: mauroottaviani@tiscali.it

References

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