APPLICATION NOTE

# Using Wider, Deeper Views of Elusive Signals to Characterize Complex Systems and Environments

KEYSIGHT

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# Introduction

Advanced analog and digital technologies have spawned radar systems that utilize frequency agility and wide bandwidths. For example, greater performance in digital signal processing (DSP) is making techniques such as pulse compression commonplace. In addition, DSP has led to advancements in digital dynamic range and algorithm complexity. Combining these developments with advances in amplifier and antenna design has enabled dynamic capabilities such as complex beam steering.

All of this leads to very complex signal activity, and the dense and dynamic challenges today's electromagnetic spectrum operation (EMSO) systems face. Even though these systems also take advantage of technology advancements such as high-performance DSP and GaN amplifiers, they are burdened by the breadth of possible real-world scenarios. As a result, if you work on radar, EMSO, or Signal Intelligence (SIGINT) systems, it is highly likely that you have been—or soon will be—tasked with measuring or identifying a much more complex signal environment than what was seen in the past.

For decades, spectrum analyzers have been used in the development and characterization of radar and EMSO systems. However, traditional swept measurements are rapidly becoming insufficient for today's agile and adaptive systems. This is driving the need for a solution that has significant speed, flexibility, and performance. Today's best alternative is a signal analyzer equipped with real-time spectrum analysis (RTSA), coupled with vector signal analysis (VSA) software.

This application note has two parts. The first provides an overview of signal-identification techniques that can be used when monitoring EMSO scenarios, identifying unwanted spectral events, or detecting issues in transmitted waveforms; further, for identified signals, the narrative discusses methods for making pulsed vector measurements in both the time and frequency domains. The second part outlines several analysis options that support typical requirements in dynamic range and bandwidth.

# Signal Analysis for Transient and Pulse Analysis

In radar applications, spectrum analyzers are very useful for measurements of spurs, noise figure and spectrum occupancy. The analyzer is also a handy tool when checking component behavior in response to stimulation with various signals.

In EMSO, spectrum analysis can be useful for monitoring system output to determine its accuracy. When stimulating an EMSO receiver with pulses, spectrum analysis is a useful way to monitor the stimulus sent to the receiver; if a test fails, spectrum analysis can help verify delivery of the correct stimulus to the system under test (SUT).

Unfortunately, typical spectrum analyzers have two significant shortcomings: a limited dynamic range, and difficulty capturing elusive or intermittent signals. For example, traditional swept analysis can fall short when measuring signals that carry pulse modulation, use wideband frequency hopping, or have very short durations. Even when such signals are properly identified, the next challenge is capturing them in a manner that enables detailed analysis through flexible post-processing.

The best complement—or alternative—is a signal analyzer, which can measure amplitude and phase. As defined by the industry, a signal analyzer combines the capabilities of a spectrum analyzer and a vector signal analyzer. Vector measurements are necessary for tasks such as viewing phase versus time, demodulating signals with pulse compression, or measuring wideband power (e.g., crest factor or complementary cumulative distribution function (CCDF)). With today's radar and EMSO systems, these measurements will be useful in multiple phases of the product life cycle.

A signal analyzer is well equipped for basic spectrum monitoring, especially in a high-density, pulsed-signal environment. Similar to an Electronic Intelligence (ELINT) receiver, many of the latest signal analyzers include fast-scan and real-time capabilities that support wide bandwidths and high dynamic range. This makes monitoring much more productive and efficient than is possible with traditional swept spectrum analysis.

The measurement challenge goes beyond signal identification. As mentioned earlier, many modern systems use some form of pulse compression. Thus, it is not only important to seamlessly transition to vector signal analysis but to also have the measurement range to accurately measure closely spaced signals of large and small amplitudes. In a signal analyzer this means the ability to perform vector measurements with high dynamic range.

# Part 1: Four Ways to Measure a Transient Signal Environment

A variety of techniques can be used to find intermittent spurious signals or pulses with low duty cycles. Some are unique to swept analyzers while others are specific to signal analyzers.

To illustrate these methods, a Keysight UXG agile signal generator was configured to use very fast frequency hopping and generate a broad spectrum of pulses with widths as narrow as 50 ns. This signal activity is similar to what might be used to test an EMSO receiver. While this section focuses on identifying pulsed signals within an EMSO environment, this method can also be used to detect intermittent spurs and other transient signals.

# Swept Methods: Fast Sweep and Dwelling

Swept techniques can be useful but display only those signals that are active—purely coincidentally—with the analyzer sweep. Two techniques can be used to capture such signals: fast sweep or dwelling. The key tradeoffs between the two are the longer measurement time of dwelling, and the limited measurement range of fast sweep. In the case of nonrepeating signals or scenarios, analysis bandwidth can be sacrificed to ensure all signal activity is captured, even if said signal only occurs once.

## Fast sweep

The analyzer is configured to sweep as fast as possible using a relatively narrow resolution bandwidth (RBW). Specifically, the RBW-to-span ratio should be less than 10,000:1. The advantage of a narrower RBW is a lower noise level; the disadvantage is a longer sweep time, which impairs the ability to find pulses or intermittent spurs. Compared with traditional swept techniques, fast sweep dramatically reduces sweep time by using either wideband stepped FFTs or new swept algorithms.

Another drawback of fast sweep is the inability to see the complete spectral content: a typical fast sweep will show only a subset of the signals in the chosen frequency span. Taking multiple sweeps and using the max hold function can highlight the envelope of the spectrum.

Plotting frequency versus time will help illustrate the process. In Figures 1, 2, 4, and 6, the black lines are signals that last for a finite period of time. While a pulse may generate wideband spectral content, the examples focus on the carrier frequency to help illustrate the key points.

In Figure 1, the RBW filter and sweep trajectory are shown in green and are plotted against time; the grey dashed lines show the retrace time. Every time the green line intersects with one of the signals (in black) it will appear on the analyzer trace. Any signals that do not intersect with the sweep will be neither detected nor displayed.

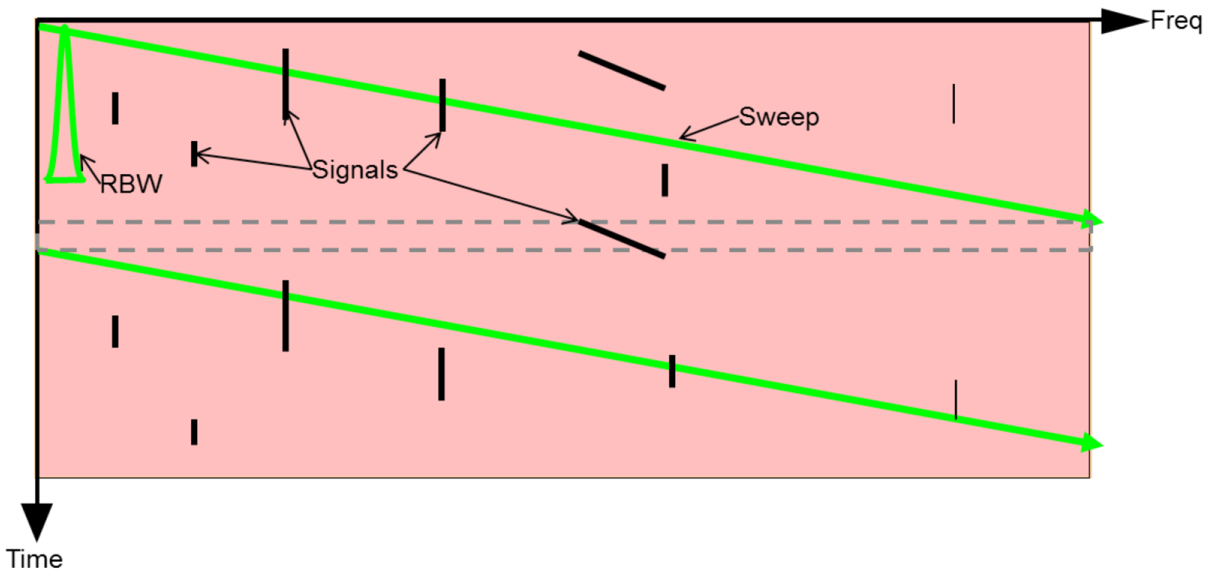


**Figure 1.** In this example of a traditional sweep, each time the green line coincides with one of the signals (in black) it will appear on the analyzer trace.

Decreasing the sweep time produces the situation illustrated in Figure 2. This produces more interactions with the various signals in the environment.

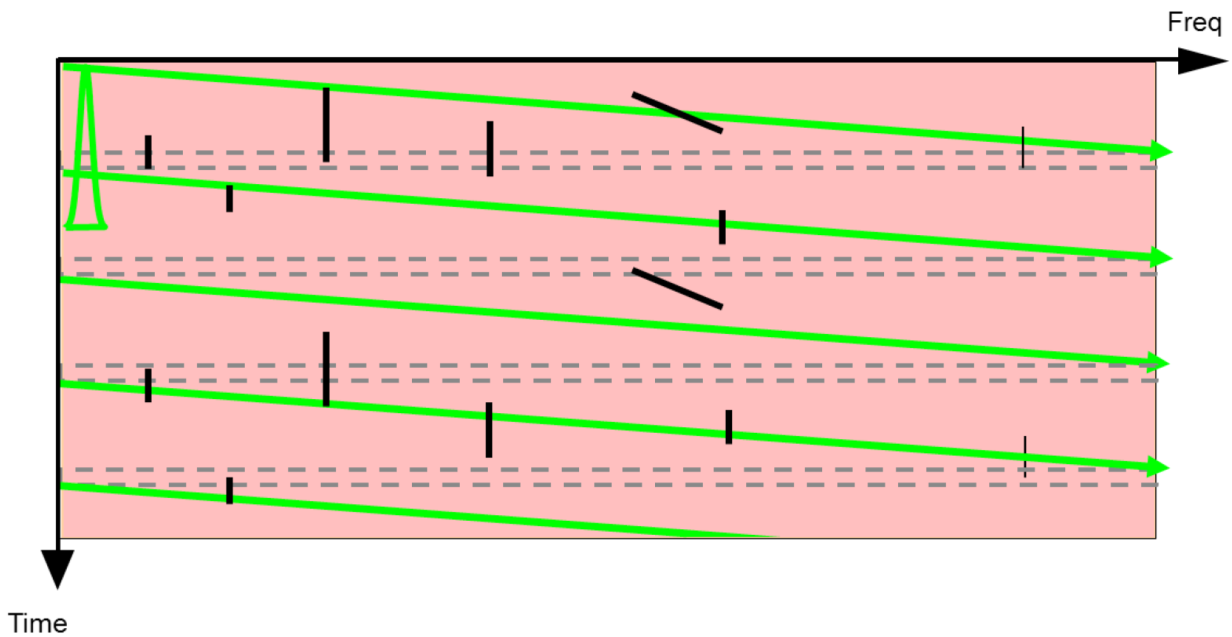


**Figure 2.** Using the fast sweep technique, the green line takes less time (Y-axis) to go from left to right. As a result, there are more intersections with the signals.

Actual measurement results are shown in Figure 3. These were performed using a Keysight UXA X-Series signal analyzer equipped with the fast-sweep capability.

**Figure 3.** The figure on the left shows a single measurement with fast sweep in the UXA. Notice that the analyzer caught some but not all of the signal content. On the right, the instrument is in max-hold mode and multiple sweeps are taken, making the envelope of the signal content more apparent.

## Dwelling

A swept measurement can be forced to dwell on specific sections of the spectrum by either using a constant RBW or holding sweep time constant and increasing the RBW (Figure 4). This method has been commonly used for pulsed measurements and is very effective in helping define the envelope of the spectrum.

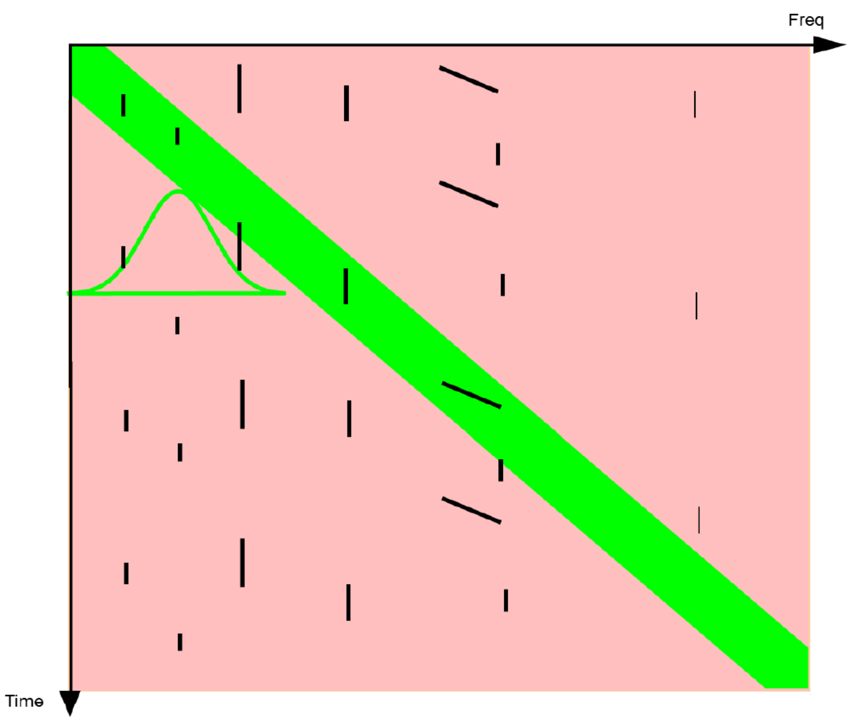


**Figure 4.** With a slower sweep time and wide RBW, the green sweep line widens and increases the probability that a signal will appear on the screen. Here, the time plot is long so can dependably capture repetitive signals; even so, it misses the repeating signal at the right.

Slowing down the sweep can help capture signals with a period similar or identical to the speed of a fast sweep. Using an RBW that is very small relative to the span can have a similar effect because it dramatically increases sweep time. Figure 5 shows an example of actual measurement results.

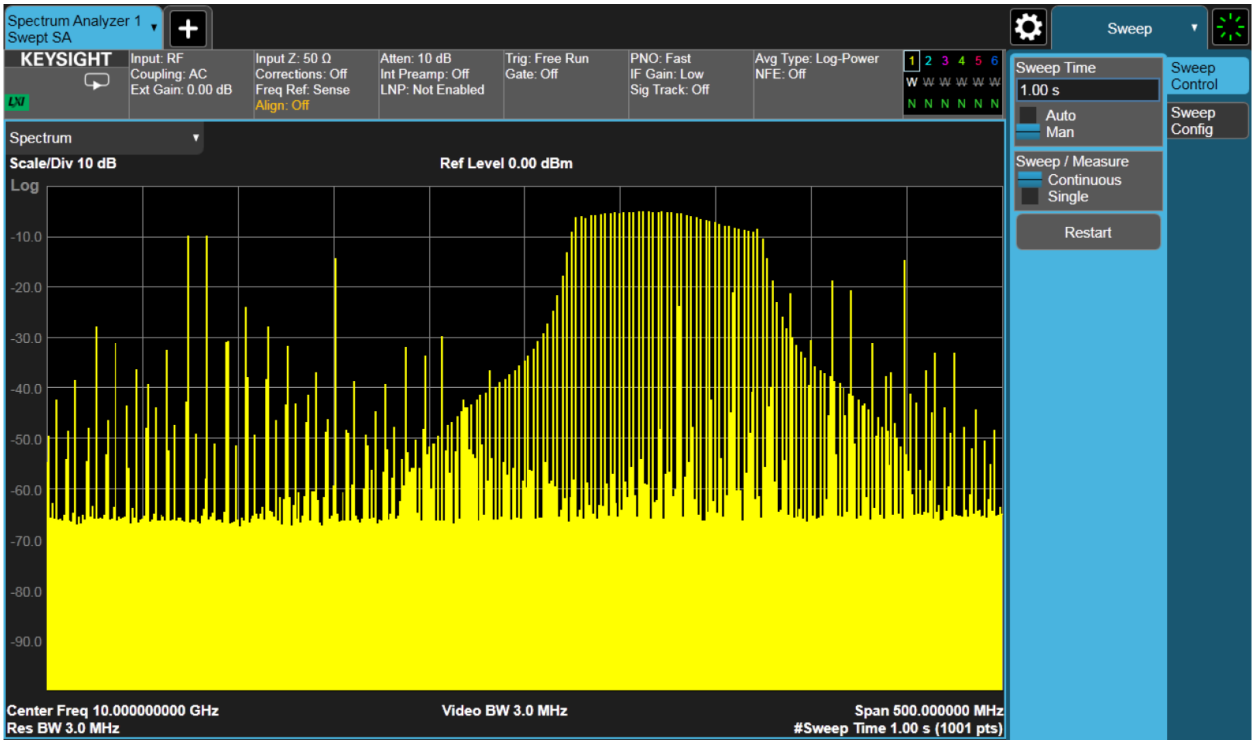


**Figure 5.** This example illustrates the type of spectral content that may be displayed with a slow sweep time or when sweep speed is decoupled from the default setting.

# Comparing fast sweep and dwelling

A discussion of the detailed mathematical probability of catching signals is outside the scope of this paper. However, the concepts covered here allow some useful generalizations. For example, the dwell technique is good for finding highly repetitive signal activity; the fast sweep technique is very good for analyzing a wider bandwidth while maintaining a lower noise floor; and the use of a narrower RBW helps resolve closely spaced signals.

# Characterizing pulses in swept mode

Two more analysis techniques can be used to measure pulse parameters: line spectrum, in which RBW is less than the pulse repetition frequency (PRF); and pulse spectrum, in which RBW is greater than the PRF.

These techniques can be used to measure pulse repetition interval (PRI), pulse width and pulse power (using the pulse desensitization equations). However, it can become difficult to use these traditional techniques with highly complex pulse trains (i.e., those with varying pulse widths and periods).

# Real-Time Methods: RTSA and Stepped RTSA

The methods described previously are useful for identifying signals that have a relatively short repetition interval. However, they are much less effective with signals that occur just once, have much longer repetition intervals, or are closely spaced and appear at virtually the same time. Depending on the maximum analysis bandwidth of the signal analyzer, real-time spectrum analysis (RTSA) and stepped RTSA are powerful alternatives.

## RTSA

In this mode, the local oscillator is stationary at a specific frequency and the analyzer digitizes the incoming spectrum. After digitization, FPGAs process FFTs at a rate equal to or faster than the collection rate (Figure 6). With improvements in digitizers and DSP technology, this technique has evolved from narrow bandwidths, which are inadequate for today's EMSO systems, to gap-free spans of up to 2 GHz in standalone signal analyzers.

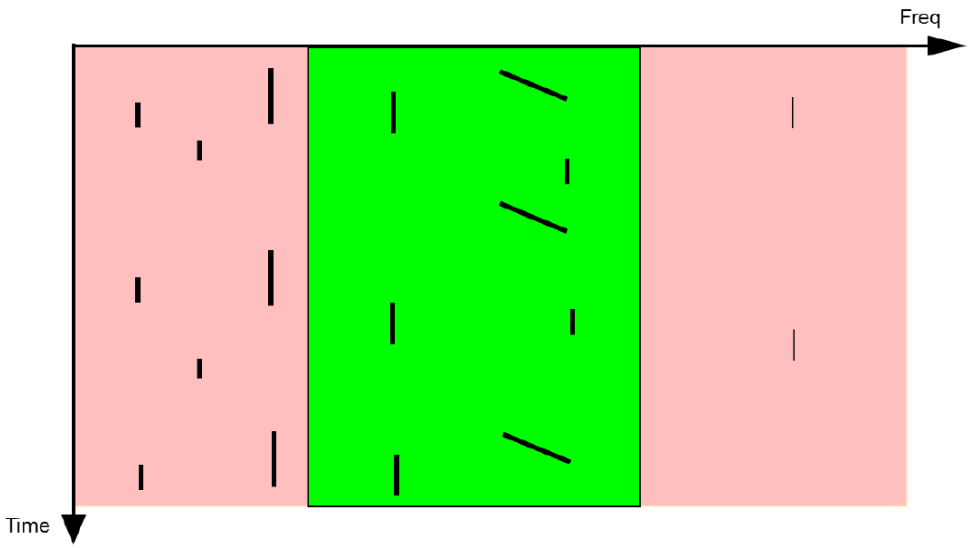


**Figure 6.** With the stationary LO, data is continuously analyzed and displayed, and all signal content is captured independent of repetition rate. Notice that the bandwidth is narrower than that of the swept measurements shown earlier.

Beyond the ability to monitor more of the spectrum without missing signals, real-time measurements can catch signals with very short durations. In addition, maintaining wide bandwidth and wide dynamic range also helps accurately identify smaller signals in the presence of larger ones.

At the higher sample rates needed for wider bandwidths, the analyzer can catch smaller signals. If at least 60 dB of signal margin is available, a real-time analyzer can detect virtually any signal that is as narrow as the reciprocal of the analyzer's effective sampling rate (1/fs). For example, an analyzer with an effective sampling rate of 300 MHz is able to detect a single signal of >3.33 ns, 100 percent of the time.

For more about probability of intercept (POI), please see the Keysight application note 5991-4317, Understanding and Applying Probability of Intercept in Real-time Spectrum Analysis.

For pulses of less than 3 μs, even a real-time analyzer may not deliver its fully specified amplitude accuracy. However, using a UXA and the 89600 VSA software, the signal can be captured and reprocessed, and the true amplitude can be recovered.

In post-processing, today's ASICs and FPGAs are fast enough to not only process the FFTs but also do arbitrary resampling, decimation, and corrections. These can be very helpful in maintaining dynamic range and ensuring accurate characterization of the signal.

When FFT processing is done at a very high rate, views such as the density display are used to enhance data interpretation. These displays provide a view that plots frequency, amplitude, and signal duration in a single trace (Figure 7).

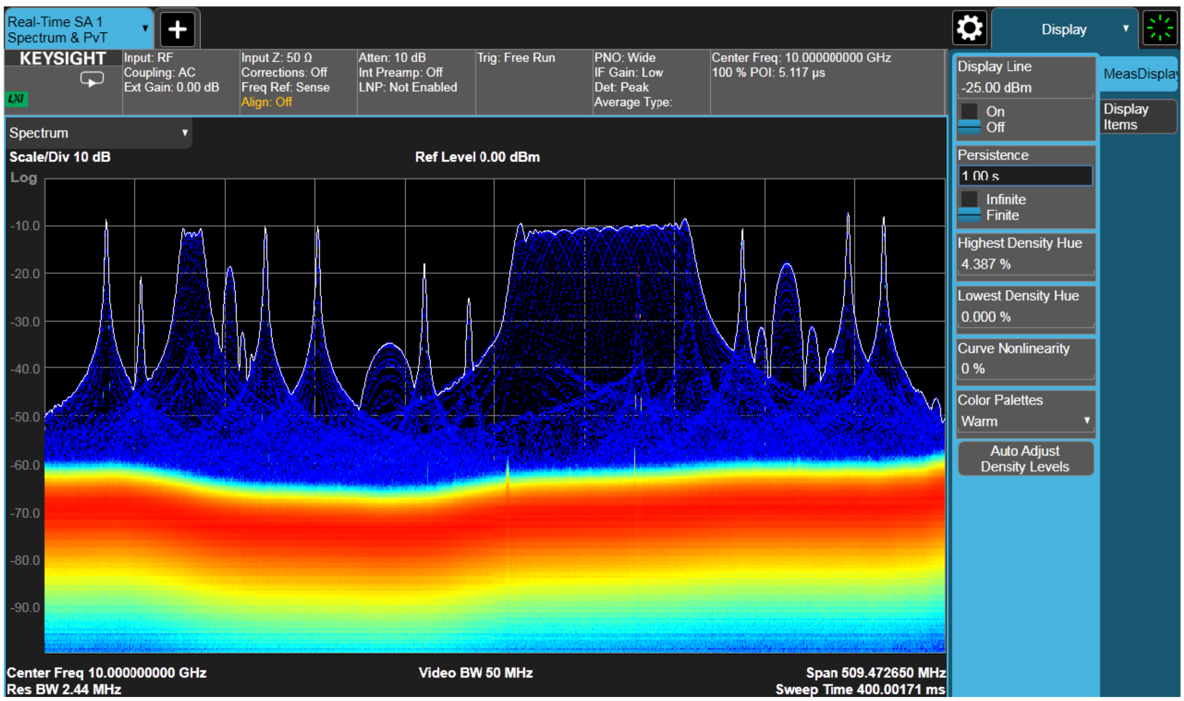


**Figure 7.** This density display is from a UXA signal analyzer with RTSA mode. It clearly reveals coincident signals, including two pulses that occupy the same spectrum within the pulse density.

# Stepped RTSA

Some instruments provide a hybrid approach that stitches together a series of measurements across a wide frequency span. In this "stepped RTSA" method, each real-time block of data is captured and analyzed for a period of time, and then the LO steps to an adjacent frequency band and takes another real-time acquisition (Figure 8).

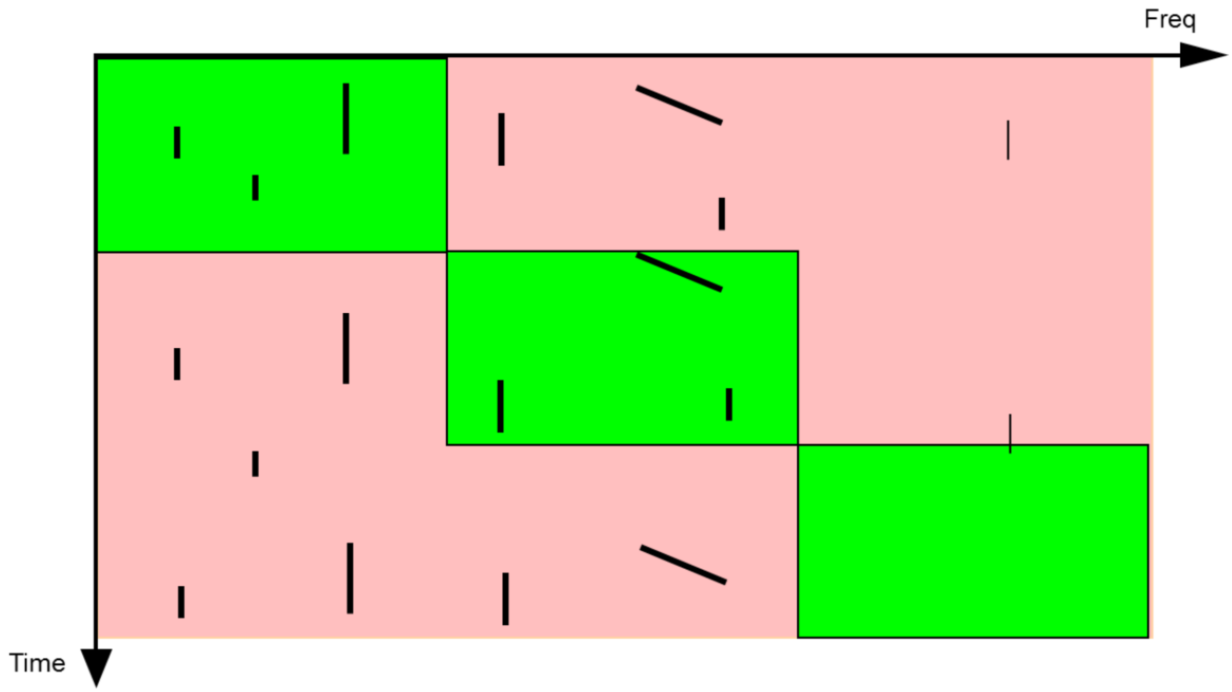


**Figure 8.** In stepped RTSA mode, the acquisition time determines how long (Y-axis) the signal analyzer dwells in each section of the spectrum. Here, the stepped RTSA method captures at least one instance of each pulse train but does not capture all signal content.

One key advantage of this approach is a maximum measurement bandwidth that can be equal to the full range of the analyzer. Another is the ability to find fleeting or intermittent signals that occur over a specific time period. Contrast this to a single-frequency RTSA measurement: it is certainly possible to find a very small signal by making measurements over a very long time period; however, this may not be realistic when test time is limited, or the signal is not repetitive.

As an example, suppose a full test scenario for a transmitter takes 10 seconds but there is reason to be concerned about the presence of unwanted spurs within 1 GHz above and below the measurement. By setting the real-time acquisition period to 10 seconds, any spurs that occur during the test interval will appear. With the UXA, the analyzer can cover more than the required 2-GHz span in real time by stepping through eight 250-MHz spans. In this mode, the UXA will be able to detect spurs as brief as 3.33 ns in each acquisition. Figure 9 shows an example of the resulting spectrum.

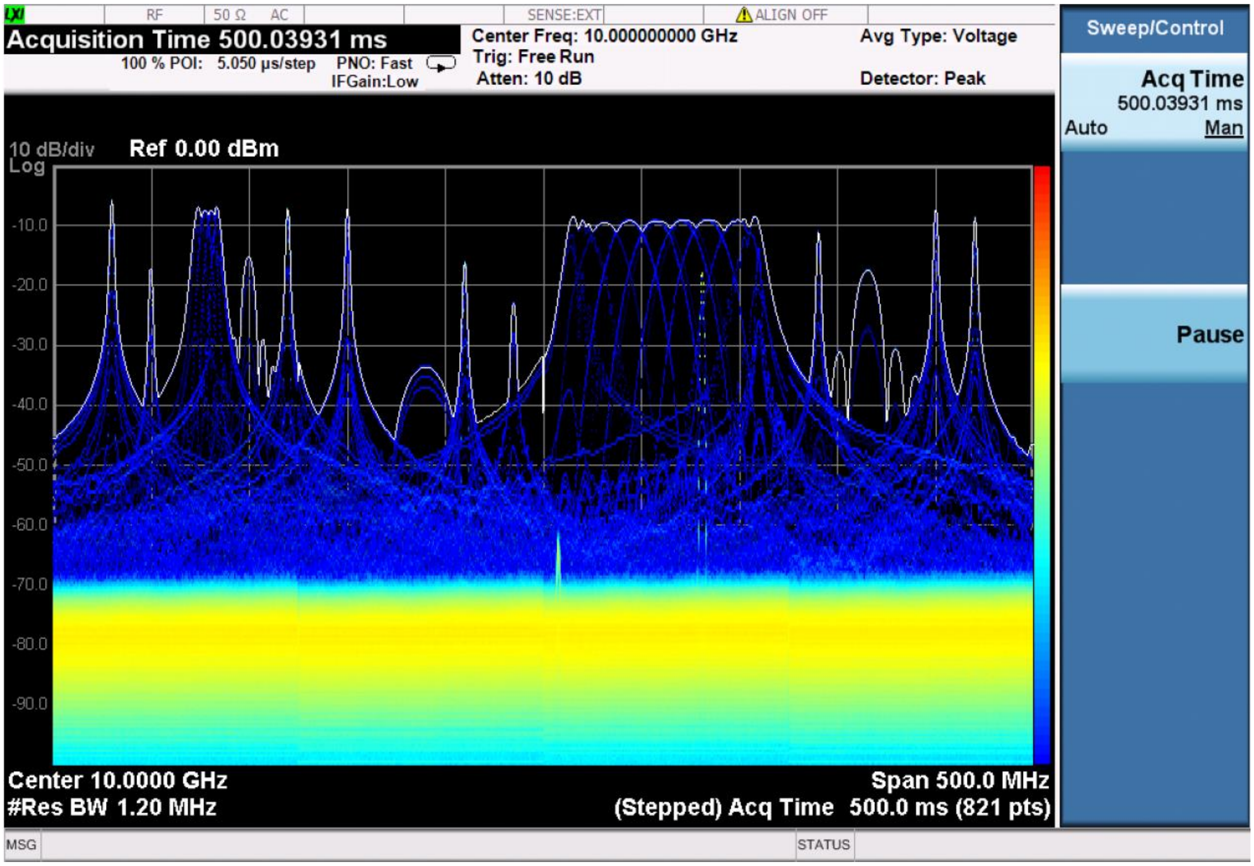


**Figure 9.** This example captures the same 500-MHz span shown in Figures 3, 5, and 7. Here, a Keysight PXA signal analyzer was stepped across 500 MHz using five 100-MHz real-time chunks of spectrum. Acquisition time was set long enough to ensure that each section could capture all the signal content.

This approach does have two disadvantages worth mentioning. First, there is less flexibility in the setting of analyzer parameters such as RBW than the swept approach. Second, and perhaps more significant, is the longer time required to analyze the resulting spectrum if the task is to monitor a span of several gigahertz. This is compounded when monitoring scenarios in which the repetition period is very long.

# Pinpointing Signals of Interest

Either real-time method makes it possible to see multiple elusive signals within a frequency range of interest. However, when analyzing a dense EMSO environment, it may be necessary to pick out a single signal of interest, be it a carrier, spur, or pulse.

The DSP that enables real-time measurements also supports advanced triggering capabilities that can detect signals of interest and then initiate measurements. Available trigger attributes include signal frequency, amplitude, and duration (i.e., signal “on” time), or a combination (Figure 10). This can be an extremely useful way to find individual unwanted signals from an operating transmitter, something that is virtually impossible to do in the time domain. In EMSO, this can reveal specific threats in a crowded environment. Identified signals can be output as a trigger, or an I/Q recording can be saved for further analysis.

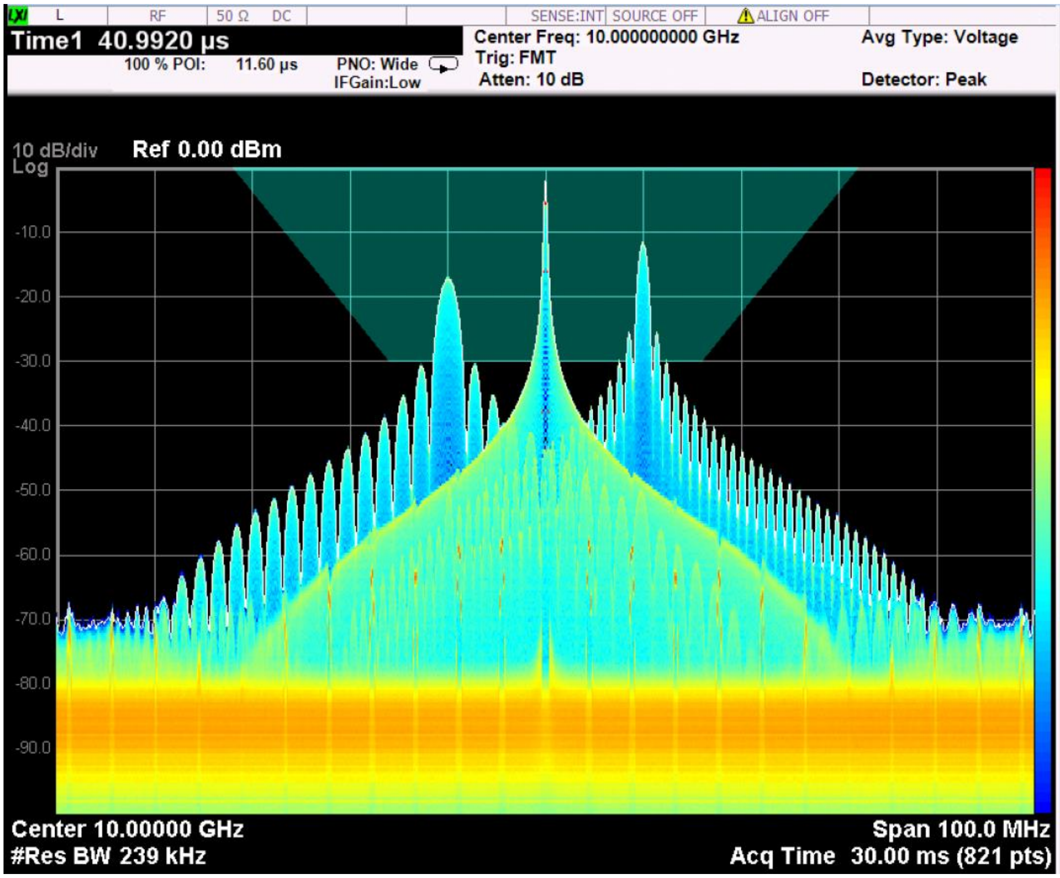


**Figure 10.** Frequency mask triggering can initiate measurements based on attributes such as signal amplitude and frequency. Here, the frequency mask is the green section at the top center of the display.

# Part 2: Making Quality Measurements

The signal identification capabilities described above are essential measurement techniques; moreover, it is important to understand how accurately the found signals can be measured. This depends on many things. In some cases, the main concern is the measurement dynamic range of the signal analyzer versus the expected dynamic range of the SUT. Fully understanding measurement dynamic range—and how it translates to actual performance—depends on more than one or two specifications from a data sheet.

# A Traditional View of Dynamic Range

Virtually all signal analyzers use a heterodyne architecture: the first mixer is used to down convert the incoming signal which can be the source of distortion caused by high-power signals. Attenuation and filtering can often be used to help eliminate these issues; however, this can affect bandwidth and the ability to see smaller signals.

In the case of a signal analyzer, the most common dynamic range specification is third-order intercept (TOI) versus the displayed average noise level (DANL); phase noise may be plotted as well. This gives some indication of how well the instrument can handle large signals and still measure small signals: phase noise gives an indication of how well the analyzer can measure signals next to the carrier. These parameters are relevant for vector measurements and real-time analysis.

Figure 11 illustrates a common type of dynamic range plot used to characterize swept spectrum analyzers. The X-axis is the power level at the first mixer, and this can be adjusted through the analyzer's input attenuators; the Y-axis is the dynamic range in dBc.

Keysight's high-performance X-Series signal analyzers include a relatively recent technique based on a low-noise path (LNP) that bypasses some of the noisier components commonly used in signal analyzers. The improvement increases at higher carrier frequencies. This can become important to the dynamic range plot because it moves the DANL curve farther to the left without sacrificing SOI distortion performance.

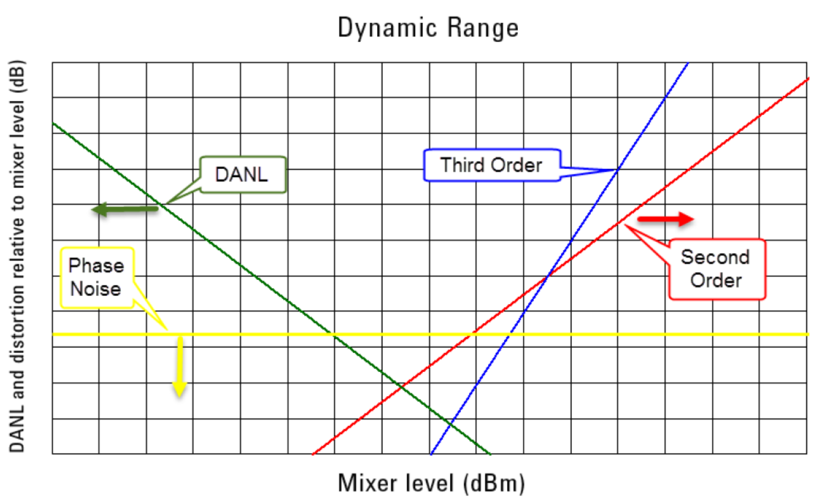


**Figure 11.** The downward-sloping green line is the noise level of the instrument at a given curve; the upward slanted blue line is the third order curve and the red line is the second-order intercept (SOI). Optimum dynamic range is at the intersection of the noise and distortion curves. The phase noise is in yellow.

Phase noise is a significant factor if vector measurements are needed or if measurements close to the carrier are important. Using a very stable reference can improve phase noise close to the carrier, generally at offsets of 100 Hz and below. At offsets greater than 100 Hz, contributions come from oscillators and other components inside the analyzer. In the UXA, the use of a direct digital synthesizer (DDS) in the local oscillator (LO) helps produce industry-leading phase noise performance.

# Dynamic Range for Vector Signal Analysis

In vector analysis, the analog and digital IF—and more specifically the ADC hardware—can generate unwanted spurious content when stimulated with an input signal. Understanding how much ADC resolution can be used is an indication of vector dynamic range.

Most modern analyzers with less than 80 MHz of bandwidth use an ADC with at least 14 bits of resolution. Unfortunately, there are very few digitizers with high dynamic range at sample rates above 1 GHz. One common solution is to incorporate multiple analog-to-digital sections that are used for various bandwidths. While this method is good for retaining or maximizing dynamic range at lower spans, it does not address dynamic range at wider bandwidths. This can be a significant issue when testing wideband solid-state amplifiers and systems that have 70 dBc to 80 dBc of spurious-free dynamic range (SFDR).

Applications that require significant dynamic range include the collection of distortion products at one or more multiples of the transmit bandwidth, the measurement of wideband chirps, or the acquisition of wideband, fast-hopping signal activity. To provide accurate results, instrument performance must be better than that of the SUT. The UXA addresses these issues by using a Keysight-proprietary, metrology-grade 14-bit ADC that runs at more than 1 GSa/s (Figure 12).

While ADC resolution is a good indication of device performance, it is does not ensure a specific level of measurement performance. For example, a 16-bit ADC can perform like an 8-bit converter if proper care isn't taken in maintaining dynamic range.

Using SFDR as a figure of merit can help highlight ADC spur performance. For example, the spec highlighted in Figure 12 can describe the level at which unwanted signals may appear and thereby interfere with measurement performance. The SFDR number usually is specified with a single tone at a specific offset or offset range. In an EMSO environment, many of these parameters will change constantly, making it difficult to determine true instrument performance. Additionally, it is of note that SFDR does not help describe noise performance or the amount of spurious activity that the instrument itself might exhibit.

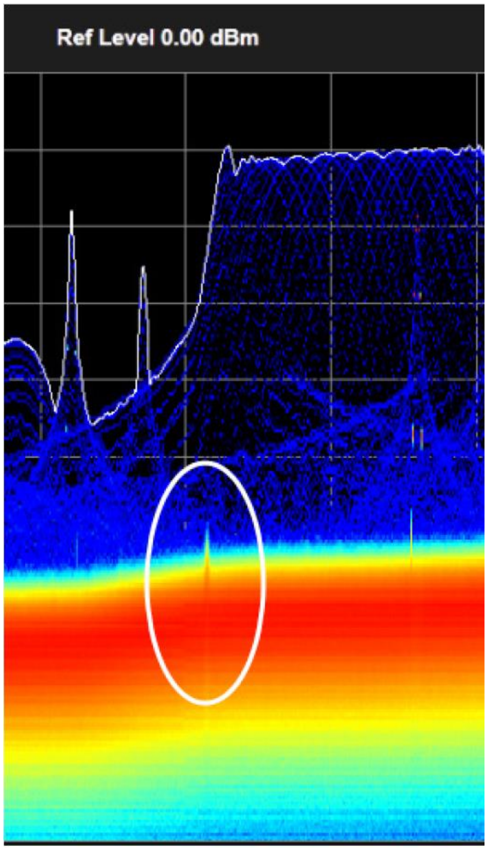


**Figure 12.** This slice of a density measurement comes from a UXA equipped with RTSA. The circled spur was intentionally created using a signal generator. An instrument with insufficient SFDR performance might generate such spurs internally, making it difficult to characterize SUT performance.

When analyzing multiple pulses, a good way to ascertain dynamic range performance is to generate such signals and observe their behavior. The examples below use two pulsed signals at the same carrier frequency but with different power levels. The measurements were made with an oscilloscope and a signal analyzer to show how each can measure or identify the small signal in the presence of the large one. To ensure measurement consistency, vector signal analysis (VSA) software was used with both instruments to view signals in multiple domains.

# Demonstrating ADC Performance

In the UXA, a measurement-grade ADC uses a digital dynamic linearity corrector (and other technologies) to push distortion products down much farther than is seen with virtually any commercial ADCs. To highlight the comparatively excellent performance of the ADC, a continuous-wave tone was swept across a 510-MHz span in the UXA and a 500-MHz span of another instrument.

In Figure 13, the spectrograms are configured to black out information below -92 dBc. The color bar on the left of each trace is keyed to signal levels between -92 dBc (purple) and -50 dBc (red). Notice there are far fewer spurs in the UXA measurement (upper trace) than in the other instrument.

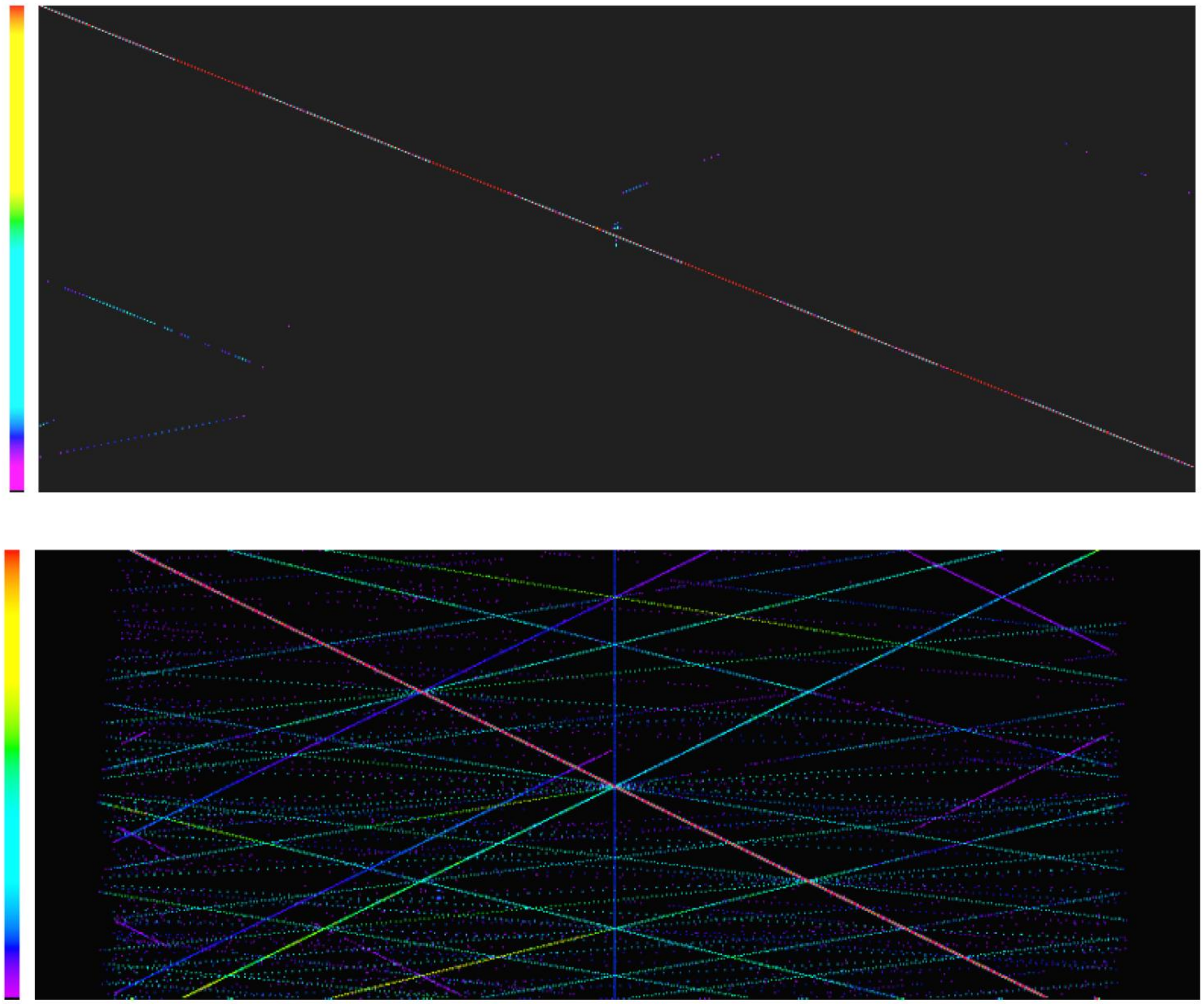

**Figure 13.** In the upper trace, the swept tone crosses from left to right and top to bottom. All other lines are spurs generated by each example instrument. As shown in the upper trace, the UXA produces far fewer spurs. This is due primarily to the performance of the Keysight-proprietary ADC.

In Figure 14, the scope measurements are on the left and the analyzer results are on the right. The upper screens show views of the two pulsed signals: they have the same frequency but are 20 dB different in amplitude.

Adjustments to gain or attenuation ensured the largest measurement range. It is clear that the signal analyzer has much more measurement range than the oscilloscope, even when the two pulses are only 20 dB different in amplitude.

With repetitive signals, time, or hardware, averaging can be used to help extend the noise floor and thereby provide more than 90 dB of measurement range with a 200 MHz span (Figure 15). This method can be used if there is little variability in both the PRI and the trigger. In addition, the SUT and the instrument should share a frequency reference to ensure stability. This method is also possible with the oscilloscope and the 89600 VSA software.

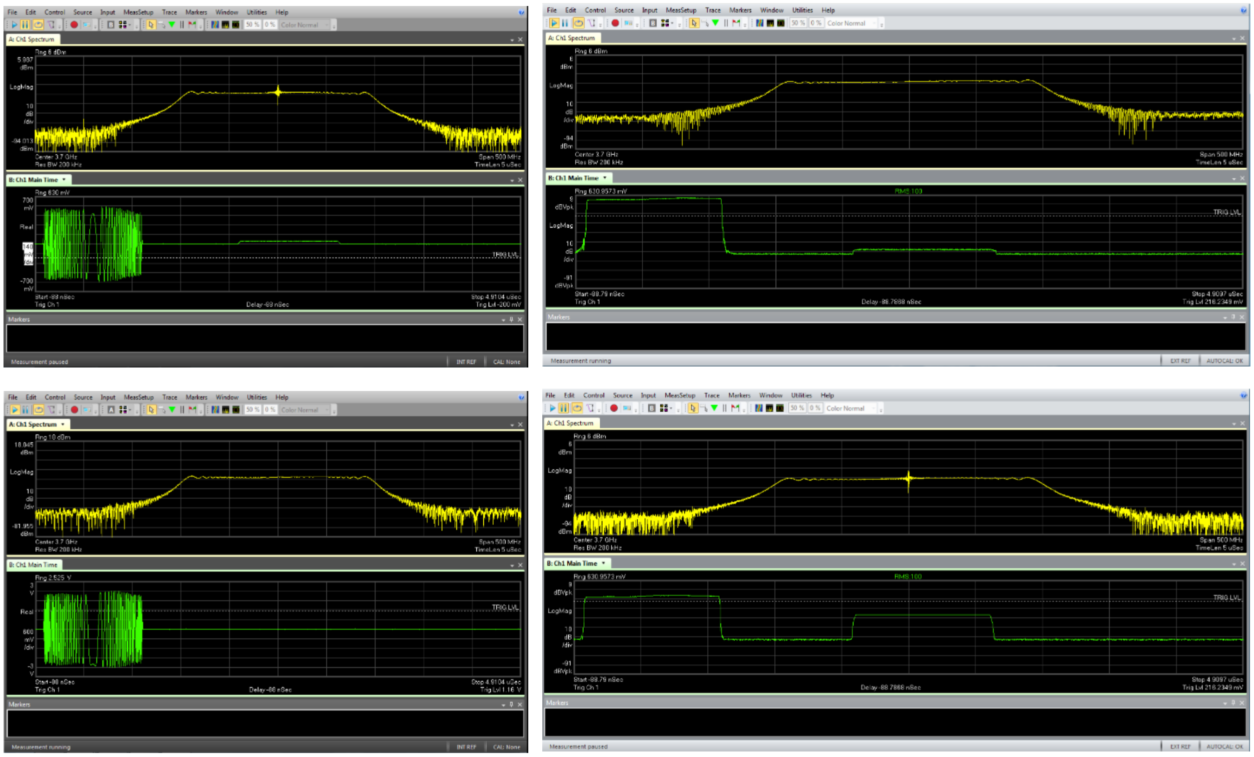

**Figure 14.** In this comparison of scope (left) and analyzer (right) measurements, the first is at -20 dBc and the second is at -60 dBc. Using the same settings with a larger difference between the two pulses, the scope has significant difficulty measuring the lower pulse; the superior dynamic range of the UXA easily exposes the second signal.

Most instrument vendors offer software packages that will automatically calculate and present measurement results for all pulses within the vector bandwidth and dynamic range of the instrument. It's equally important to use applicable sample rates and appropriate dynamic range to ensure that the metrics are complete and accurate (i.e., account for all pulses in the band). Metrics such as rise time, overshoot, droop, and others, are sample rate dependent. Independent of vendor, these analysis packages commonly post-process acquired data to extract pulse characteristics. This should not be confused with the real-time processing described earlier in this note.


**Figure 15.** In this example, time averaging in the 89600 VSA software extends the measurement range of the instrument. In the table, relative marker 3D1 shows more than 91 dBc of measurement range with the UXA signal analyzer.

# Conclusion

In the testing of agile, wideband systems, signal analyzers are needed to find spurs and monitor the frequency spectrum. In the past, standard swept spectrum analyzers were used to measure such signals. These traditional tools are no longer up to the task of characterizing systems that utilize wide bandwidths and extreme frequency agility.

Today, signal analyzers and real-time analysis provide the speed, flexibility and performance needed to characterize complex systems and signal environments. In addition, these analyzers provide advanced real-time triggering that can be used to isolate a single signal of interest by initiating measurements based on specific frequency, amplitude, and time criteria.

The UXA signal analyzer utilizes Keysight-proprietary ADC technology to enable wideband real-time analysis and maintain high dynamic range. The result is an ability to see the true behavior of dynamic signals and the real performance of leading-edge designs.




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