Harmonics Measurements

Scorpion™

Application Note

Swept Vector Harmonic Measurements
Using a VNMS

Introduction

Harmonic measurements have long been used to characterize a device-under-test's (DUT) non-linearity and have traditionally been measured with a synthesizer and a spectrum analyzer. A potentially faster, more integrated, and more flexible solution is to measure the DUT's harmonics on a Vector Network Measurement System (VNMS). This application is intended to enable the measurement of a device's harmonics on a MS462xx over a possibly large dynamic range (up to 60 dB or more in some cases) with a number of measurement options. There are two modes of operation to allow maximum flexibility: a CW mode (for a display similar to that of a spectrum analyzer) and a swept mode where both the source fundamental and the receiver (tuned to a harmonic) are swept. In addition, there are three calibration states. A scalar state in which the only possible calibration is for absolute power level, an enhanced calibrated state where source effects are vectorially removed, and a phase calibrated state where rudimentary harmonic phase measurements can be made.

CW RCVR vs. Swept Measurements

The distinction between these two modes is quite straightforward. In CW RCVR mode, the source is kept at a fixed frequency while the receiver is swept over the various integral harmonics of that signal. Only scalar measurements are permitted in this mode meaning that only receiver calibrations (establishing a power reference) can be performed. This mode can be helpful for quickly assessing the overall relative harmonic performance of a DUT.

Swept measurements (termed SOURCE mode in the menus), on the other hand, involve sweeping the source fundamental over some range [f_1,f_2] while the receiver sweeps over a harmonic of that frequency range [nf_1,nf_2] (which must be in the range of the instrument; n=1,…,9). Only one harmonic can be examined per channel but different channels can be used to measure different harmonics. When in this mode, all calibration states are available and are discussed in the following sections.

"Uncalibrated" Measurements

A significant percentage of measurements will fall into this category where the harmonic levels are relatively high (–30 to –40 dBc or higher). If absolute harmonic level measurements are desired (in dBm instead of dBc), a receiver cal, discussed in the MS462xx Operation Manual, is available to establish the necessary reference.

Examples of measurements in this state are shown below for both CW RCVR and SOURCE swept modes.

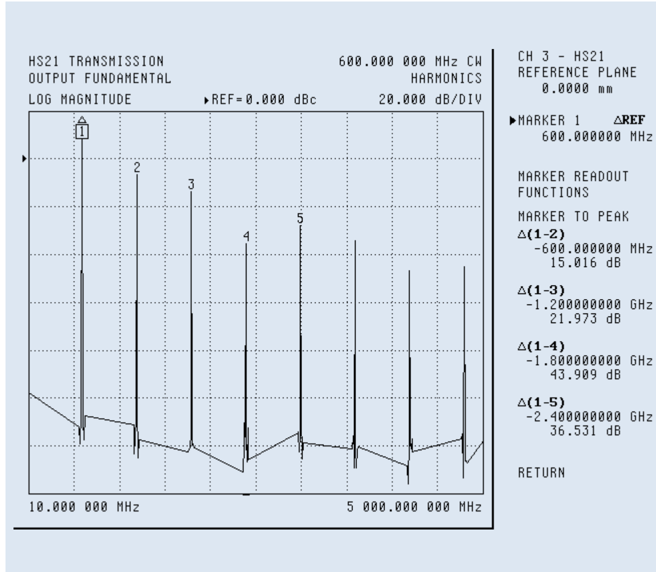

***Figure 1**. A plot in CW RCVR mode of the harmonics of a sample amplifier. The relative harmonic levels are displayed via marker reference. The source in this case is at 600 MHz and the first 8 harmonics are displayed.*

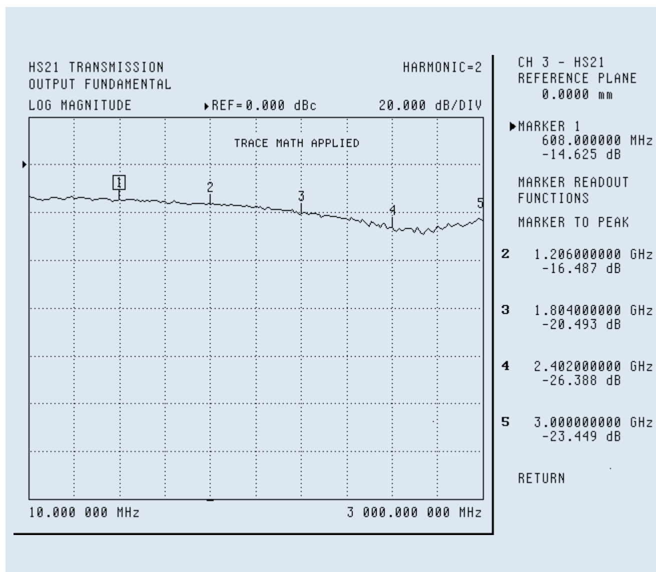

***Figure 2.** The 2nd harmonic of a sample amplifier in SOURCE swept mode. The trace data is divided by a normalization (obtained with harmonic = 1) so the displayed values are relative to the fundamental. Note that the reference level will always be labeled "dBc" with an absolute power reference, a reference to the fundamental carrier, or no reference at all. The user must interpret the displayed values as appropriate.*

The steps required to make measurements like the examples in Figures 1-2 are summarized below.

1. Enter the harmonics measurement application. Select either SOURCE or CW RCVR sweep mode. Select the 1,2 port pair combination.
2. Set the source power appropriately (0 dBm for these examples).
3. If performing a SOURCE swept measurement, enter a harmonic number of 2 (for Figure 2) under Harmonic Setup. One may select Display output relative to OUTPUT FUNDAMENTAL although it has no effect during uncalibrated measurements.
4. Also if performing a SOURCE swept measurement, select the desired start and stop frequencies for the fundamental sweep (10-3000 MHz here). If true relative harmonic measurements are desired, first store a trace with harmonic= 1 (using trace memory) then select trace math (/) and switch back to harmonic= 2.
5. If performing a CW RCVR measurement, enter the CW frequency on the frequency control menu (600 MHz for Figure 1). This establishes the source frequency. The start and stop frequencies determine the receiver sweep range and hence how many harmonics may be observed (10-5000 MHz for Figure 1).
6. Since trace math normalization was performed for the SOURCE measurements, markers will read directly in dBc (relative to the fundamental). In CW RCVR mode, one may use delta markers to accomplish the same task without performing a normalization.

Initial Measurements

Several general points about the harmonic measurement application can be gleaned from these simple initial measurements:

- The CW receiver mode will sample several points around the fundamental and its harmonics (up through 9th currently). Because of the way data is displayed, this leads to straight-line segments connecting the data groups. In the case of first or last point anomalies on the screen, it is possible that a spurious receiver response has been intercepted [see IMD application note]. This cosmetic defect can be removed by slightly changing the start and/or stop frequencies (since this will not affect the harmonics being displayed).
- In SOURCE swept mode, the horizontal axis is ALWAYS in terms of the fundamental frequency.
- In swept mode, the system will not stop the user from examining invalid receiver frequencies. As an example, consider a MS4623 model (6 GHz machine) set to examine the 3rd harmonic. While fundamental frequencies must remain below 2 GHz (3 x 2 GHz= 6 GHz) to be valid, the user may set the frequency limit all the way up to 6 GHz. For invalid frequencies, meaningless data will be displayed.
- Presently only harmonics up through the 9th are available in either mode. The presence or absence of a receiver cal does not affect this availability.
- Harmonic mode only works between pairs of ports (either between 1 and 2, or between 1 and 3). Mixer measurements are not allowed within the application although they can be performed in Transmit/Receive mode using multiple source control. The four S-parameters associated with a given port pair are all available.
- The harmonics shown in the examples are of relatively high level. If the desired harmonic levels start to be on the order of source harmonics (2nd as high as –30 to –40 dBc, others lower) then errors can result. Uncalibrated harmonic measurement specifications are limited to the case when source power is < –10 dBm since source harmonics tend to be smaller at lower power levels. If this is believed to be an issue, consider an enhancement calibration state discussed in the next section or use an external synthesizer (with lower harmonics presumably) as the signal source. If the latter approach is chosen, multiple source control can be used to simplify the measurement.
- Do not overload the receiver. In order to avoid receiver-generated harmonics, keep receive-port levels below +10 dBm.
- Note that the labeled parameter is "HS21" in the plots of Figures 1-2. All of the measurement parameters in this application have an H appended to the front to remind the user that definition may be different from that of the traditional S-parameter. When uncalibrated, the displayed variable is actually the unratioed test channel ($b_2/1$ instead of b_2/a_1 in this case) since no reference signal is used. When the Enhancement cal is applied, the parameter is ratioed (b_2/a_1 in this case). In both calibration states, the parameter is measured at the harmonic frequency.

Enhancement Calibrations

The enhancement calibration is designed to remove some of the effects of source harmonics in relatively linear measurements. Suppose that an amplifier is being measured in a sufficiently linear mode that most superposition rules still apply (primarily the assumption is that the source harmonics do not noticeably affect the DUT's operating point). Upon excitation by a source with some harmonic content, the output at the harmonic frequency is a vector sum of the DUT's self-generated harmonic and the source harmonic passed through the DUT linearly. See the illustration in Figure 3.

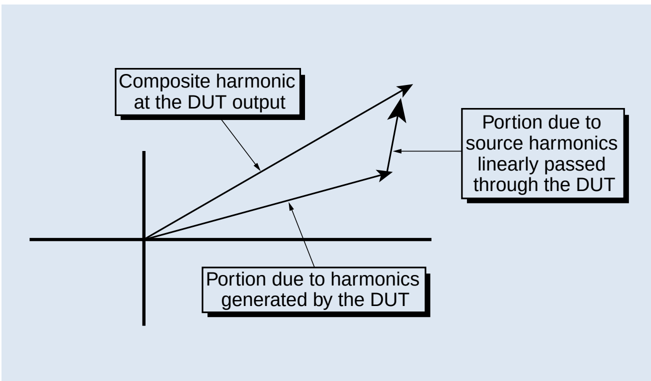

***Figure 3**. An illustration of the composition of the harmonic signal at the DUT output assuming the source harmonics are not so large as to affect the DUT's operating state.*

The vector sum is what is measured directly (uncalibrated mode) while the DUT harmonic term is usually the value that is of interest. Assuming the system has vector knowledge of the source harmonics and the DUT's linear performance, the vector addition can be undone thus revealing a better picture of the DUT's actual harmonic generation. While this operation radically reduces the effect of source harmonics, it does not correct for other system non-ideal characteristics such as port match.

To see this effect, consider the harmonics measured with just a through line in place for the DUT. The result with an enhancement cal in place is shown in Figure 4. In the uncalibrated mode, the measurement floor would be in the –30 to –40 dBc range for the 2nd harmonic and somewhat lower for the third harmonic. This calibration and measurement were performed with 0 dBm source power and a 100 Hz IF BW. Note that the reference is with respect to the output fundamental as will be the case for the reference example plots.

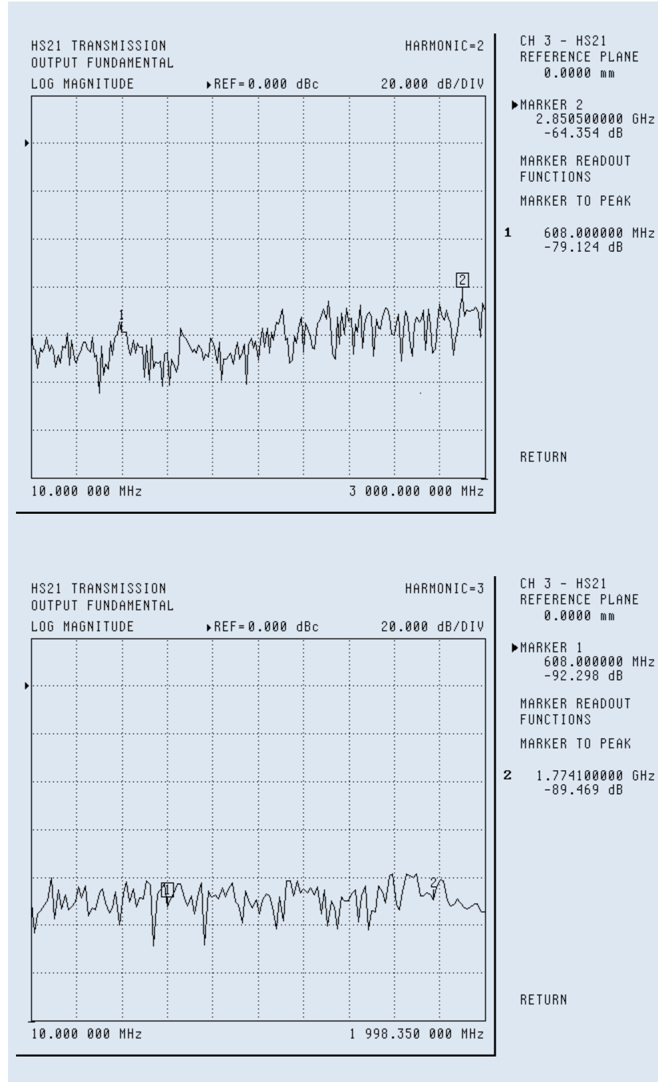

***Figure 4.** Example dynamic range plots under ENHANCEMENT cal for both 2nd and 3rd harmonics are shown here. The calibration and measurement power is +0 dBm. The measurement is performed with the same thru line in place as was used during the cal.*

A few remarks about the Enhancement calibration process can be made:

- The enhancement calibration is available only for the 2nd and 3rd harmonics. This limitation is due to a requirement for sufficient reference power to ensure that the vector calculations suffer from relatively low jitter. The calibration utilizes source harmonics to reference the computations and these must be sufficiently high to avoid excessive high level noise.

- The cal is strongly dependent on source power (since the source harmonics that are being removed are a strong function of source power). While no warning may be given, an enhancement cal should not be applied when the source power has changed. Note that it is acceptable to increase or decrease the step attenuator or add external pads since these steps do not affect source harmonics.
- As with T/R measurements, the noise floor will be dependent on IF BW. Since reference powers are lower when measuring harmonics (as compared to linear S-parameters), higher noise levels will be seen for the same IF BW than in the T/R application.
- Pay attention to the measurement reference whether it is relative to source harmonic, source fundamental, or output fundamental. Output fundamental is the most common selection since that is how amplifiers and other DUTs are normally specified. A source fundamental selection will cause the results to be input-referred.
- The cal simultaneously covers both 2nd and 3rd harmonics and all 4 S-parameters associated with the selected port pair.

An example amplifier measurement is shown in Figure 5. The cal and measurement were performed at 0 dBm source power. The particular amplifier has about 12 dB of small signal gain and an output-referred 1 dB compression point of about 13 dBm. The amplifier output was padded with 6 dB to avoid receiver non-linearity effects.

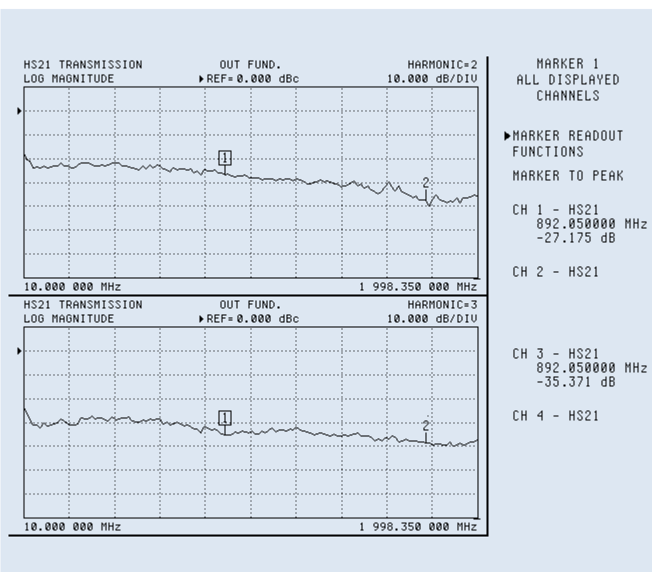

Figure 5. *A two channel plot showing the 2nd and 3rd relative harmonic levels of an amplifier using the ENHANCEMENT calibration state. The cal and measurement were performed with a source power of +0 dBm and the amplifier output was padded to avoid receiver compression.*

The steps to make the enhanced measurement in Figure 5 can be summarized as follows:

1. Set the frequency and power range as necessary (10-3000 MHz, 0 dBm). In the harmonic measurement application, select SOURCE swept mode, port 1-2 pairing, and display output relative to output fundamental.
2. Perform the Enhancement cal. This will involve connecting a thru line between ports 1 and 2 and later shorts on both ports. It may be desirable to reduce the IFBW during the cal in some cases.
3. Connect the DUT and apply bias. For this display of Figure 5, dual channel mode was used with channel 1 set to harmonic= 2 and channel 3 to harmonic= 3. The frequency range was reduced to about 2 GHz since the data above that frequency is meaningless for harmonic= 3.

Phase Calibration

In some applications, most notably with ultralinear power amplifiers and device modeling, knowledge of harmonic phase would be useful either for improved efficiencies or a better understanding of device physics. Since this cannot be easily done with an ordinary spectrum analyzer, this type of measurement is usually not performed. An additional cal is available in this instrument that builds upon the vector information obtained in the enhancement cal to obtain potentially useful phase data.

The measurement results from the enhancement cal include phase data relative to the source harmonic. While perhaps interesting, this is not particularly useful since the system cannot know *a priori* the phase relationship of the source harmonic to the source fundamental or output fundamental. If this relationship could be established, then at least rudimentary harmonic phase information could be extracted.

To determine this relationship, a known waveform must be supplied to the receiver such that the harmonic phase differential can be computed on a frequency-by-frequency basis. While many options are possible, a self-biased shunt Schottky diode has been selected as a harmonic phase standard. When sufficient RF power is applied, the output waveform is basically a clipped sinusoid where the harmonic phase relationships are quite well-defined. When this waveform is sent to the receiver, the absolute source harmonic phases can then be computed to lead to a more interesting relative phase parameter.

Phase Calibration Continued

An example measurement (HS21, 3rd harmonic) of an amplifier is shown in Figure 6. The calibration and measurement was done at a source power of +5 dBm in this case. Such a measurement may be used to investigate/validate the non-linear model for the amplifier.

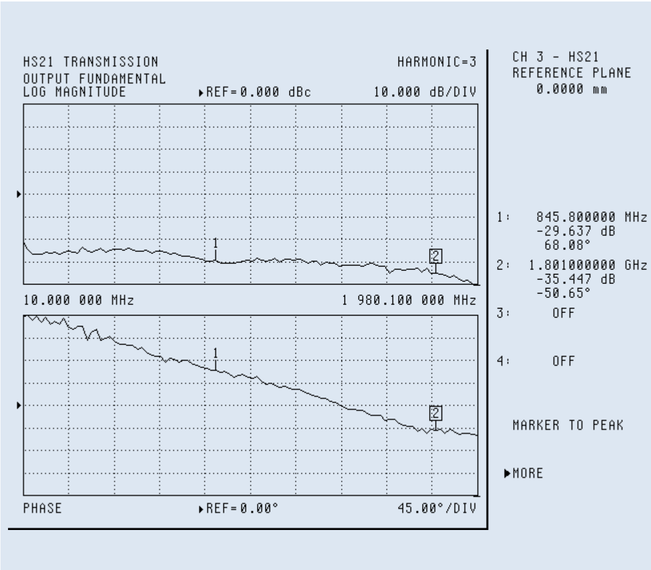

Figure 6. *The 3rd harmonic (magnitude and phase) of an example amplifier under fully calibrated conditions is shown here. This amplifier was driven with +5 dBm and had a 10 dB pad on the output to minimize non-linear receiver effects. A 10 Hz IFBW was used during measurement and calibration.*

The steps to obtain the data in Figure 6 are summarized below. Since the power level has changed from the previous figure, a new enhancement cal will be performed. If a valid enhancement cal already exists for the setup, that step could be omitted (just select PHASE CAL from the calibration menu).

1. Select the appropriate frequency range and power level (10-2000 MHz, +5 dBm). In the harmonic measurement application, keep the settings from before (Figure 5) and keep harmonic= 3. Select a magnitude & phase graph type, and a single channel display set for channel 3 (for this example).
2. Perform an ENHANCEMENT AND PHASE cal. For the enhancement portion, a thru line and shorts will again be used. For the phase cal portion, the harmonic phase standard must be placed (with a thru line) between ports 1 and 2. The position of the phase standard during this measurement establishes the reference plane.
3. Connect the DUT in the location of the phase standard. Apply bias and measure on the desired channel.

Accuracy and Uncertainty Issues

For the uncalibrated measurements, the uncertainty is that of relative power measurements of the receiver which is determined primarily by receiver linearity. This uncertainty will be comparable to that seen with a spectrum analyzer. The uncertainty will vary from between 0.5 and 1 dB for higher power levels to between 1 and 1.5 dB for lower levels (assuming an appropriate IF BW is selected for the level being measured). If an absolute power reference is established, that uncertainty will be determined by the power reference used. An ordinary ALC cal has a specified accuracy of 1 dB while it is typically better than 0.5 dB. If a flat power cal precedes the receiver cal, this added uncertainty will drop to below 0.1 dB typically. These values all assume the criteria of sufficiently high harmonic levels that source harmonics are not an issue.

The uncertainty during an Enhancement cal is available over a larger dynamic range because of source correction and over a larger range of source powers. The typical uncertainty is around 1 dB for harmonic levels sufficiently out of the noise floor (this is the specification for levels above –40 dBm).

Some Important Notes:

- Sufficient power must be applied to the harmonic phase standard to minimize jitter. While any source power will work to some degree, it is recommended that the calibrations be performed at 0 dBm or higher. Pads and/or step attenuator steps can be added during the measurement.
- The phase cal establishes an absolute phase reference plane at the location of the phase standard.
- The phase cal requires an enhancement cal and also applies only to 2nd and 3rd harmonics.
- The phase displayed, like the magnitude, is relative to the indicated variable (usually the output fundamental). If the “absolute” phase of the fundamental (relative to the phase standard) is required, it can be determined in T/R mode through the use of trace math.

SUMMARY

This application note has attempted to present the various modes and calibration states of the harmonic measurement application along with examples and tips on their operation. The harmonic measurement application is quite flexible and can be used to quickly measure large scale harmonics at one source frequency or measure (possibly vectorially) swept harmonics over an extended dynamic range depending on need.

To quickly summarize the various states and modes within the application:

CW RCVR Mode:

Fixed source frequency, receiver swept over one or more harmonics.
Use only uncalibrated (or with a receiver cal for an absolute power reference)

Swept Mode:

Source sweeping and receiver sweeping at one harmonic (per channel).
Use with any calibration state.

Uncalibrated State (or with receiver cal):

For quick harmonic measurements at higher levels
(–30 to –40 dBc or higher generally). Limited source power range to ensure accuracy.

Enhancement Calibration:

Vectorially removes source harmonic effects to extend dynamic range to as high as 60 or 70 dB.
Assumes the DUT does not change its operating point because of source harmonics.

Phase Calibration:

Builds on the enhancement cal to offer fundamental-referenced harmonic phase data.
Requires the use of the harmonic phase standard to establish internal phase relationships.

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