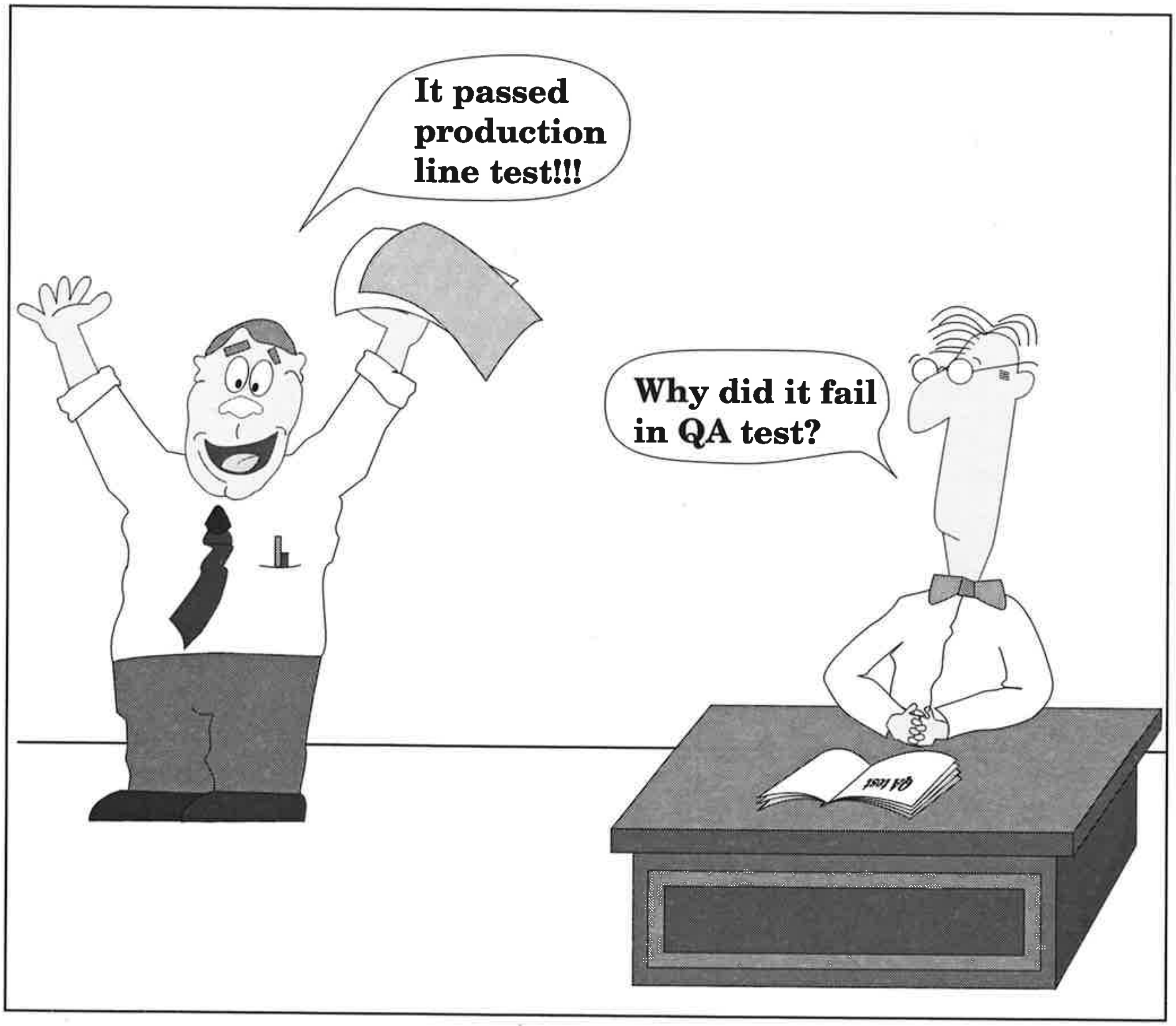
HEWLETT
PACKARD

Effective Spectrum Analysis Testing for Consumer Electronics Production Lines

Application Note 1301



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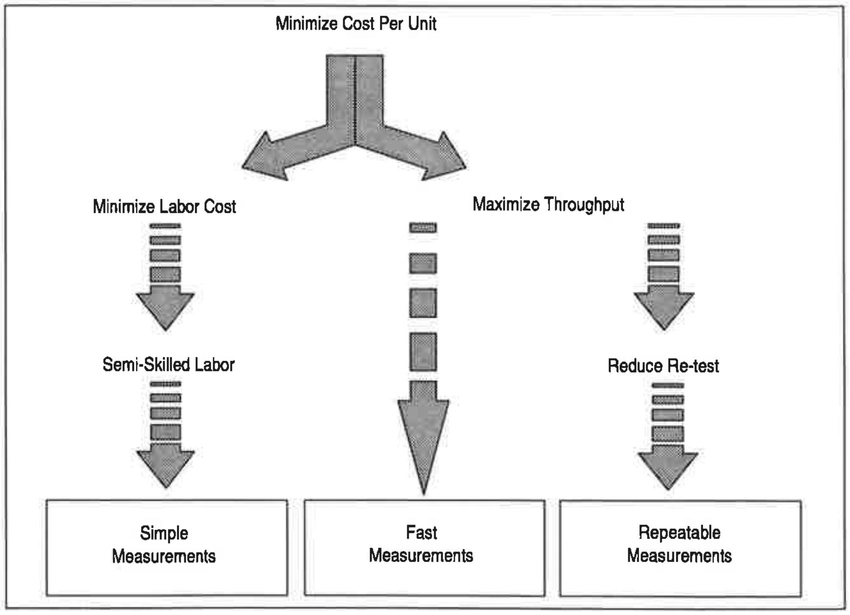
One of the primary challenges for today's consumer electronics manufacturers is to minimize the cost per unit and maximize throughput. Profit margins for consumer electronics are often very low so the manufacturing cost per unit and manufacturing throughput are both critical elements to profitability.

Typical products in this high-volume, low-cost market are fixed and mobile two-way radios, cellular phones, baby monitors, wireless speakers, TV tuners, TVs, cordless phones, and pagers. Typical components used in consumer electronics are amplifiers and filters for cellular phone systems.

Minimizing the cost per unit

Labor and equipment are two of manufacturer's biggest expenses. Manufacturers continually try to reduce the cost of labor while maximizing throughput. Since testing is one of the more costly processes for production lines, the effective use of test instruments (such as spectrum analyzers, network analyzers, signal sources, LCR meters, etc.) means that measurements can be made more quickly and less expensively.

Figure 1 Major ways to minimize the cost per unit



One way to minimize the labor cost is to use semi-skilled labor. This approach is often used in labor-intensive manufacturing (LIM). LIMs are those manufacturers who have chosen not to invest in capital-intensive automated test systems, and instead rely on many operators to assemble and test the products. The challenges for LIM production line test managers and engineers is to make testing procedures as easy as possible.

There are several effective ways to maximize throughput. One way is to reduce the time spent at each test station by making the instrument measurements as quickly as possible. Another is to reduce the need to re-test at different test stations by making repeatable and accurate measurements.

Although many different test instruments can be used on production lines, this article will focus on spectrum analysis applications. This paper will introduce how to simplify production line tests by fully using all of the features of the spectrum analyzer, how to maximize test throughput by understanding measurement speed, and how to reduce the need to re-test by improving the measurement repeatability. This paper will show how to make spectrum analysis tests in labor intensive manufacturing easier, faster, and more repeatable.

Minimize Labor Cost with Simple Measurements

A typical labor-intensive production line might be 30 to 50 meters long, with 20 to 40 positions. The production process begins with component level assembly, followed by tests or adjustments and more assembly until the product is complete. The products flow along the lines, then go through the final test. A quality control station is often set up to monitor the test process by sampling assembled products. At each station the operator performs one or two simple connections, adjustments, or measurements on the device under test (DUT). The operator focuses on the DUT's adjustments and tests, spending minimal time on test instrument operations.

For labor-intensive manufacturers, one of the challenges is to make the tests as easy as possible. In order to make each test easier, a distributed test strategy is often adopted. For example, several spectrum analyzers may be stationed along the production line. At each station, only one or two simple tests are performed. The operator needs to connect the DUT to the spectrum analyzer, push one or two buttons on the test instrument, and observe the display. Adjustments are then made to the DUT until the displayed trace is within a specified range. To make this easier, many manufacturers use grease pencils to draw a mask on the instrument screen. Then, the operator must compare the trace to the mask while making an adjustment.

This paper will highlight some of the features of spectrum analyzers that simplify measurements for the operator such as save/load, limit lines (pass/fail), marker functions, one-button test, automatic background alignment, and video output. Many of these useful features, formerly found only on high-performance, expensive instruments, are now available on low-cost units such as HP's ESA-L1500A.

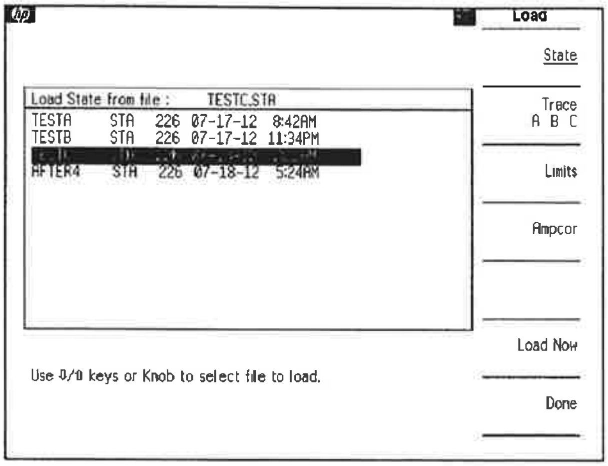
Features that make production line testing easier

Save/Load

One of the responsibilities of production line test engineers or technicians is to set up the instruments for the operators. With the spectrum analyzer's Save/Load function, the test engineers can set-up the instrument once and save the states. The operators just follow the process to load the test states for testing.

The spectrum analyzer settings such as center frequency, span, etc. can be saved by using the Save State function. States are saved in the spectrum analyzer's non-volatile memory. They are retained in memory even if the instrument is turned off or reset. Many modern spectrum analyzers allow the user to store states and traces with full alpha-numeric file names, much like a PC. For each test station, different file names can be used to save different settings (e.g.. TESTA, TESTB, etc.). It is quite easy to recall the instrument setting by following the key sequence: File = > Load = > State = > Select File = > Load Now = > Done, as shown in Figure 2.

Figure 2
Save/Load features



```
Load State from file :     TESTC.STA
TESTA      STA   226  07-17-12   8:42AM
TESTB      STA   226  07-17-12  11:34PM
[illegible]
AFTER4     STA   226  07-18-12   5:24AM
```

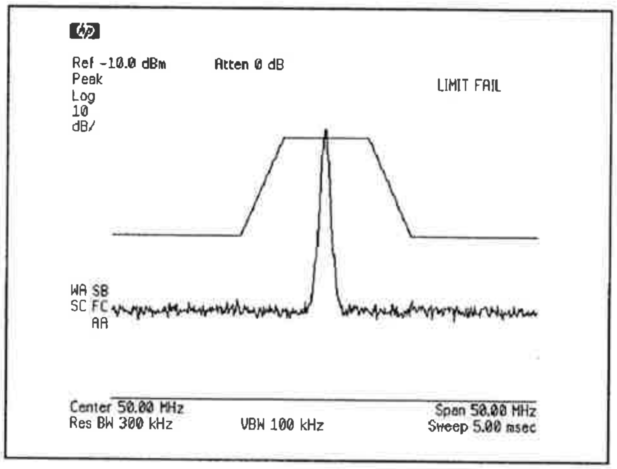
Use ⇩/⇧ keys or Knob to select file to load.

Limit Line (Pass/Fail)

Limit lines simplify amplitude measurements by simultaneously showing the measurement and the test limit. For example, in tuner manufacturing, a spectrum analyzer is used to measure image rejection. The operator will check if the tuner spurious response is below a specified level. By using the Limit-Line function, it is easy to compare trace data to a set of amplitude and frequency limits, while the spectrum analyzer is sweeping the measurement range. The Limit-Line function replaces the grease pencil mask and ensures more accurate test results. The operator can see the result immediately rather than have to examine the whole trace. Also, unlike the grease pencil approach, it is easy to change the limit for each product on the production line.

As shown in Figure 3, a limit line can be displayed on the screen. During every measurement sweep, the trace is compared to these limit lines. If the trace is at or within the bounds of the limit lines, LIMIT PASS is displayed. Otherwise, LIMIT FAIL will appear.

Figure 3
Typical Limit-Line Display



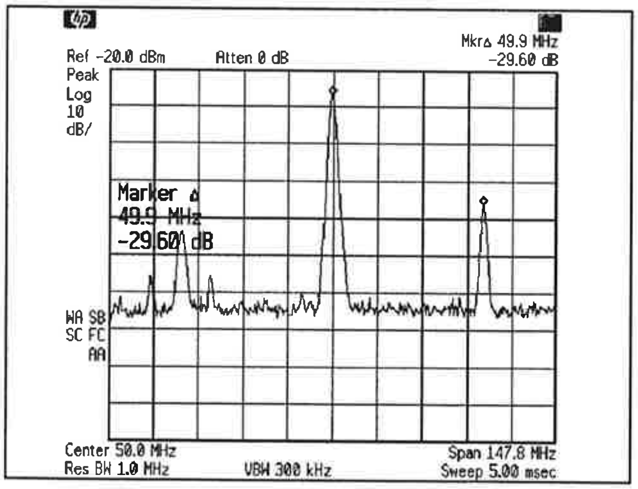
Markers

Basic marker functions

Modern spectrum analyzers have many marker functions. Instead of counting display divisions, the operators can read the test results easier and more accurately with the marker, avoiding potential errors.

Signal frequency and amplitude can be measured by using single marker. Peak search puts a marker on the largest signal displayed and the marker readout indicates the absolute frequency and amplitude of that signal. Delta markers can be used to compare two signals and display the frequency and amplitude difference (see Figure 4). Marker-to-minimum moves the active marker to the minimum detected amplitude value. Marker to peak-peak finds and displays the frequency and amplitude differences between the highest and lowest trace points.

Figure 4
Basic marker functions



Marker table

Sometimes it is necessary to keep track of several points on a signal trace. For example, in cordless phone manufacturing, the phone must be tested at high, medium, and low frequencies. Marker table can be used to make this job easier and accurate.

Using the Multiple markers feature, up to four markers may be placed on a trace. Using Marker table, all the markers on the display are annotated in a window below the trace. The information is updated after each sweep or whenever a marker is activated or updated. Each marker can be independently set to read frequency, time, or amplitude.

One-button tests

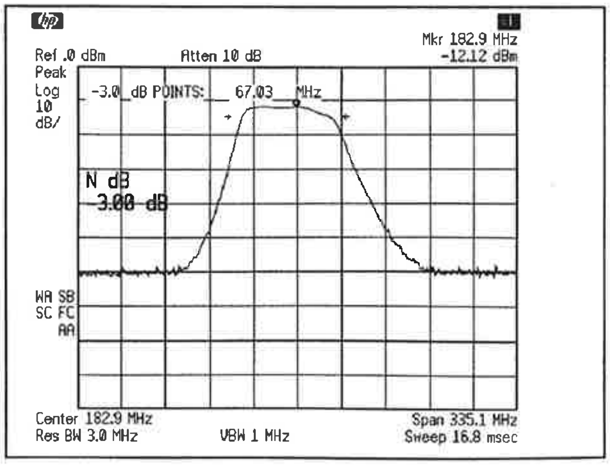
The spectrum analyzer's one-button test function simplifies the operation and increases the repeatability of the measurements by eliminating complicated set-up steps. Here are three one-button tests that address different test requirements.

N dB Bandwidth Measurement

It is often necessary to measure a signal or device bandwidth. For example, the N dB bandwidth function can be used to measure a signal bandwidth of a transmitter. When using the N dB bandwidth measurement, there are two things that need to be considered. First, the signal's bandwidth needs to be wider than the spectrum analyzer's RBW used for the measurement. Secondly, the signal to be measured needs to be relatively smooth. If the spectrum analyzer includes a tracking generator for scalar network analysis, the feature can be used to measure a filter's bandwidth.

In Figure 5, a bandpass filter is measured by using the HP ESA-L1500A with its tracking generator. When N dB Points is turned on, the instrument sets arrow markers at default –3 dB points on both sides of the response and indicates the bandwidth. Users may select in dB any point on the skirt of filter to measure bandwidth. In this example, the –3 dB bandwidth of the filter is 67.03 MHz.

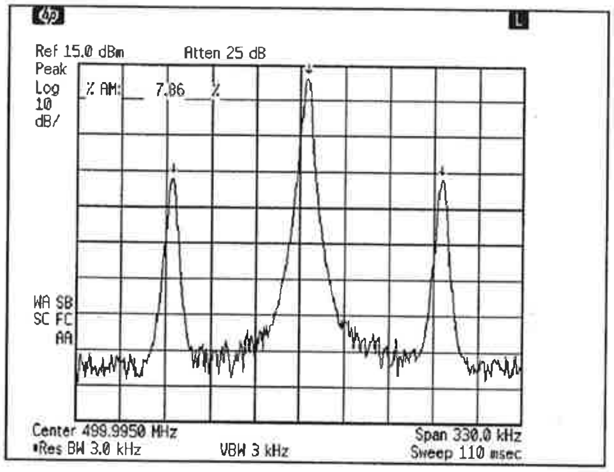
Figure 5
N dB Bandwidth Measurement



Percent AM Measurement

Modulation quality of an AM signal such as percent amplitude modulation can be measured quickly and easily using the one button percent AM function. As shown in Figure 6, the spectrum analyzer places arrow markers on the three signals used to compute percent amplitude modulation, and displays the measurement result in the upper left of the display.

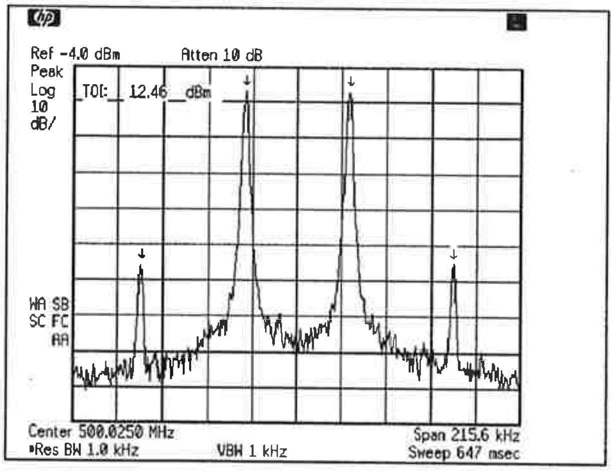
Figure 6
Percent AM Measurement



Third Order Intermodulation Measurement

In wireless communication systems, two-tone, third-order intermodulation distortion is a common specification. The third order intermodulation one-button measurement provides quick and easy intermodulation tests. As shown in Figure 7, when the two test signals and their two associated distortion products are present on the display, the user presses a single key and the spectrum analyzer computes and displays the third order intercept (TOI) of the displayed signals, marking all four signals with arrows to confirm the correct signal selection. The two test tones can be at different amplitudes. The measurement is updated at the end of every sweep, allowing real-time optimization of devices or systems under test.

Figure 7
Third-Order Intermodulation Measurement



Automatic background alignment

This feature offers continuous internal calibration between sweeps, eliminates the need for daily calibration, and ensures measurement accuracy over temperature. It does not interrupt the normal production flow because it works in the background without operator interaction.

To maintain the most accurate frequency and amplitude measurements, most spectrum analyzers provide a self calibration feature. The self-calibration routine updates correction factors used to minimize many systematic errors. Although most spectrum analyzers have a calibration signal and manual self-calibration routine, the self-calibration process may be time consuming and neglected by operators. The manual self-calibration may interrupt normal production. In addition, it requires the connection of a specific cable and disconnection of the DUT.

HP's new low cost spectrum analyzer ESA-L1500A has an automatic background alignment feature that performs the self-calibration. When Auto Align is turned on, the spectrum analyzer uses an internal alignment signal to auto align all the instrument circuits.

VGA output

Another way to make an operator's work easier is to use a large external display which can eliminate eye strain for those who work with the display constantly. With a large display, the operators can view and interpret test results easier and faster. This is especially helpful when tuning the DUT. In addition, this is useful for training new operators.

HP ESA-L1500A's VGA output allows you to connect the instrument to an external VGA color monitor and display test results on it.

Time Saving Features

Spectrum analyzer features such as Save/Load, Limit Lines, Markers, One-button test, Automatic background alignment, and VGA Output all help to make test procedures easier to set up for less skilled operators. These are all possible without sacrificing measurement accuracy.

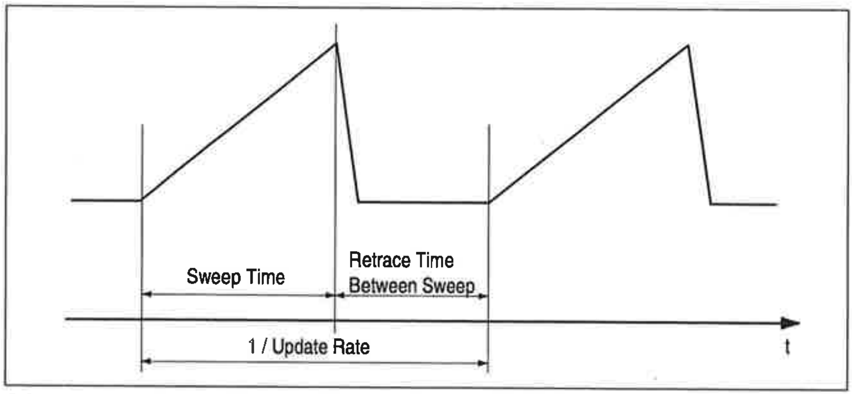
Maximize Throughput with Fast Measurements

Maximizing production line throughput is another major way to minimize the cost per unit. One way to speed up the production line test is to reduce the measurement time. It is important to understand measurement speed when purchasing and configuring a spectrum analyzer for production line test. In the following pages the elements of measurement speed will be introduced and defined.

Understanding measurement speed

As shown in Figure 8, every measurement of the spectrum analyzer consists of two parts: sweep, and retrace between sweeps.

Figure 8 Spectrum analyzer measurement speed



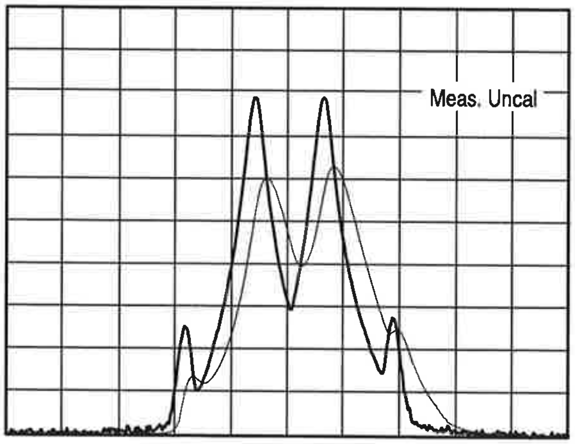
These, as well as "tune, zoom and transfer" time, which will be discussed shortly, are the main factors that affect measurement speed.

Sweep time

Measurement speed can be increased by reducing sweep time, but to choose the proper sweep time, we need to understand the factors that affect the measurement speed and accuracy.

Sweep time is primarily limited by the analog resolution bandwidth filters (IF filters). These IF filters are band-limited circuits that require finite times to charge and discharge. If the measurement is forced to sweep through the filters too quickly, there will be a loss of displayed amplitude and offset of the displayed frequency as shown in Figure 9. The measurement uncalibration message will be shown.

Figure 9 Penalty for sweeping too fast



Penalty For Sweeping Too Fast Is An Uncalibrated Display

The bandwidth of the IF filter is called the resolution bandwidth (RBW). The sweep time is ST. The measurement speed is Span/ST. Therefore, the time that signal stays in the IF filter passband is: RBW/[Span/ST].

On the other hand, the rise time of a filter is inversely proportional to its bandwidth. That is: Rise Time = k / (RBW), where k is a constant of proportionality.

To assure the output of the filter rise to the correct amplitude we need:

$$\text{time in passband} \geq \text{rise time:}$$
$$(\mathrm{RBW})/[(\mathrm{Span})/(\mathrm{ST})] \geq k/(\mathrm{RBW})$$

therefore, $\mathrm{ST} \geq k\,(\mathrm{Span})/(\mathrm{RBW})^2$

This equation shows that a change in resolution bandwidth dramatically affects the sweep time. For example, if the RBW is changed from 10 kHz to 1 kHz, the sweep time increases by a factor of 100. So for the shorter sweep time, a wider RBW would be selected. On the other hand, the RBW determines the analyzer's ability to separate closely spaced signals. As RBW is narrowed, selectivity is improved. At the same time, this will also often improve signal-to-noise ratio (SNR). It is quite important for the production line test engineers to select the widest possible resolution bandwidth for the best compromise between frequency resolution, SNR, and sweep time.

The HP ESA-L1500A has many RBWs to choose from by employing a 1,3,10 sequence to best optimize trade offs of sweep time, resolution, and sensitivity.

Besides the resolution bandwidth, many other factors such as the type of IF filter, the tuning technology and the hardware used in the spectrum analyzer could affect the sweep time. For very fast sweeps, the spectrum analyzer's local oscillator (LO) must be fast. In general, the spectrum analyzer keeps track of all the user setting and automatically chooses the best sweep time for accurate measurements.

The sweep time of modern spectrum analyzers such as the HP ESA-L1500A can be as low as 5 ms.

Retrace time between sweeps

Usually, when test instrument sweep speed is specified, only the shortest possible forward sweep time is indicated. Besides this sweep time, we must add the time it takes for the instrument to retrace. Total sweep speed, then, is the sum of sweep time plus retrace time.

The spectrum analyzer's tunable LO must be very fast during retrace to set up quickly for the next sweep. The instrument needs time to make sure that the LO is locked to a stable reference and tuned to the correct frequencies before and during a sweep. Depending on the sweep processes and the tuning technology used by the spectrum analyzer the time spent on retrace can differ dramatically.

The HP ESA-L1500A uses fractional-N synthesizer technology, which can be re-tuned very quickly. This results in very fast sweep times and very short retrace times.

As shown in Figure 8, by adding sweep time and retrace time the instrument update rate can be calculated. Retrace time is an important factor that greatly affects the measurement speed, but is often not on a product data sheet. The HP ESA-L1500A updates about 27 times per second (about the same as professional movie film speed), which allows you to view measurements practically in real-time.

Tune, zoom, and transfer time

For automatic test systems under computer control, we would also need to consider other factors. One simple automation example using spectrum analyzer is: tune, zoom, and transfer. The measurement time includes the instrument locating the signal and setting the center frequency of the analyzer (tune), reducing the span (zoom), sweeping the selected span and then sending the measured data to system controller. Since most labor intensive manufacturing does not use much automation, this type of automation feature is not a primary consideration. However, the HP ESA-L1500A has a very rich remote control language providing high speed and flexibility for production areas moving toward automated control.

In summary, there are two major factors that affect spectrum analyzer measurement speed; sweep time and retrace time between sweeps. The sweep time range can be found from the instrument data sheet. By setting up the appropriate resolution bandwidth and span of the spectrum analyzer, the sweep time, SNR, and resolution can be optimized. Retrace time may be more difficult to determine from the data sheet. However, it is important to evaluate the overall performance of a test instrument by considering all factors, not simply focusing on the sweep time specification. For automatic test systems, the other factors that take time for instrument operation need to be considered as well.

Maximize Throughput by Reducing Re-test

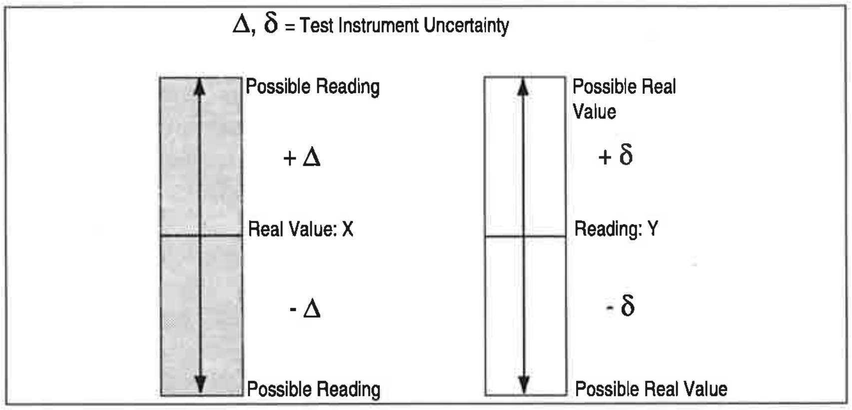
Besides measurement speed, another factor that affects production line throughput is the re-test due to test result inconsistencies. An annoying issue for test managers or engineers is that a unit might pass the production line test but fail the quality control test where higher performance test equipment is often used. Improving measurement accuracy and repeatability can reduce the need to re-test at different test stations.

Improving measurement repeatability

For any measurement there is always the possibility that the measurement does not represent the input signals' real value. More precise equipment reduces the measurement uncertainty by providing better accuracy and repeatability. However, this equipment is more expensive.

To illustrate the effect of measurement uncertainty, if the test instrument reading is Y, the possible real value of the DUT could be Y plus or minus the measurement uncertainty (Y ± d).

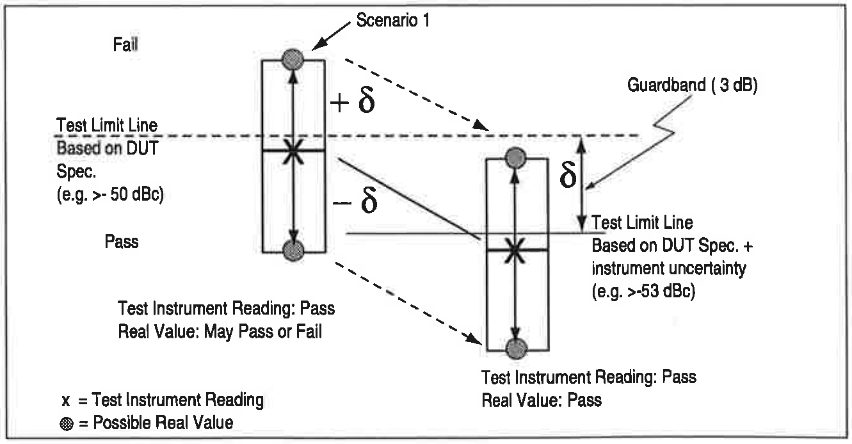
Figure 10
Measurement uncertainty



Let us analyze a typical production line test case. In this scenario, the DUT is tested one time for a specific measurement using a test instrument (such as a spectrum analyzer). We set up the test limit line on the test instrument based on the specification we are testing. Any DUT that tested above the limit line would fail and any DUT that tested below the limit line, would pass. Let us say the test instrument's uncertainty is ±3 dB.

There are two scenarios which can happen because of the measurement uncertainty of the test instrument. Scenario 1 (the worst for a manufacturer) is that the test instrument will pass a DUT which should fail because its real value does not meet the required specification. Scenario 2 is that the test instrument will fail a DUT whose real value actually does meet the specification.

Figure 11
Correcting the test instrument's uncertainty for a single test.



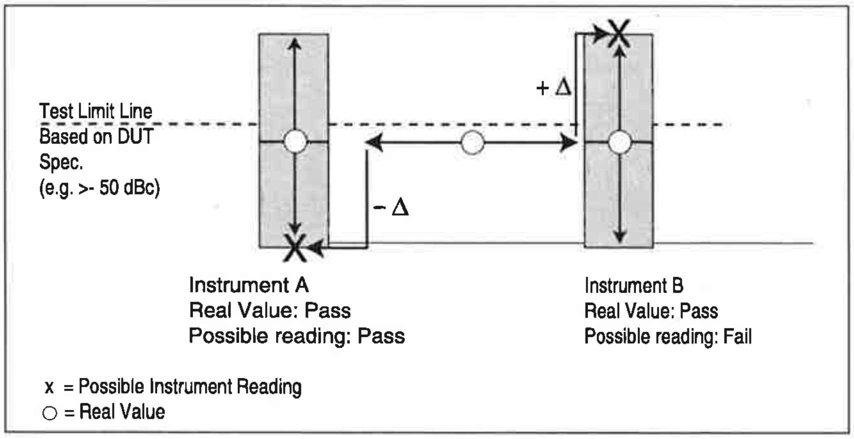
Scenario 1 Passing Bad Products (DUT's)

To avoid scenario 1 where we may pass bad products, we need to set up a guardband. This is shown on the right in Figure 11. In this case, based on the instrument's uncertainty (±3 dB), we set up a guardband that is equal to the minus uncertainty (in this case, 3 dB). Now, if the test result indicates that the DUT passes the new limit line (Test limit line with guardband), its real value will always pass the specification (as shown in Figure 11).

However, in production lines there is often more than one test station (e.g. production line test and quality control test). This means that in some cases we need to test the DUT at two different test stations. This is a "multiple tests" situation.

As shown in Figure 12, suppose the real value of the DUT is right below the test limit line (pass). If we use instrument A to test the DUT, the possible reading could be as shown by the X on the left of Figure 12, which is still pass. If we use instrument B to test the DUT at the second station, the possible reading could be as shown as the X on the right of Figure 12, which is fail.

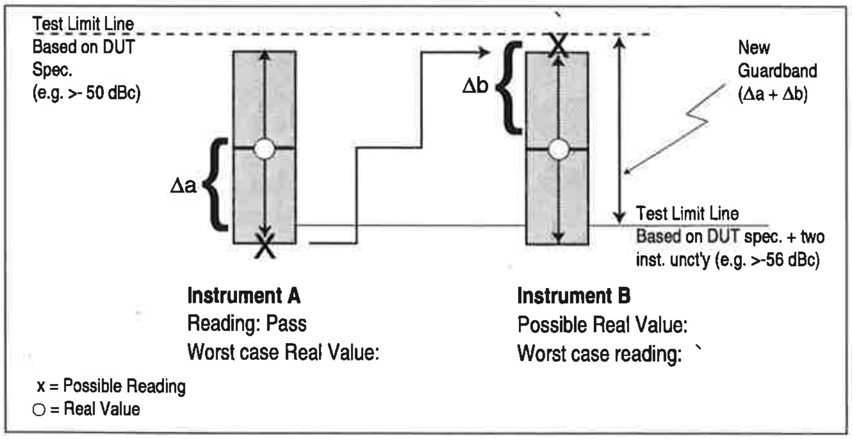
Figure 12 Analysis of test instrument's uncertainty when testing twice



To ensure that we will not pass a DUT at one station and fail at the other, we need to enlarge the guardband. As shown in Figure 13, **if the uncertainty of the instrument used at one station is Δa, and at the other station is Δb, then we need to set up a guardband of Δa+Δb for the first test and we do not use the guardband for the second test.**

Based on Figure 13, let us analyze this situation. For the first test, we use instrument A. Instrument A's reading passes the test limit line. The worst case real value of the DUT could be at dot 1. For the second test, we use instrument B. Here, the worst case test instrument reading could be at position 2, which still meets the DUT's specification. Therefore, for two test instruments with ±3 dB uncertainty, the new test limit line must be at –56 dBc.

Figure 13 Guardband to ensure the DUT passes multiple tests



Scenario 2 Failing Good Products (DUT's)

The downside of compensating for measurement uncertainty in a test instrument is that there is an increasing risk of failing good devices-under-test. In other words, the real value was within the pass range for the specification but the test instrument's reading was in the fail range.

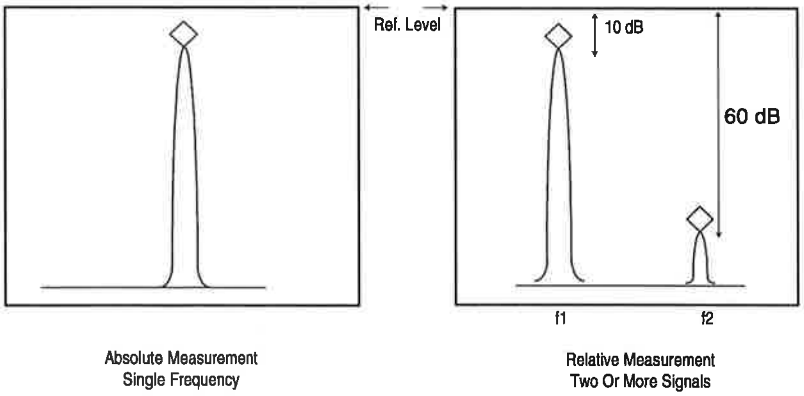
If the instrument uncertainty is small, the guardband will be small, meaning that there will be fewer Case II mistakes. (Remember, we are assuming that it is more important that the manufacturer never pass a failing device). The test engineer wants the guardband to be as small as possible so that all passing devices are correctly identified. Often this requires selecting more expensive equipment or more complicated test methods to get better measurement uncertainty.

To choose the correct guardbands and limit lines, we need to understand the uncertainties of each measurement. The following section will discuss the spectrum analyzer measurement uncertainties of amplitude, frequency, and distortion tests.

Calculating amplitude measurement uncertainty

Amplitude and frequency are the two basic parameters often measured when using spectrum analyzers on production lines. As shown in Figure 14, there are two kinds of measurements: absolute and relative. Absolute measures one signal. Relative measures compare the difference between two signals.

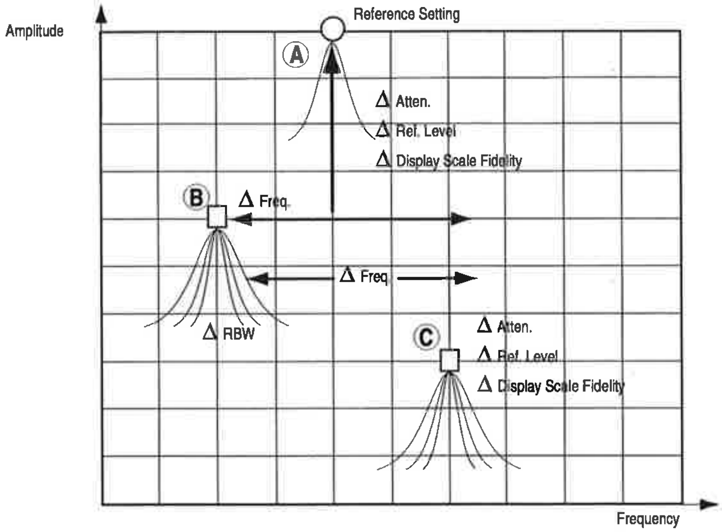
Figure 14
Absolute and relative measurements



The amplitude accuracy specifications for a spectrum analyzer include an absolute accuracy number (the absolute reference) at a single frequency and amplitude, and an absolute accuracy number for a specified instrument state (settings for the attenuation, IF and video BW, reference level setting, etc.). This specification applies only when making absolute amplitude measurements. The amplitude accuracy specifications also include a number of other factors that also may apply to an absolute measurement when the signal is not at the specified frequency and amplitude, and when the instrument is not at the specified state settings. These other amplitude accuracy factors may also apply to relative amplitude measurements.

By appropriately adding each contribution uncertainty to the absolute specification, we can calculate a new absolute specification for any measurement condition. An example is shown in Figure 15 where one point (point A) is the absolute reference. Taking the HP ESA-L1500A as an example, the reference setting of point A is: reference level –25 dBm; input attenuation 10 dB; center frequency 50 MHz; resolution bandwidth 3 kHz; video bandwidth 10 kHz; scale linear; span 2 kHz; sweep time coupled, sample detector, signal at the reference level.

Figure 15
Amplitude measurement uncertainty



Amplitude uncertainty factors are shown in Table 1. The process of calculating amplitude measurement uncertainty is discussed in the following paragraphs.

If we wish to determine the absolute accuracy at point B, we need to check the absolute associated factors listed in Table 1. Then we add the absolute accuracy at point A to the associated accuracy of the settings that have changed in moving from point A to point B. (e.g. item 2 to 7)

If we wish to determine the relative accuracy of point C relative to point B, we need to check the relative associated factors in Table 1. Then we add the relative accuracy of all factors that contribute to uncertainty in moving from point B to point C. The absolute accuracy of point A is not needed. (e.g. all items except 4)

Table 1 Amplitude uncertainty calculation check list

Item	Uncertainty factors	Apply to	Applicable
1	Band Switching	R	if signals are in different harmonic bands
2	Frequency Response	R	if signals' frequencies separation is large
		A	if the signal is not at reference setting
3	Res. BW Switching	R	if signals are measured with different RBW (no error when using same RBW)
		A	if the setting is not at reference setting
4	Absolute Amplitude Accuracy	A	always applied
5	Input Attenuation Switching	R	if two signals are measured with different input atten. (no error when using same input atten.)
		A	if the input attenuation setting is not at reference setting
6	Display Scale Fidelity	R	if signals are not placed at the reference level
		A	if signal is not at the reference level
7	Reference Level (IF Gain)	R	if signals are measured with different reference level (no error when using same ref. level)
		A	if the reference level is not at reference setting
8	Linear to Log Switching	R	if the display scale changed between linear and log
		A	if the measurement is in log scale

A: Absolute; R: Relative

Relative amplitude uncertainties

In a relative measurement, two amplitude measurements are either subtracted on a log scale or divided on a linear scale. When making these relative amplitude measurements, many uncertainty factors such as input mismatch, input attenuation switching, and resolution-bandwidth switching will cancel. This is because the error in both of the measurements is subtracted or divided out. Therefore relative measurements often have less uncertainty than absolute measurements.

A typical measurement requires measuring the amplitude difference between two signals that are displayed on a test instrument screen at the same time. In this case, we put a marker on each signal and read the delta marker amplitude. Since no settings are changed, the uncertainties of the linear to log switching, reference level, input attenuation, and resolution bandwidth (item 8,7,5,3 in Table 1), for example, can be ignored. In this measurement, only the display scale fidelity and frequency response errors contribute to the uncertainty. In addition, if the frequency separation is small, many people neglect the frequency response error in comparison to the display fidelity errors.

Display fidelity

Display fidelity includes log amplifier fidelity (accuracy of the logarithmic amplifier), detector linearity, and the linearity of the digitizing circuit. (Note: because marker data are taken from memory, the display itself does not contribute to uncertainty.)

Take the HP ESA-L1500A as an example. From the data sheet we can get the following specifications:

Display Scale Fidelity: the minimum of:
Log Maximum Cumulative (0 to –85 dB from ref. level):
±(0.3 dB + 0.01 x dB from ref. level)
or
Log Incremental Accuracy (0 to –70 dB from ref. level):
±0.4 dB/4 dB

The incremental specification gives the best uncertainty when the two signals are close to each other in amplitude. The cumulative specification gives the best uncertainty when the two signals are far from each other in amplitude. In addition, signals are most accurate near the reference level.

Frequency response
The spectrum analyzer's input connector, input attenuator, preselector, front-end mixer, and internal cabling all contribute to instrument frequency response. The input attenuator consists of several switched pads and connections. With different combinations, 0 to 60 dB of attenuation can be used. A different connection path could lead to a different frequency response.

For the HP ESA-L1500A, the frequency response (10 dB input attenuation) specification is:
Relative to 50 MHz : ±1.0 dB.

Since there are two signals and each one has ±1.0 dB uncertainty, the worst case for the uncertainty of the delta marker is
2x ±1 dB = ±2 dB.

Example
Let's look at the graph on the right in Figure 14 again. For this example, using Table 1 we find that items 1,3,5,7,8 will not contribute to the uncertainty calculation. Only items 2 and 6 need to be taken into account. Using the specifications for the HP ESA-L1500A:

Frequency response uncertainty is: ±2.0 dB;

Log Maximum Cumulative for f1 is:
±(0.3 dB + 0.01 x 10 dB freq. ref. level) = ±0.4 dB;
Log Maximum Cumulative for f2 is:
±(0.3 dB + 0.01 x 60 dB freq. ref. level) = ±0.9 dB
So the total uncertainty due to Log Max. cumulative is
±(0.4 + 0.9) = ±1.3 dB

Log Incremental accuracy is ±0.4 dB/4 dB x (60 – 10) = ±5 dB.

Take the smaller one of Log Maximum Cumulative and Log Incremental, that is 1.3 dB.

The total uncertainty is : ±(frequency response uncertainty
+ total uncertainty due to Log Max cumulative)
= ±(2.0 + 1.3) = ±3.3 dB.

If the measurement uncertainty is too large, it can degrade the production yield. This means that the number of good products which fail manufacturing test is large. Fortunately there are several ways to reduce this uncertainty.

1) Lower the reference level to the signal (f1) level because measurements are most accurate near the reference level.
Now the uncertainty is*:
Log Maximum Cumulative for f1 is not applicable
Log Maximum Cumulative for f2 is: ±(0.3 dB + 0.01 x 50 dB fr. ref. level) = ±0.8 dB
So the total uncertainty due to Log Max cumulative is ±(0.0 + 0.8) = ±0.8 dB.
The frequency response uncertainty is: ±2.0 dB
The total uncertainty = ±(2.0 + 0.8) = ±2.8 dB

2) Use room temperature specifications wherever possible. The HP ESA-L1500A has a room temperature frequency response characteristic of ±0.75 dB, or 1.5 dB peak-to-peak. With this room temperature limitation, the total uncertainty
= ±(1.5 + 0.8) = ±2.3 dB.

3) Another improvement comes from a statistical analysis. In the uncertainty analysis, we can recognize that the above error is a worst case condition where the measurement is made at the worst frequency and the worst amplitude simultaneously. This is very unlikely to occur. It is a common practice to recognize that these errors are statistically independent and therefore they can be combined as the square root of the sum of the squares (RSS). Then the total uncertainty in an RSS sense is $\pm(1.5^2 + 0.8^2)^{1/2} = \pm 1.7$ dB

4) If the signals are closely spaced in frequency, another improvement would be to neglect any frequency response in comparison to the scale fidelity. For HP ESA-L1500A, the ±1.5 dB error is between the worst two frequencies in the 1.5 GHz range of the instrument. If the frequency separation is less than 1 MHz, it is reasonable to neglect the frequency response errors in comparison to the 0.8 dB scale fidelity error. Then the total uncertainty is about ±0.8 dB for closely spaced signals.

5) Further reduction can be achieved by performing custom calibrations. However these techniques are not commonly used in LIM operations.

Absolute amplitude uncertainties

When making absolute amplitude measurements, we check the items 2 to 8 listed in Table 1. Depending on circumstances, we may be able to trade off reference level uncertainty against display fidelity, using the more accurate one and eliminating the other.

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* Even though reference level was changed, the reference level uncertainty cancels out since it applies to both signals.

Example
If we want to measure a signal at a reference level of 0 dBm with an attenuation setting of 20 dB linear scale and a 3kHz RBW, the total uncertainty can be calculated as follows. Using Table 1, items 2,4,5,7 will contribute to the uncertainty. From the HP ESA-L1500A's technical datasheet we can find:

Reference setting accuracy: ±0.3 dB
Frequency response: ±1.0 dB
Reference level uncertainty: ±(0.3 dB + 0.01 x absolute value (ref level - attenuator setting + 35 dBm) = ±(0.3 + 0.01 x 15) = ±0.45 dB
Input attenuation switching uncertainty: ±(0.1 dB + 0.01 x attenuator setting) = ±(0.1 + 0.01x20) = ±0.3 dB
Resolution bandwidth switching uncertainty: zero since the 3 kHz RBW is our reference
Display scale fidelity: zero since the signal is at reference level
Linear to log switching: zero since linear scale is used

So the total worst case uncertainty is: ± (0.3 + 1.0 + 0.45 + 0.3) = ±2.05 dB

Recognizing that as these errors are independent they can be combined in an RSS sum rather than a worst-case sum, the total uncertainty is:

$$\pm (0.3^2 + 1.0^2 + 0.45^2 + 0.3^2)^{1/2} = \pm 1.2 \text{ dB}$$

Calculating frequency measurement uncertainty

When using spectrum analyzers to measure frequency, the accuracy is referenced to the start frequency (or the center frequency) during each sweep. Accuracy at points other than the reference are determined by the span accuracy.

Based on the spectrum analyzer's operation theory, the frequency accuracy depends on the frequency reference error (timebase) , span linearity, and IF filter characteristics (resolution bandwidth). The narrower the span or resolution bandwidth, the more accurate the absolute frequency measurement.

The computation of frequency readout accuracy is easy. There are equations for Frequency Readout Accuracy (markers, center, start, and stop) on a spectrum analyzer's datasheet. For example, the equation for the HP ESA-L1500A is:

Frequency Readout Accuracy :
±(freq. readout x freq. ref. error + span accuracy + 20% of RBW), where the freq. ref. error = (aging rate x period of time since adjustment + setability + temperature stability).

Example
If the center frequency is set to 1.0 GHz, the span is 400 kHz, and the resolution bandwidth is 3 kHz, how accurate is the marker frequency readout?

The frequency reference error is :
±2 x 10^{-6} aging per year
\+ ±5 x 10^{-6} temperature stability
\+ ±0.5 x 10^{-6} setability
so the reference error = ± 7.5 x 10^{-6}
Therefore, the frequency accuracy is:

± (1 x 10^9 Hz) x (7.5 x 10^{-6})	= 7500 Hz
+span accuracy: ±1% of span	= 400 kHz x 1% = 4000 Hz
+20% of RBW: 3 kHz x 20%	= 600 Hz
Total uncertainty	= ±12.1 kHz

There are several ways to improve this accuracy:
1) Reduce the span
2) Reduce the resolution bandwidth
3) Connect the analyzer to a precise 10 MHz house reference such as HP 58503A GPS time and frequency reference receiver
4) Use the marker count feature
5) Maintain a stable environmental temperature

Frequency counter uncertainty

If the signal to noise ratio is >25dB, we can use the counter function to improve the measurement accuracy. Most spectrum analyzers have a built-in frequency counter. The marker count accuracy is independent of the span and the resolution bandwidth. On the datasheet we can find the specification on the Marker Frequency Counter accuracy like this:
±(marker freq. x freq. ref. error + counter resolution)

So using the same example as shown above and if the counter resolution is 1 Hz, then the accuracy is: 7500 + 1 = ±7.50 kHz

If a precise 10 MHz house reference is used in the factory, then the frequency reference error can be eliminated and the accuracy is simply ±1 Hz.

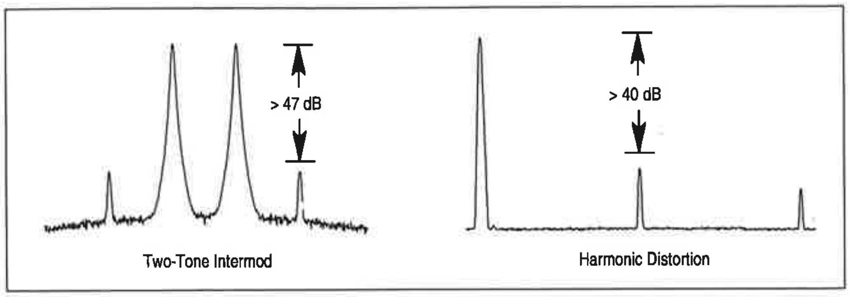
In many cases, a spectrum analyzer counter is superior to a frequency counter because the spectrum analyzer is frequency selective. It can count any signal that is sufficiently high above the noise floor. In comparison, a frequency counter typically just counts the largest amplitude signal.

Calculating harmonic and intermodulation distortion test uncertainty

Harmonic and intermodulation distortion

In production line tests, distortion is another specification often tested with spectrum analyzers. For non-linear devices, there are two important types of distortion: harmonic and intermodulation. The specification for distortion is defined by the relative amplitude of a fundamental signal to its harmonics in dBc. As shown in Figure 16, a tuner intermodulation specification might be –47 dBc.

Figure 16
Specification of distortions

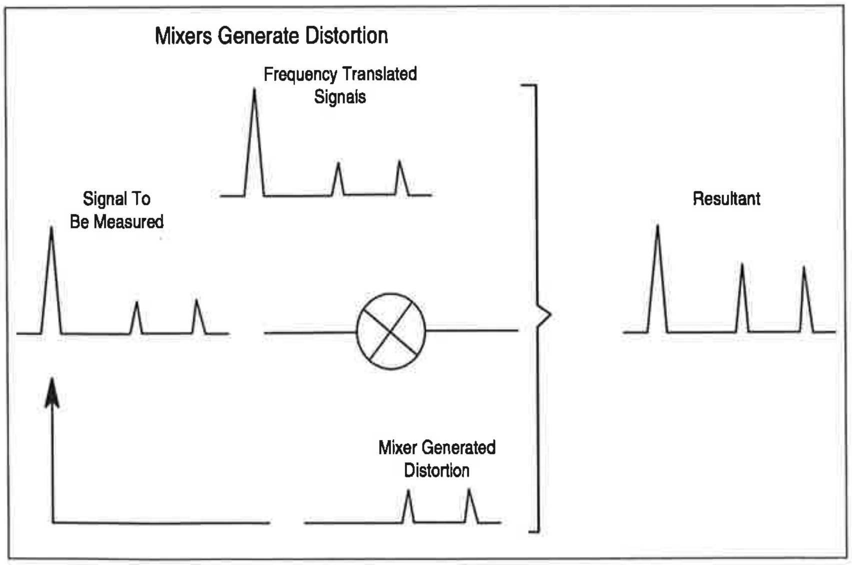


Several factors affect the distortion test uncertainty. The major ones are the spectrum analyzer internally generated distortion products and noise level. In addition, phase noise of the LO's, the skirts of the filters, and internally generated spurs and residuals can also limit measurement dynamic range. (see [1] for details)

Dynamic range versus internal distortion

The spectrum analyzer uses mixers that are non-linear devices and therefore generate internal distortion. This internal distortion might cause errors in the measurement of the (external) distortion of the DUT (see Figure 17). The internally generated intermodulation and harmonic distortions are a function of the input signal amplitude. For every 1 dB amplitude change of the input signal, the internally generated 2nd harmonic and 3rd harmonic distortion products change by 2 dB and 3 dB, respectively. (see [1] for details)

Figure 17
Internal distortion causes errors in test



Dynamic range curves are used to show the relationship of a spectrum analyzer's internal distortion products and the input signal level.

Figure 18 Dynamic Range Chart

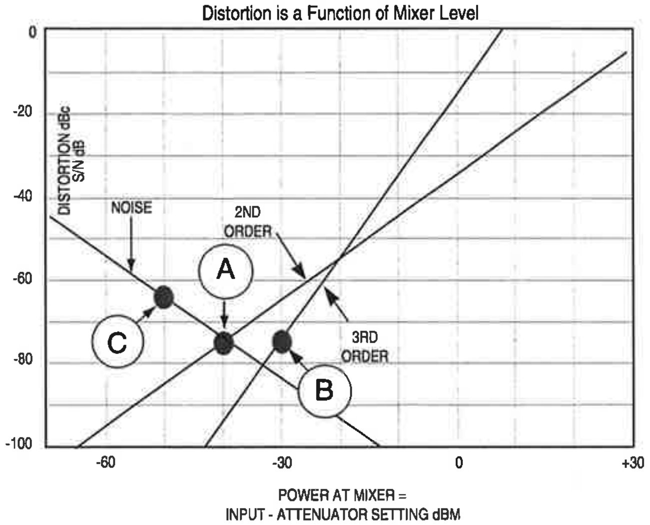


Figure 18 is a typical dynamic range chart. The X-axis is the signal power at the first mixer. The Y-axis is the spectrum analyzer's internally generated distortion level and noise level in dBc. Referring to the HP ESA-L1500A spectrum analyzer's technical data sheet for the Spurious Responses specification, the second harmonic distortion is –74 dBc for two –30 dBm signals at the input mixer (point B). The slope of the 2nd and 3rd-order distortion curves is 1 and 2, respectively. (see [1] for details)

Dynamic range versus noise floor

Another constraint on dynamic range is the noise floor of the spectrum analyzer. The average noise of the spectrum analyzer determines how small a signal can be measured. So, dynamic range versus noise becomes signal-to-noise ratio, in which the signal is the fundamental whose distortion is the parameter to be measured.

Take the HP ESA-L1500A as an example. The instrument's Displayed Average Noise Level (DANL) with 1 kHz RBW and frequency range from 500 MHz to 1.2 GHz is < = –116 dBm. If the signal fundamental has a level of –50 dBm at the mixer, it is 66 dB above the average noise. Therefore, the signal-to-noise ratio is 66 dB (point C in Figure 18). For every dB reduction of the signal level at the mixer, 1 dB of signal-to-noise ratio is lost. On the dynamic range chart, we can plot the noise curve as a straight line having a slope of –1.

Based on the dynamic range chart we can get the best dynamic range for a specified RBW, which would be at the intersection of the appropriate distortion curve and the noise curve. In Figure 18, the maximum dynamic range for second-order distortion is 75.5 dB and for third-order distortion, 82 dB.

Dynamic range versus measurement uncertainty

During measurement of an external signal, the instrument's internally generated distortion components can fall at exactly the same frequencies as the distortion components to be measured. The phase relationship between the external and internal signals is unknown. The error in the measurement could range from the two signals exactly in phase to the two signals exactly out of phase.

Let us determine a potential range of measurement uncertainty: $V_{internal}$ represents the internally generated distortion and $V_{external}$ represents the distortion components to be measured.

The difference in dBc between $V_{internal}$ and $V_{external}$ is:

$$dBc = 20 \log (V_{internal} / V_{external})$$

so, $V_{internal} = V_{external} * 10dBc/20$

$$\text{Measurement Uncertainty (dB)} = 20 \log [(V_{external} \pm V_{internal}) / V_{external}]$$

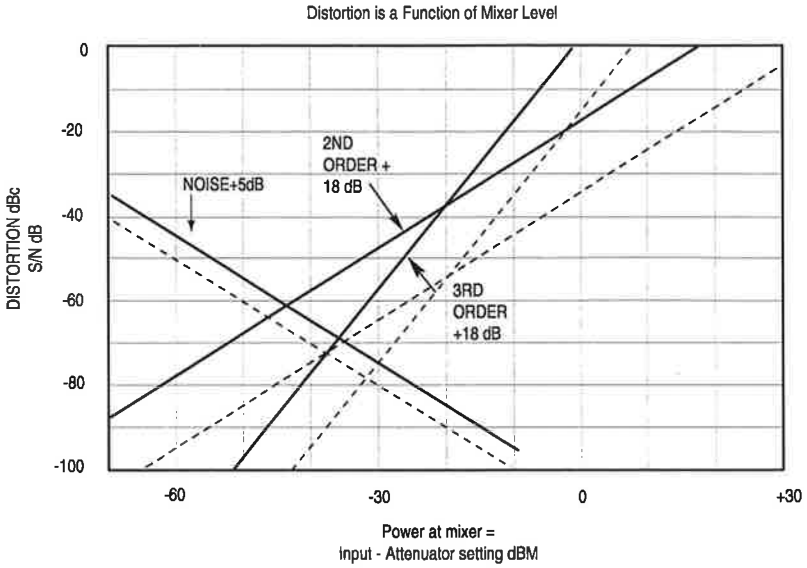
$$= 20 \log [1 \pm 10^{dBc/20}]$$

For this example, let us put a limit of 1 dB on the measurement uncertainty. Based on the above equation we can calculate that the spectrum analyzer's internal distortion product would have to be at least 18 dB below that of the external distortion product to be measured. To draw a dynamic-range chart for a measurement with no more than 1 dB of measurement error, we can offset the curves of Figure 18 by 18 dB, as shown in Figure 19.

To quickly check if a distortion product is due to the DUT or the test equipment, we can increase the attenuation between the DUT and the test equipment. An increase in attenuation will not change the distortion level in dBc if the distortion is due to the DUT. If the distortion level in dBc changes, the distortion must be due to the test equipment plus DUT.

Besides the instrument's internal distortion, low signal-to-noise ratio could contribute to the uncertainty as well. If the distortion components to be measured are at or very close to the noise level of the spectrum analyzer, the displayed signal-plus-noise is greater than the actual signal. Correction factors have been empirically determined that can be applied to correct for such measurement errors. It is common to make sure that the signal is at least 5 dB above the noise floor, giving a maximum error less than 0.5 dB.

Figure 19
Dynamic range for 1.5 dB maximum error



Using the solid line of the noise curve, the error is Using the solid line of the noise curve, the error is < 0.5 dB. Using the solid line of the distortion curve, the error is 1.0 dB. At the intersection of the curves, the total error is 1.5 dB. In practice, we can choose the desired error uncertainty and then identify the mixer power required to achieve that uncertainty from the dynamic range chart.

Summarizing measurement uncertainty

To address the challenge of minimizing the cost per unit, it is necessary for consumer electronics manufacturers to maximize throughput. One major way is to reduce re-test of the measurement. All test instruments have their own test uncertainty. Based on the understanding of the uncertainties of amplitude, frequency and distortion measurements, the test line limit can be set correctly. By setting up a proper test guardbands, the yield and repeatability can be dramatically improved.

Trends in production line test

Several trends in production testing focus on minimizing the cost-per-unit for consumer electronics production lines:

Automation

Growing labor costs and labor shortages, demand for ISO 9000 certification as well as improved working environments, and company-wide computer-integrated manufacturing have made automation a necessity for many companies. The trend for some manufacturers is to change from labor-intensive to capital-intensive automated production.

There are several stages of production-line-test automation. The move from manually operated tests to instrument controlled tests can be termed first-step automation. Examples of these are the automated bandwidth, percent AM, and TOI measurements built into the HP ESA-L1500A spectrum analyzer described previously. Second-step automation means there is computer control of the test instruments, but still manual connections to be made.

The HP ESA-L1500A has a rich control language that makes it easily controllable by external computers using a IEEE-488 or RS-232 interface. Third-step automation will be networked computers controlling the test instruments and pneumatic fixtures making the connections. The computer network allows data from the tests to be collected for advanced process control, statistical quality control (SQC) and constant process improvement (CPI). This is a fully automated test process.

Based on the trend of automation, test equipment should be capable of moving to first, second and third step manufacturing. In particular, when spectrum analyzers are selected for production line testing, their automation capabilities, such as remotely controlled functions, IEEE-488 interface, and data-transfer speed should be assessed for future production line improvement. However, a detailed discussion of a spectrum analyzer's automation capabilities is beyond the scope of this application note.

Considering total ownership cost

Cost-per-unit on a production line is influenced heavily by test equipment cost. Although the purchase price is the majority of the test instrument cost, the total ownership cost is a very important factor.

It is critical for consumer-electronics manufacturers to keep production lines running. Some production lines have backup test instruments sitting next to the production line for immediate replacement. This is expensive but not as expensive as a production line shutdown. Important factors beyond the purchase price of a test instrument are its reliability, warranty, calibration features, overload protection features. Additionally, a manufacturer will want to consider the vendor's service capability and the repair turn around time.

Minimizing cost-per-unit, automation and total ownership costs currently are and will continue to be a major focus in consumer electronics manufacturing.

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