MAURY MICROWAVE
CORPORATION

14 Dec 1999

NOISE CHARACTERIZATION USING THE MAURY AUTOMATED TUNER SYSTEM

Introduction

The purpose of these notes is to provide the user of a Maury Automated Tuner System (**ATS**) with some insight into achieving precise, consistent results in a noise characterization measurement.

The suggestions presented are meant to augment the formal procedures detailed in the manuals provided with the system and, in some cases, involve general microwave measurement practices not normally found in such manuals.

Prerequisites

These notes assume that the reader is:

a) familiar with noise characterization;
b) has operated the system and is familiar with the procedures detailed in the manuals.

Scope

These notes apply specifically to the MT989A, revision 1.0 software.

Several options are available to the user performing a noise characterization using the Maury **ATS**. Experience has shown that the most consistent, accurate results are obtained using the two tuner configuration and the in-circuit thru for second stage calibration.

These notes, while aimed primarily at the dual tuner/in-circuit thru configuration, include some general practices applicable to single tuner systems and those using the direct thru method of second stage calibration.

CONNECTION REPEATABILITY

Connector Care

Noise characterization depends quite heavily on an accurate knowledge of the S-parameters of several of the measurement system components. Connector performance will influence these characteristics, and non-repeatable connections will result in changing parameters and inaccurate, imprecise measurement data.

Consistent results from any microwave measurement can only be achieved if the connectors are maintained in good condition. Microwave connectors on precision laboratory components should be cleaned, inspected, and gaged each time they are disconnected and mated. When the connectors are not in use, they should be capped.

Uncapped connectors, even in a well kept, clean laboratory, can collect dust and lab debris. In addition, every time a connector pair is mated, no matter how careful the alignment, there is a certain amount of scrubbing of metal on metal surfaces. This generates microscopic metallic particles which collect in the connector cavities. These particles and debris, if not routinely removed by cleaning, can eventually build up to the point where the connector components are distorted and surfaces are scarred when the connector is mated. Such damage can distort and damage the mating connector and result in inconsistent, inaccurate measurement data.

There are three very simple means of avoiding poor measurement performance due to connector damage:

a) Keep connectors capped when not in use to prevent the collection of dust and debris in the connector cavities.
b) Clean the connectors prior to each time they are mated. Use a lint-free swab or cloth moistened with a solvent such as liquid Freon to wipe the mating surfaces and the internal cavity. Do not allow the Freon to contact the dielectric bead support. Blow out loose debris with clean, compressed air. ***DO NOT BLOW***

LIQUID SOLVENT INTO THE CONNECTOR UNDER PRESSURE.

c) Gage the connectors just prior to each time they are mated to insure there is no damage due to prior mistreatment. Most typical "push-on" gages will detect serious connector distortion; however, for a critical measurement application such as noise characterization, a metrology grade, thread-on gage is recommended. **Table I** below lists some such gages available from Maury.

Model	Connector	Resolution
A020D	N	0.0001 in.
A028D	7mm	0.0001 in.
A034E	3.5mm	0.0001 in.

Table 1: Metrology Grade Connector Gages

Connector Alignment

Connector alignment is critical to maintaining the accuracy of the measured S-parameters of the measurement system components and preventing the type of damage noted above. This is particularly true of the tuners and test fixture.

Experience has shown that the best method of connecting the tuner/bias network combination, either to the network analyzer for characterization or in the measurement system, is as follows:

a) Suspend the unit with one hand with the legs retracted.

b) Align the unit horizontally and vertically until the coupling nut starts to thread freely onto the mating connector.

c) Adjust the levelling legs until they just contact the support bench.

d) Tighten the coupling nut to the specified torque.

In terms of ease of connector alignment, the recommended connection sequence is as follows:

a) Connect the test fixture and output bias T to the output tuner.

b) Connect the output bias T to the noise receiver.

c) Connect the input bias T to the input tuner.

d) Connect the input tuner to the test fixture.

e) Connect the noise generator to the input bias T.

Connection Torque

The transmission and reflection characteristics of a mated connector pair can also be affected by the connection torque. To insure consistency, the coupling nut should be pulled up to the same torque every time. This is especially critical with the smaller connector series such as 3.5mm. Consistent connection torque is most easily accomplished with a calibrated torque wrench designed for the particular connectors in use. **Table II** lists the torque wrenches available for the most common connector series.

Model	Connector	Torque
2498T	14mm	12±0.5 in-lbs
2698C	7mm, N	12±0.5 in-lbs
8799A	3.5mm, SMA, MPC3	8±0.3 in-lbs

Table 2: Calibrated Torque Wrenches

In some connector series, most notably, Type N, the coupling nut on the typical industrial grade connector is knurled or fluted and cannot be pulled up with a torque wrench. If at all possible, these connectors should be avoided in critical measurement applications such as noise characterization.

Maury laboratory and metrology grade N and 14mm connectors, adapters and components are equipped with hexagonal coupling nuts which permit application of a standard, calibrated open-ended torque wrench.

MECHANICAL STABILITY

RF Components

The microwave/RF components of the **ATS** noise characterization setup should be mounted on a level, solidly constructed laboratory bench free from wobble and resistant to deflection caused by heavy objects placed on the bench.

Deflection or movement of the bench will stress the connectors which will cause the microwave characteristics of the connectors to change resulting in inaccurate and inconsistent measurements.

For the same reasons laboratory personnel should be discouraged from leaning or sitting on the bench supporting the system.

Cable Stability

Flexible, even semirigid, cable connections should be avoided whenever possible in a noise characterization setup. This is particularly important in the microwave path from the noise generator to the noise receiver input. These connections should be rigid.

There are, however, two usually unavoidable RF cable connections required in the **ATS** noise characterization setup:

a) the connection from the local oscillator (LO) to the mixer or noise figure test set;

b) the connection from the IF output of the mixer or noise figure test set to the noise figure meter.

Of the two, the latter is the most critical. Although the frequency is relatively low (< 2 GHz), any change in the characteristics of this cable during a measurement could result in significant measurement errors. This connection should be, at the least, semirigid, and considerable care should be exercised to avoid vibrating, bending or otherwise distorting the cable during the measurement.

Experience has shown that high quality flexible cable can be used for the LO connection; however, as with the IF cable, disturbances should be avoided.

S-PARAMETER MEASUREMENTS

VNA Calibration

Noise characterization requires an accurate knowledge of four sets of full, two-port S-parameters:

a) The S-parameters of the input tuner.

b) The S-parameters of the output tuner.

c) The S-parameters of the DUT.

d) The S-parameters of the in-circuit thru.

These characteristics are measured off-line prior to the actual noise measurement. A major feature of the Maury software is that it does not require full-time utilization of a vector network analyzer (VNA); however, for the noise characterization to produce accurate results, these s-parameter measurements must be as accurate as possible.

Some practices which can help the user achieve the required accuracy are outlined below.

a) Exercise the connector considerations detailed earlier.

b) Use the synthesized, stepped measurement mode of the VNA.

c) Avoid short cutting the VNA calibration process and do a full two-port calibration. A simple response calibration, while faster, is not sufficiently accurate for noise characterization.

d) Another shortcut often employed, and to be avoided, is the use of a fixed termination even at the higher microwave frequencies. Use a high quality, metrology grade sliding load, as provided in Maury high precision calibration kits, for the one-port segments of the full calibration in the appropriate frequency bands. Fixed loads should only be used below 2 GHz.

e) A corollary to the preceding paragraph is to use the best calibration standards available. If possible, use a calibration kit in which the constants of the standards have been specifically characterized rather than use the nominal constants.

f) If attenuation is used to reduce the VNA output level, make certain the instrument is calibrated with that attenuation in place.

Tuner Characterization

Because of the importance to measurement accuracy, measurement of the tuner S-parameters is discussed later in a separate section.

DUT and In-Circuit Thru S-parameters

The S-parameters of each DUT and the in-circuit thru used for the second stage noise calibration must be measured prior to the noise characterization. The thru need only be measured once for any series of measurements, and, as long as it is not bent or distorted, the data will remain valid for long periods of time, typically months.

The DUT and thru S-parameters are measured on an off-line VNA using a stand-alone program called SPARA. The program is part of the MT989A noise characterization software and is available from the MSEE menu.

Test Fixture

A major criterion for accuracy is that these measurements must be made using the same test fixture as that used for the actual noise characterization.

Device Alignment

Another factor that often improves measurement consistency and accuracy is consistent alignment of the devices in the test fixture. The dimensional tolerances on semiconductor packages are such that some movement within the fixture is often possible. In such instances, it is good practice to butt the device against two sides of the fixture (e.g.: down and left) for the S-parameter measurement and use the same alignment during the noise measurements.

The same considerations hold true for the in-circuit thru; however, due to the design of the longitudinal slot in the Maury MT850 series test fixture, simply sliding the thru all the way to one side will align it in two dimensions.

DUT Linearity

The primary application of noise characterization is the measurement of small signal devices. Quite often this consideration is overlooked during the S-parameter measurements, and the VNA output is set to a level that drives the DUT into the nonlinear region. The result is invalid S-parameter data and inaccurate noise characterization.

If the linear input power level range of the DUT is unknown, the Maury MT988A load/source pull software can be used in the power sweep mode to determine the maximum input power at which the device becomes nonlinear.

It is imperative that the VNA output level be attenuated so that the DUT is operated in the linear region. Equally as important is that the VNA be calibrated with the attenuation in place.

TUNER CHARACTERIZATION

General

The tuner S-parameters are measured using the tuner characterization module resident in the noise characterization software. Typically, 50 to 100 sets of four parameters (S11, S12, S21, and S22) are required at each measurement frequency.

The tuners must be characterized with the bias network connected. All references to tuner characterization should be interpreted to mean the tuner plus the appropriate bias network.

Characterization Frequencies

The noise characterization frequencies must be a subset of the tuner characterization frequencies. This should be a consideration when setting up the frequency conditions for a tuner characterization since the tuner S-parameters are very stable with time and need not be measured for every measurement setup. If the tuners are not mishandled, a tuner characterization can remain valid for many months.

Characterization Mode

The software allows both manual and automatic characterization. In a manual characterization the user moves the tuner to specific points. In the automatic mode the user simply specifies the position ranges and number of steps. The manual method has the advantage of providing specific source impedances for the DUT, while the automatic mode is more convenient and can operate unattended.

Source Impedance Distribution

When automatic tuner characterization is selected, it is good practice to review the impedance plane plots of the source reflection coefficients available at each frequency before an actual noise characterization to insure a good distribution of source impedances.

The typical distribution resulting from an automatic characterization will consist of a series of spokes on the impedance chart. Each spoke represents a slide (linear) position of the tuner. The spokes are made up of a number of impedance points representing each probe position.

The reflection coefficient magnitude versus probe position is a nonlinear and often non-monotonic function. Because of this, there will often be a cluster of two or three points near the outer end of each spoke. This condition will almost always can lead to inconsistent results if the software selects impedances from among such groupings since they are not sufficiently removed from each other to provide unique, independent conditions for the calculation of the noise parameters.

This condition can be avoided quite easily as described in the following section.

Modifying the Distribution — Scan Positions

The MT989A noise characterization software incorporates what is referred to as a Scan Positions mode.

The Scan Positions mode is an active noise figure measurement mode which requires a second stage noise calibration be performed first. The display in this mode consists of impedance plane plots of the source and load tuner available impedances at a single frequency. The primary purpose of this mode is to allow the user to select specific source and load impedances and measure the noise figure of the DUT under those conditions.

Another function of the Scan Positions mode is to prevent specific impedance points from being used in the measurement. The primary purpose is to eliminate those that may cause instability of the DUT. Points deleted in this mode are not removed from the tuner characterization file; however, they are made unavailable for use during the measurement. The Scan Positions mode can also be used to restore previously deleted points.

This mode may also be used to delete the point clusters at the end of each spoke referred to above. When the point selection for automatic tuner characterization recommended in the manual is used, it has been found that deletion of the second and third points from the end of each spoke (on a spoke which includes five or six points) improves the measurement accuracy and repeatability.

NOISE MEASUREMENT RECEIVER

General

The noise measurement receiver is the term used here to describe the microwave downconverter and noise figure meter which provide the noise power readouts for the noise characterization. Although these are ancillary to the Maury **ATS**, they are a critical part of the system and can have a significant impact on accuracy.

Second Stage Noise — Measurement Accuracy

The noise characterization software uses the standard cascade noise figure relation to correct the measured noise figure for the effects of the measurement system noise and extract the noise figure of the DUT alone. It is often thought, therefore, that the magnitude of the noise measurement receiver noise figure has little or no bearing on the measurement. Quite to the contrary, the second stage noise figure can have a seriously degrading effect on measurement accuracy.

Without going into great detail here, a large second stage noise figure will simplify the random uncertainties inherent in a noise measurement. In fact, the primary purpose in recommending a two tuner system is to maintain a reasonable second stage noise figure. Those readers interested in the theory underlying these statements are referred to Simpson and Pastori, "Using a Load Tuner to Improve the Accuracy of Noise Characterization", Automatic RF Techniques Group 33rd Conference Digest, June 1989. This paper shows that with a second stage noise figure greater than about 10 dB, the random uncertainties can easily exceed ±1 dB for a 1 dB measurement!

Considering that noise characterization is typically performed on small signal, low gain, low noise devices, it is almost mandatory that the noise measurement receiver noise figure be held below 10 dB, and for optimal results in broadband applications it should be less than 8 dB.

These considerations make it virtually mandatory to insert a low noise amplifier (LNA) ahead of the downconverter. This is particularly true if the setup includes a noise figure test set such as the Hewlett-Packard 8971B or 8971C which can exhibit a noise figure as large as 28 dB.

LNA Dynamic Range

Overkill is a frequent reaction to the prior statement This is especially true if the application is broadband — for example: 2 to 18 GHz. A typical, affordable amplifier operating over this frequency range would have a noise figure of about 8 dB — just in the desirable range. If the downconverter has a 25 dB noise figure, the cascade noise figure relation shows that a minimum of 25 dB gain is required to hold the overall second stage noise figure between 8 and 9 dB. A safety factor is usually added, and the gain would probably be specified at 30 dB.

Two factors are often overlooked in these considerations:

1) absolute noise power is directly proportional to noise bandwidth — something greater than 16 GHz in the example given;
2) noise power calculations are in terms of average power, but the instantaneous signal can exceed the average by large amounts over significant time intervals.

The noise power available at the output of a DUT with 1 dB noise figure and 20 dB gain over a 16 GHz bandwidth is about -51 dBm. This is approximated as follows:

-114	dBm	Thermal noise power in a 1 MHz bandwidth (290K)
+ 1	dB	Noise figure
+ 20	dB	Gain
+ 42	dB	10 Log (base 10) BW (in MHz)
- 51	dBm	Noise power available at the DUT output

With 30 dB gain in the LNA preceding the downconverter the LNA output stage is required to linearly handle -21 dBm average noise power. The typical amplifier will have a 1 dB compression specification of about +10 dBm, and on the surface, it appears that this arrangement should work.

What actually happens, however, is that a significant number of noise signal peaks will drive the amplifier nonlinear introducing measurement errors.

A practical rule-of-thumb is to hold the average noise power level about 40 dB below the 1 dB compression point.

Single Sideband versus Double Sideband

These terms refer to the method of down converting the microwave noise signal to an intermediate frequency (IF) within the range of the noise figure meter. In a noise measurement, where the RF signal is broadband, a simple non-preselected mixer will convert both noise sidebands surrounding the LO to the IF. This is referred to as a double sideband measurement. If a preselector is inserted ahead of the mixer to eliminate one of the sidebands, the measurement is single sideband.

Since the introduction of the Hewlett-Packard 8971B noise figure test set and the Eaton 2160 frequency extender a few years ago, a considerable amount has been written about the benefits of single sideband over double sideband measurements. Theoretically, single sideband will be more accurate than double sideband; however, in a practical implementation of single sideband using the type of instruments noted above (including the recently introduced HP8971C), there may be little to choose between the two methods other than cost.

These instruments utilize a YIG preselector ahead of the mixer to remove one sideband from the conversion process. The preselector is required to track a synthesized LO. If the tracking is not perfect (and it is not), a tracking repeatability uncertainty is introduced into the measurement.

The net result is that any gain in accuracy due to the removal of one sideband is usually offset by the tracking error. This is illustrated by a comparison of the noise figure instrumentation uncertainty of a noise figure meter with and without a preselected test set. The HP8970B noise figure meter is rated at ±0.1 dB. When the 8971C test set is added, the uncertainty increases to ±0.2 dB plus typical drift of ±0.015 dB/deg C.

The decision whether to use a simple double sideband LNA/mixer downconverter or more expensive single sideband conversion is a function of the particular setup and the characteristics of the DUT. If the ripple in the DUT noise passband is small, and the IF is low (typically 10 to 100 MHz), the deviation between single and double sideband measurements will be insignificant — typically less than ±0.1 dB. This condition is aided by the broad frequency response of a single probe in a slide screw tuner such as the Maury MT980 series. Other types of tuners with sharp responses will not provide such good correlation between single and double sideband measurements.

If the DUT exhibits severe and rapid noise passband changes within the measurement frequency range, or if the tuner response is narrow band, then single sideband may be required and worth the additional expense.

Local Oscillator Considerations

Although the Maury MT989A software supports two swept signal sources (the HP8350 and Wiltron 6600), it is recommended that the LO used for the down conversion process be a low noise synthesizer such as the HP8672 or 8340/41. The use of a sweeper could introduce a tracking uncertainty into the measurement similar to that described above.

The noise on the LO signal is also a consideration. This noise will contribute to the second stage noise figure. The primary concern is the noise at a frequency offset from the LO signal by the IF - what is generally referred to as the floor noise of the signal source. The synthesized sources supported by the Maury software typically exhibit a noise floor in the order of -130 dBc in a 1 Hz bandwidth. This has been found to be an acceptable level. Significant increases (10 to 20 dB) will have some effect on the second stage noise figure which may or may not be important depending upon the noise figure and gain of the LNA preceding the mixer.

Spurious Signals

Harmonic and sub-harmonic signals generated by the LO are not generally troublesome to the measurement. Non-harmonically related spurious ("walk through spurs") could be a problem at specific frequencies. If such a spur is located at a frequency offset from the local oscillator by the IF, the apparent second stage noise will increase, perhaps sufficiently to completely mask the noise of the DUT.

Typically, these spurs, generated by the synthesis process, wilt be -50 to -90 dBc depending upon the make and model of the signal source and the operating frequency. With +10 dBm LO drive a spur could be at 40 dB m. At just the right frequency the spur will be converted to the IF and so mask the measurement noise signal as to prevent its detection.

Should this condition exist, it will be evidenced by a very large increase in second stage noise figure (perhaps infinite) at just one or two frequencies during the second stage calibration procedure.

The only solutions, should this occur, is to change signal sources or avoid those frequencies.

DEVICE STABILITY

General

A mismatched, active semiconductor device has the potential to break into oscillations. There are several possible causes for such instability. At low frequencies, a device designed for microwave use will generally be inherently unstable as evidenced by a k-factor (stability factor) less than unity and can oscillate at some source and/or load impedances. Certain bias conditions such as bias supply impedance can also cause a device to break into oscillation.

The measured noise parameters will usually provide some indication of device oscillations. The most typical clue is the failure of the software to find a math solution at a particular frequency. Another is a patently improbable result, for example: a negative minimum noise figure or a huge positive number.

Detecting Device Oscillations

If device oscillations are suspected, a simple, expedient method of detection (if the oscillations are within the measurement frequency range) is to connect a low frequency spectrum analyzer to the IF output port on the noise figure meter.

If a device is behaving properly, the analyzer display will be a smooth representation of the noise figure meter noise passband with no breaks, discontinuities, or sudden slope changes. Typically, the passband will about 4 to 5 MHz wide centered at the IF of the noise figure meter (20 MHz for the HP8970B, 30 MHz for the Eaton 2075B).

A single spike projecting up from the passband is usually evidence of a bias oscillation. This condition is external to the noise measurement system and can only be eliminated by improving the filtering on the bias networks or changing the bias supply.

A complete breakup of the passband is evidence of a microwave oscillation caused by a source/load impedance in the unstable region for the particular DUT at a specific frequency. This situation can be avoided by going to the Scan Positions mode while observing the passband and deleting those tuner positions that cause the display to break up.

In general, even if the oscillation frequency is outside the measurement range, the noise passband as displayed on the spectrum analyzer will be affected due to the change in the device operating point. Some users have reported that one means of detecting off-frequency oscillations is to monitor the gate and drain currents and watch for sudden changes.

CONCLUSIONS AND SUMMARY

Noise characterization is probably one of the most, if not the most, complex microwave measurements attempted in either a laboratory or production environment. The importance of noise parameters to the small signal amplifier designer, however, dictates its need.

The measurement encompasses virtually all the subdisciplines of microwave measurement technology, and, for this reason, consistent accurate results can be obtained only with the intelligent application of sound, practical microwave measurement techniques and practices.

This document is a compilation of some of the more subtle problems that may occur and their solutions - many of which, as noted, are simply application of sound practice.

As complex as the measurement is theoretically, experience has shown that accurate, precise results can easily be obtained with field-proven Maury **ATS**.

William E. Pastori
Maury Microwave Corporation
Ontario, California

Gary R. Simpson
Maury Microwave Corporation
Ontario, California

Reprinted With Minor Corrections
May 1990