APPLICATION NOTE

Overcoming the Challenges in Satellite Testing and Interference Detection

KEYSIGHT

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Introduction

The new geostationary orbit (GEO) satellite systems and the “New Space” commercial trend of thousands of low earth orbit (LEO) satellites bring new challenges to both the components and system level tests of satellites. With satellites utilizing higher frequencies and wider bandwidths, more complex testing and characterization is required to ensure components and systems meet requirements. Additionally, with the dramatic increase in the number of satellites and complexity of the electromagnetic environment, interference detection becomes a problem facing satellite operators and regulation institutions alike—especially for the detection of intermittent or transient signals.

This application note focuses on the wideband and high frequency satellite component test technologies for both bent pipe and digital regenerative payloads. On the transmitter side, the non-linear distortions of the power amplifier (PA) will be discussed. On the receiver side, the focus will be on the noise measurements. The DUT’s group delay and the phase noise of the local oscillator (LO) will be discussed. Last but not least, a novel method for interference detection on satellites is illustrated, which has capability for gapless monitoring as well as capture and analysis of intermittent, transient signals.

Satellite Payload Architecture

In the satellite communication network, the satellite in orbit performs the function of relaying transmissions.

Traditionally, most transponders use the so-called “bent pipe” style of architecture, where the uplinked signal is received by the satellite, converted to the downlink frequency, amplified, then re-transmitted. This process is pictured in Figure 1. During this process, there is no change to the nature of the transmissions between Earth stations. However, this style has limited processing and flexibility; the Earth station must organize its transmissions to make sure the transponder resources are used efficiently.

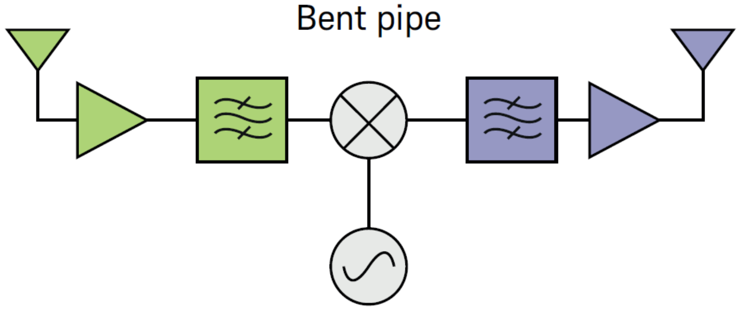

Figure 1. Traditional “bent pipe” satellite transponder architecture

Alternatively, there is a trend in modern satellites toward using onboard processing, which utilizes a “digitally regenerative payload” style of architecture. In this process, the received signal is demodulated and decoded on the satellite so that the signal may be regenerated and cleaned of any noise or interference picked up. Afterward, the signal is re-encoded and modulated before being sent back to Earth. This process is pictured in Figure 2. In this case, the digital data links provide a variety of advantages over analog links: the digital data link easily interfaces with digital computers, digital information compression schemes, and high-speed packet switching. The digital data link can also transmit wide dynamic ranges with low RF signal-to-noise ratios. However, digitally regenerative payload architectural design is considerably more complex than the traditional analog bent pipe.

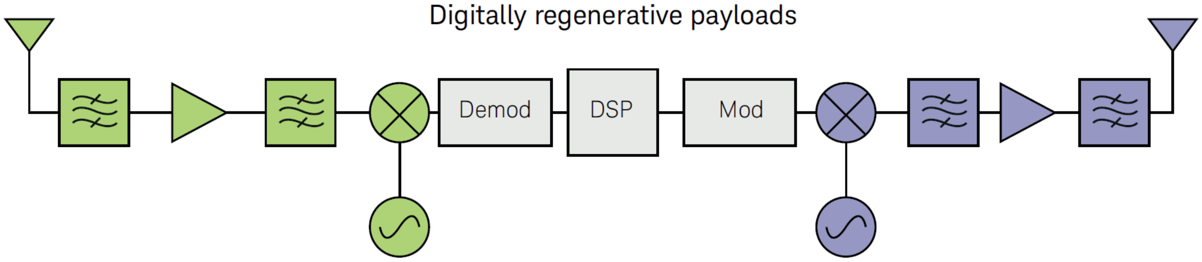

Figure 2. Modern “digitally regenerative payload” satellite transponder architecture

In the digital payload, where digitally modulated signals are present, test signals become more complex. While continuous wave (CW) tones can be used to test some of the components—such as power amplifiers (PAs)—they are insufficient for testing the complete payload. While testing digitally modulated signals within the digital payload, modulation analysis becomes more important; modulation analysis will be covered in more detail during later sections.

Wideband Satellite Component Test

In the block diagram of a satellite transponder, a low noise amplifier (LNA) along with the appropriate filter is employed as the first stage. As the noise components in the beginning of the receiver chain impact the noise level of the overall system most significantly, the emphasis on the LNA is to contribute as little noise as possible. After amplification of the received signal, the data stream is fed to a downconverter for either demodulation in digitally regenerative payloads or for re-transmission in bent-pipe transponders. For the downconverter, which is non-linear in nature, linearity issues, the phase noise of the local oscillator (LO), and group delay of the component need to be taken into consideration. In the last stage, a power amplifier (PA) is employed to obtain the required power level. The operating power will always be near to the saturation point to maximize power efficiency, at the drawback of increased signal distortions.

Low noise amplifier (LNA) test

In satellite transponders and satellite earth station receivers, an LNA is usually the first stage of the system, designed to amplify the weak signals received from the Earth station/satellite. As the noise figure of LNA determines the noise levels of the total system, it is important to make accurate noise figure measurements.

There are two main approaches for making noise figure measurements: the Y-factor method and the cold source method. The Y-factor is the most commonly used method, used within the Keysight noise figure analyzer (NFA), and spectrum analyzer. For the basics of noise figure measurement, refer to Keysight literature “Fundamentals of RF and Microwave Noise Figure Measurement” (publication number 5952-8255) and “Noise Figure Measurement Accuracy – The Y Factor Method” (publication number 5952-3706). In this application note, the focus will be measurement uncertainties.

The measurement uncertainty of Y-factor method can be expressed as:

$$\delta NF_1 = \sqrt{\left(\frac{F_{12}}{F_1}\delta NF_{12}\right)^2 + \left(\frac{F_2}{F_1 G_1}\delta NF_2\right)^2 + \left(\frac{F_2 - 1}{F_1 G_1}\delta G_{1,dB}\right)^2 + S\left(\left(\frac{F_{12}}{F_1} - \frac{F_2}{F_1 G_1}\right)\delta ENR\right)^2}$$

Where,

- (N)F_1 is the noise factor of the DUT
- (N)F_2 is the noise factor of the noise figure instrument
- (N)F_{12} is the noise factor of the complete system
- G_1 is the gain of the DUT
- ENR_{dB} is the excess noise ratio of the noise source
- δ is the uncertainty for the corresponding items
- S=1 implies single-frequency measurement
- S=0 implies measurement involving frequency conversion

The noise figure measurement uncertainty depends on several factors, including the noise figure and gain of the DUT, the noise figure of the instrument, etc. Figure 3 shows the trend of measurement uncertainty; a noise figure uncertainty calculator is used for the simulation, while all other parameters remain the same. With the decrease of instrument noise figure, the measurement uncertainty becomes lower.

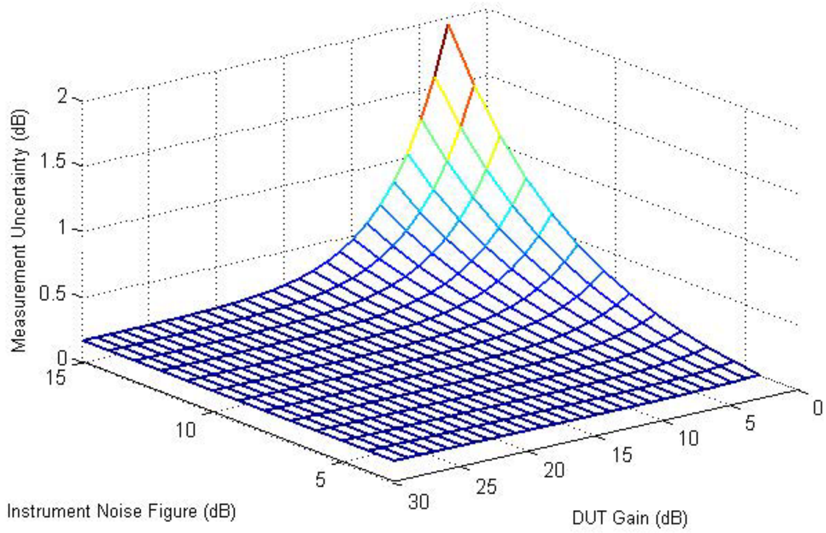

Figure 3. Measurement uncertainty results versus instrument noise figure and DUT gain.

Keysight offers external USB preamplifiers for use with signal analyzers to significantly decrease the effective instrument noise figure as shown in Figure 4.

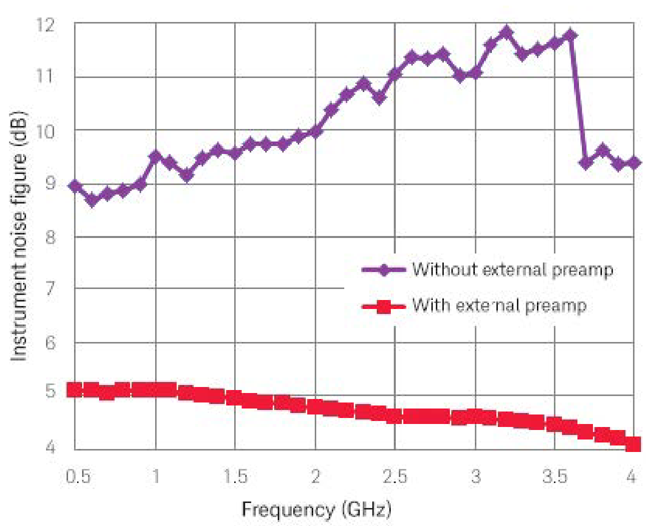

Figure 4. Effective instrument noise figure without external preamp (purple line, diamonds) and with external preamp (red line, squares).

Using Keysight noise sources with low excess noise ratio (ENR) uncertainty and external USB-powered preamplifiers, an X-Series signal analyzer can make noise figure measurements with high accuracy.

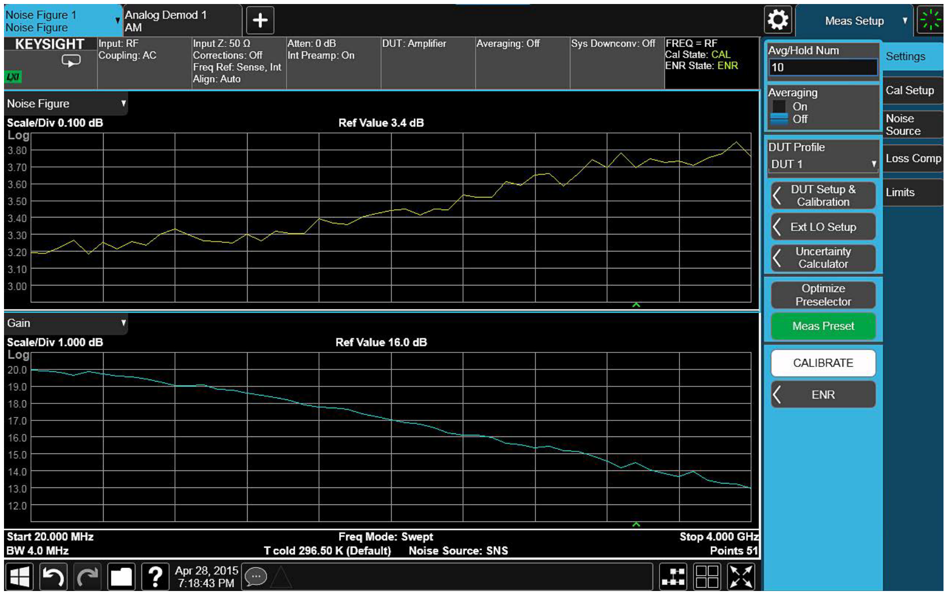

Figure 5. Noise figure measurement on LNA.

Wideband converter test

Frequency converters lie at the heart of the satellite communication systems. As data rates increase, so do the requirements on frequency response and phase. A critical measurement for this process is the group delay of the frequency converter. Also, for wideband converters, the phase noise of the local oscillator (LO) needs to be characterized, as this will pass onto the output of the converter.

Group delay test

Group delay is a measure of the phase distortion. Specifically, group delay is the rate of change of the phase shift with respect to frequency, providing insight into the time delay of the different frequency components passing through a system. Group delay flatness, a measure of the phase linearity, is therefore an important parameter in determining the transmission quality of a system.

To transmit information without distortion, a linear system for phase is required; this linear system is defined as the linear phase response over the transmission bandwidth:

$$\text{Group Delay} = -\frac{V\phi}{V\omega}$$

Where Φ is phase, ω is frequency.

Group delay’s measurement is based on phase measurements and is defined as the change of transmission phase with respect to the frequency. This is typically represented as a negative slope (see Figure 6).

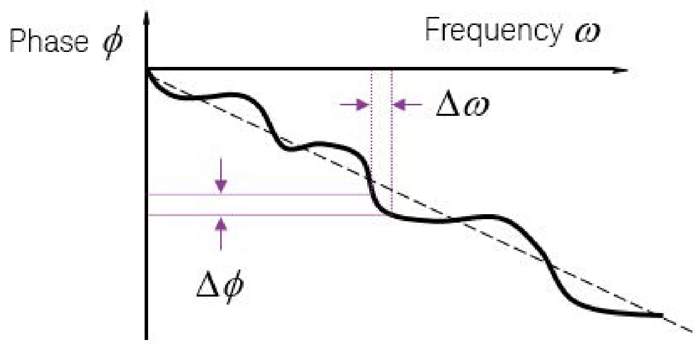

Figure 6. Group delay concept.

There are many methods to measure group delay. Traditionally, the group delay measurement is performed with a network analyzer using two tone methods. Two tone methods measure group delay by applying two tones/signals to the same system under test (SUT); group delay is then found by analyzing the phase relationship between the two tones at the output. In this application note we discuss a new approach, which uses a wideband multi-carrier signal as stimulus and a signal analyzer to capture the response of the device under test (DUT).

In this new approach, wideband multi-carrier signals are generated and applied to the DUT. In the past, an arbitrary waveform generator (AWG) would generate the wideband multi-carrier signal and a vector signal generator (VSG) was used as an external RF upconverter to move the stimulus signal to the center frequency of interest (see Fig 7). Modern signal generators, such as the M9484C VXG, no longer require external up conversion to generate wideband multi-carrier signals. The M9484C VXG has a frequency range to 54 GHz and a 2.5 GHz modulation bandwidth per channel, allowing it to generate the signals that previously required a two-box solution.

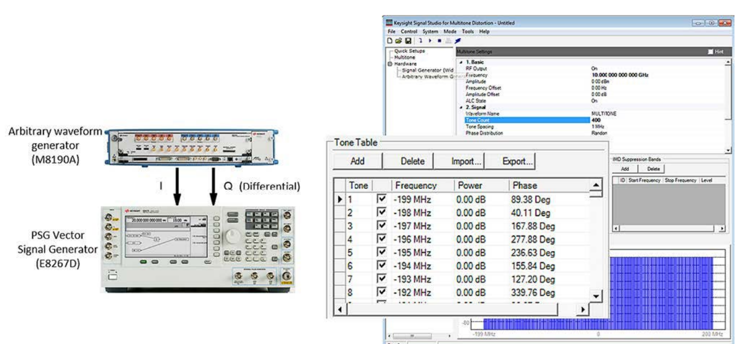

Figure 7. Multi-tone signals generated using an M8190A AWG and E8267D PSG vector signal generator with N7621B Signal Studio for multitone distortion.

In this approach of group delay test, the stimulus is a multi-tone signal consisting of an arbitrary number of tones with variable spacing. Since the measurement is a ratio of the stimulus and response signals, the phase relationship between tones can vary. Once generated, the wideband modulated signal is run through the DUT, and the output signal is analyzed by a signal analyzer which displays the gain, phase, and group delay of the DUT.

On the receiver side, an X-Series signal analyzer equipped with the N/E9056EM0E Channel Quality/Group Delay Measurement application is required to measure group delay. This combination enables you to make group delay measurements using a signal analyzer. Additionally, all settings for the VXG are made via Connection Management setup in the N/E9056EM0E Channel Quality/Group Delay Measurement application.

The measurement procedure for group delay is a two-step process: correction and measurement. In the correction step, the vector signal generator is connected directly to signal analyzer without the DUT. The influence of the instruments themselves and cables can then be determined and corrected for. Then the DUT can be inserted to measure only the response of the DUT itself.

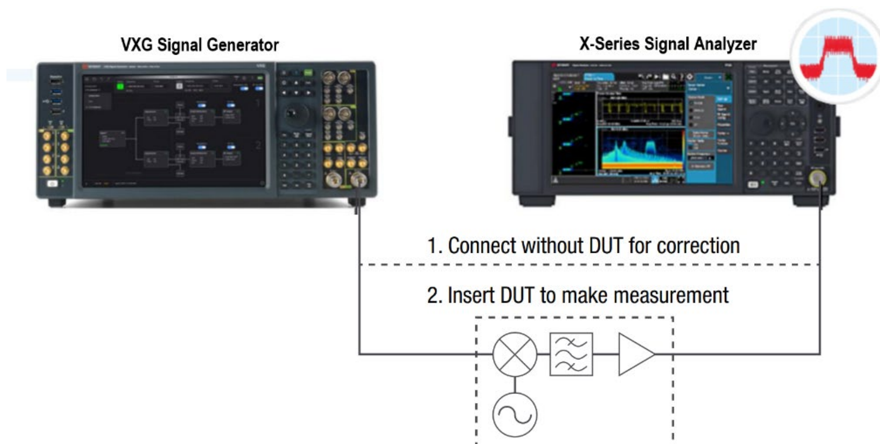

Figure 8. VXG signal generator and X-series signal analyzer group delay measurement setup, two steps.

An example of the measurement results is shown below with phase trace, magnitude trace, group delay trace, RF envelope trace and various metrics (Figure 9). For more detailed information, see technical overview Channel Quality for Group Delay (N/E9056EM0E) Noise Power Ratio (N/E9056EM1E) Measurement Application.

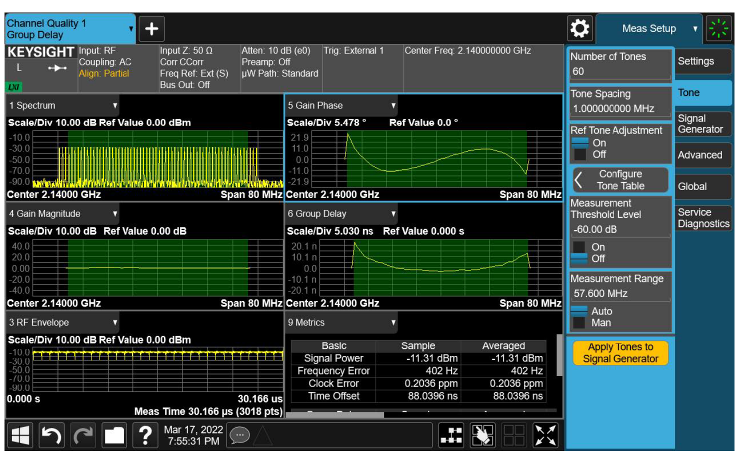

Figure 9. Example group delay measurement example using wideband filter as DUT. Top right shows phase trace, middle left magnitude trace, middle right group delay trace, bottom left RF envelope trace, and bottom right displays assorted metrics.

Phase noise test

In the frequency conversion system, the phase noise of the local oscillation will be transferred onto the mixer output signals, making phase noise measurements important for convertor tests.

So, what is phase noise? The most widely used unit of measure for phase noise has been the total single sideband power within a one hertz bandwidth at a frequency, f, away from the carrier referenced to the carrier frequency power. This unit of measure is represented as a L(f) in units of dBc/Hz.

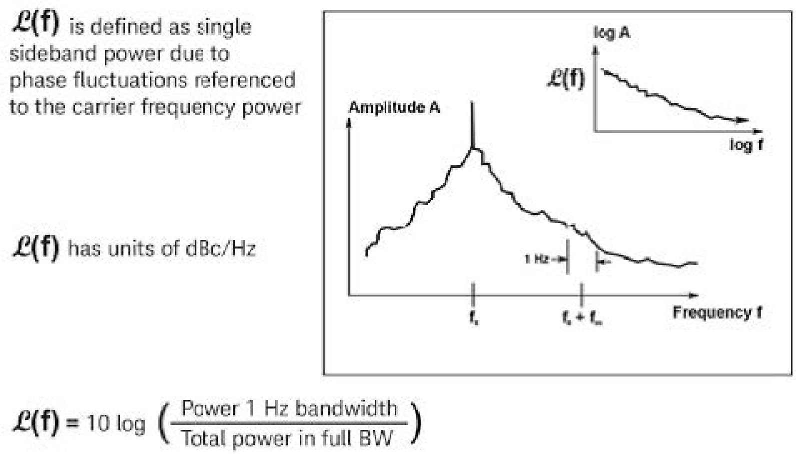

Figure 10. Phase noise definition.

Three methods of measuring phase noise include direct phase noise measurement, phase detector techniques, and two-channel cross correlation method. Among these methods, the direct phase noise measurement using signal analyzers is the most convenient; however, this method requires the phase noise of the instrument itself be much lower than the LO under test. The Keysight PXA and UXA signal analyzers have superior phase noise, which can be used for common phase noise measurements (–136 dBc/Hz @ 1 GHz carrier, 10 kHz offset typical.)

Keysight's SSA-X E505xA signal source analyzer has 1-port and 2-port phase noise measurement options. The latter option has two independent RF input ports and receiver channels, allowing for two separate absolute phase noise measurements to be done concurrently.

If the spectrum of the signal is used to measure the phase noise directly, there are many items you need to consider for making corrections as noise measurements is slightly different from the normal spectrum measurements. For the details, you can refer to "Phase Noise Measurement Solutions" publication number 5990-5729EN.

The N/E9068EM0E phase noise measurement application—built into Keysight's signal analyzers—provides one-button phase noise measurements. It automatically optimizes the measurement in each offset range to give the best possible measurement accuracy.

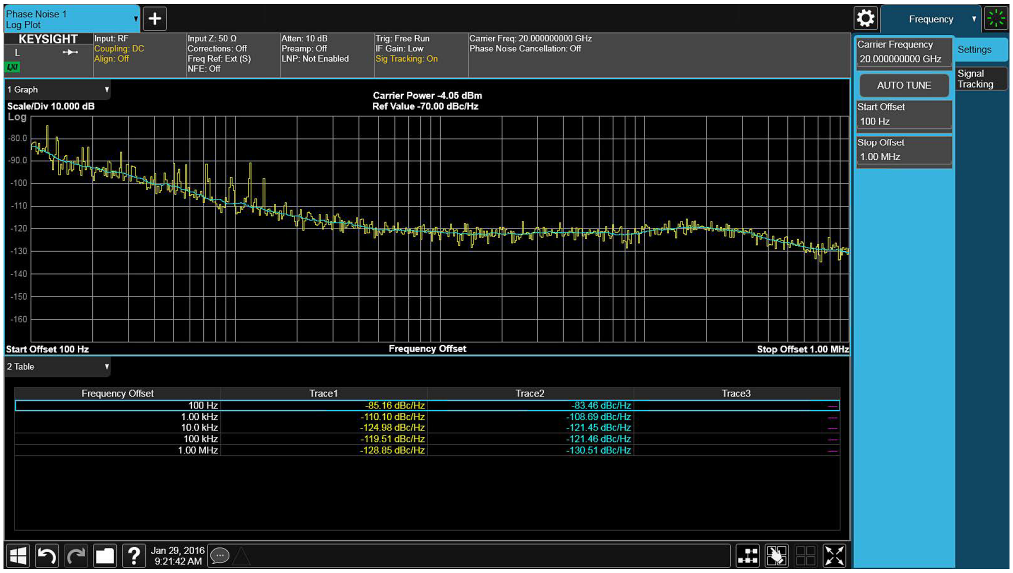

Figure 11. Phase noise measurement example.

Wideband power amplifier (PA) test

There are some significant challenges that come along with designing and testing wider bandwidth transponders; when many channels share a single transponder, there is potential for interference between the channels. A significant contributor to this interference is non-linear distortion within the transponder's power amplifier (PA). This can lead to a worse signal-to-noise (or carrier-to-noise) ratio, potentially resulting in increased bit error rates and decreased throughput. One possible trade off is to have fewer channels per transponders and wider guard bands, but this increases the number of transponders needed to achieve a given capacity. This in turn leads to increased weight and power requirements for the satellite which are undesirable.

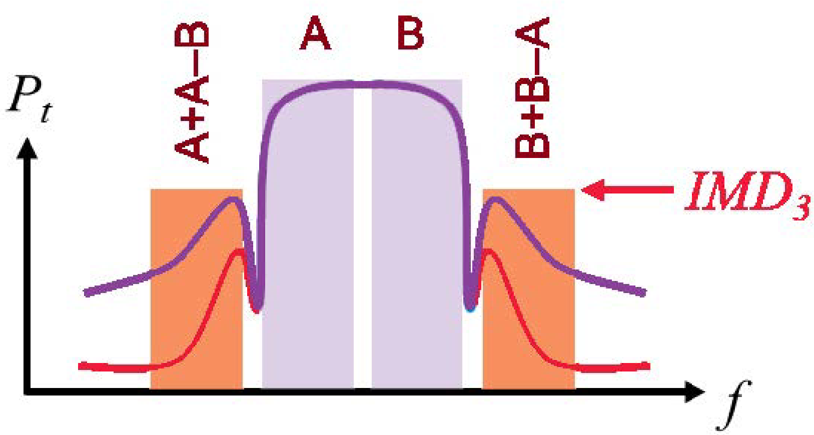

Figure 12. Non-linear distortion in PA creates interference in adjacent channels.

The non-linear behavior of a PA is commonly tested using AM/AM and AM/PM results, in which the transformation of the input amplitude variations into the variations in output amplitude and phase are shown.

Unlike the traditional two-tone test using a network analyzer, 89600 VSA software allows engineers to use a realistic signal to make the measurement. The PA input signal can be the same modulation type, bandwidth, and channel assignment as the device will see during real-world operation.

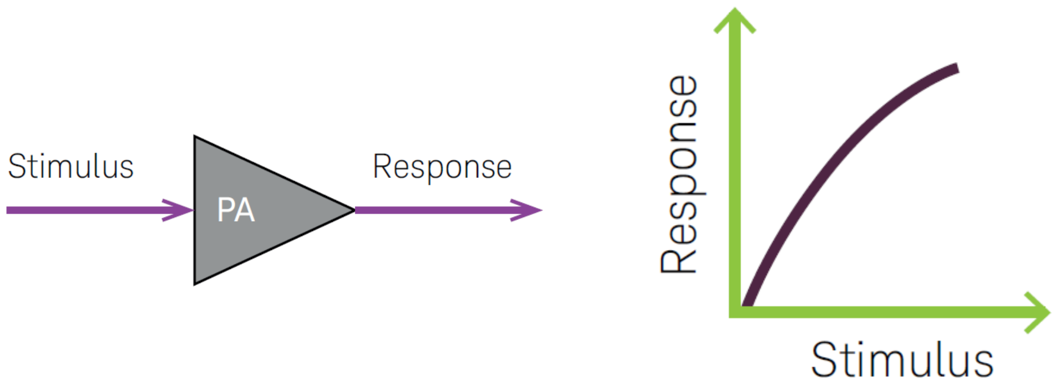

Figure 13. Stimulus and response PA test.

Non-linearity effects cause spectrum regrowth in a power amplifier where energy is spread outside the desired channel. In PA tests, it is important not only to have enough analysis bandwidth to capture the signal of interest, but to also consider capturing the multiple orders of spectral regrowth, if that information will be utilized in the system signal processing. For example, when examining a modulated signal and the 3rd order non-linear impacts that will be used in the signal conditioning, the N9032B PXA or the N9042B UXA would provide 2 GHz or 4 GHz of analysis bandwidth, which is enough to capture the wideband modulated signal along with the 3rd order spectral regrowth components.

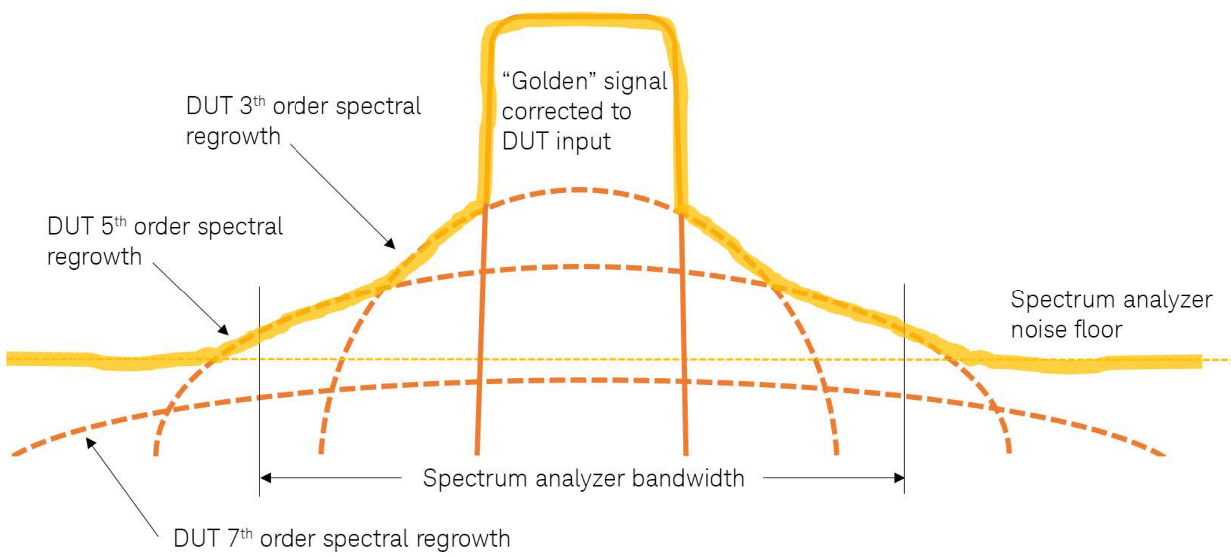

Figure 14. Power spread for PA non-linearity effects.

Through a simple stimulus-response measurement, you can see AM/AM, AM/PM, gain compression, and delta error vector magnitude (EVM).

- AM/AM shows the stimulus magnitude versus the response magnitude (input vs. output). The x-axis value of the point is the magnitude of the stimulus voltage, and the y-axis value of the point is the magnitude of the response voltage. Ideally in a device with no non-linear distortion, this would be a straight line with a slope equal to the gain of the PA, representing that the output is exactly linearly proportional to the input. (Upper left trace below)
- AM/PM shows phase difference versus the stimulus magnitude. The x-axis value of the point is the magnitude of the stimulus voltage, and the y-axis value of the point is the phase difference between stimulus and response, shown in degrees. Ideally the phase of the output would be independent of the magnitude of the input to the device, resulting in a straight horizontal line. (Upper right trace below)
- Gain compression shows the gain versus stimulus magnitude. You can see the 1 dB compression point from this trace, indicating that the PA is running out of steam. (Lower left trace below)
- Delta EVM Time shows the magnitude of the differential error vector between the stimulus and response signals over time. (Lower right trace below)

There is also a polynomial curve fit to the AM/AM, AM/PM and gain compression data, which can be exported for further processing, such as digital pre-distortion.

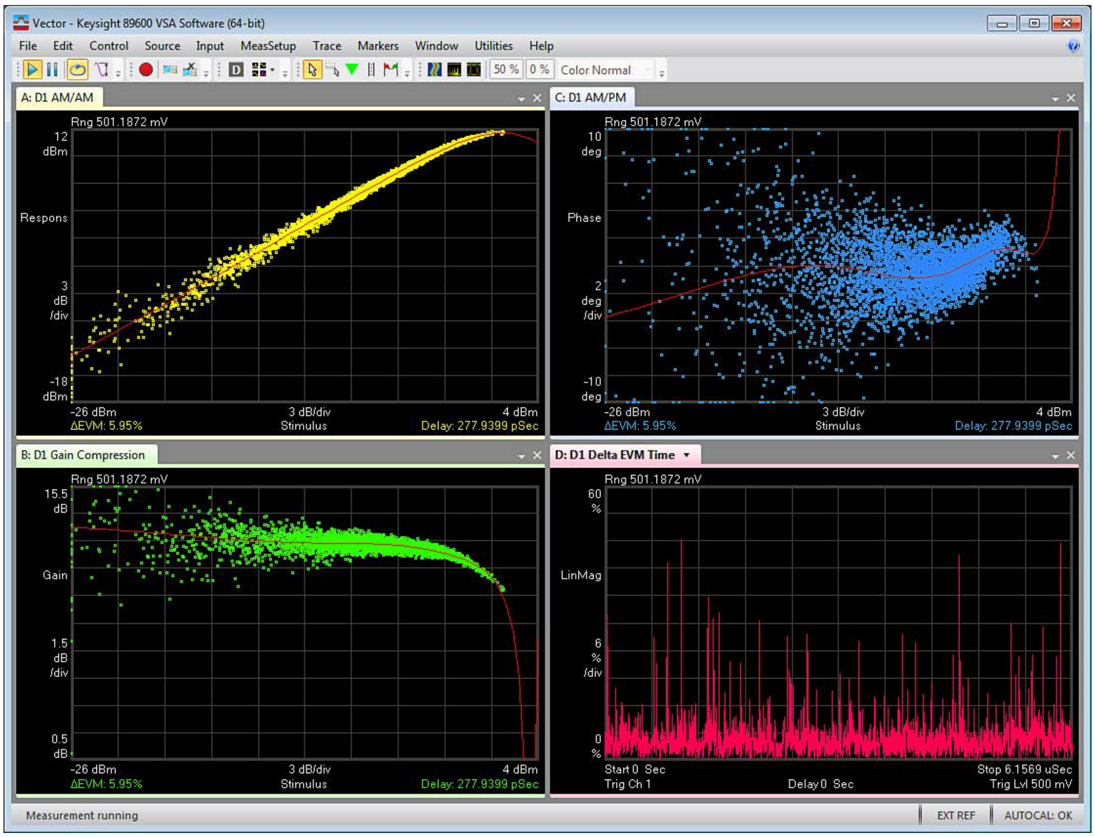

Figure 15. Examples for satellite PA measurements.

Modulation Analysis of Standard and Custom Modulation Types

One ongoing challenge for satellite operators is transmitting more data to more users at higher speeds within the available spectrum bandwidth. As a result, higher-order and more complex modulation techniques are being used. While the modulation becomes more complex, viewing the time-domain or frequency waveforms and understanding or trouble-shooting problems in signal quality has become increasingly difficult. Modulation accuracy measurement is the best choice to characterize the modulated signals at the system level.

The Error Vector Magnitude (EVM), the difference between a reference vector and the actual received signal vector (Figure 16), is a key metric in modulation accuracy tests. EVM can measure performance on an operational link that contains all impairments—including but not limited to AM/AM, AM/PM distortion of PA, group delay of converter, phase noise of LO, and noise figure of LNA. Together with other modulation analysis results and constellation displays, the error vector magnitude can tell the root cause of the problem or where the signal is degraded.

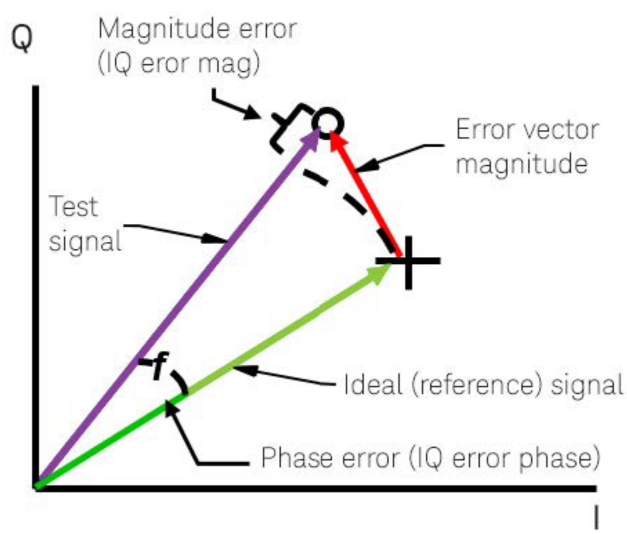

Figure 16. EVM concept.

Figure 17 provides some examples of EVM's usefulness. If the constellation is more rectangular than square (upper-left example), there is gain imbalance, indicating improper scaling of I and Q signal magnitudes relative to each other. Skewing in the quadrature relationship between I and Q can distort the constellation shape relative to the decision boundaries (upper right). Phase noise can cause an angular smearing of the symbol points (lower left). Linear distortion such as AM/AM conversion and AM/PM conversion create symbol points that are rotated in phase and fall short of the desired amplitude (lower right).

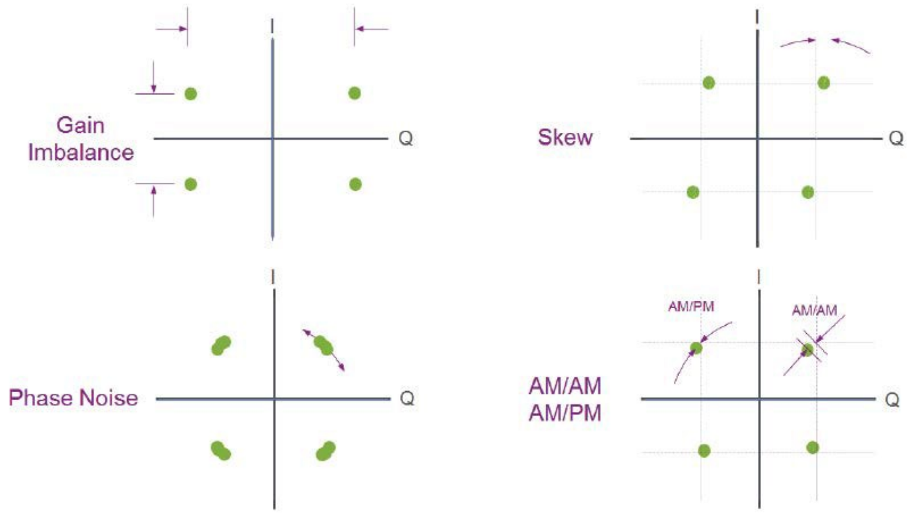

Figure 17. Each type of deviation provides clues about the underlying I/Q impairments that are affecting signal quality.

89600 VSA software together with a Keysight signal analyzer can perform the modulation accuracy measurements easily. The measurement results would include error vector magnitude (EVM), IQ offset, quadrature error, and gain imbalance. 89600 VSA supports all the standard digital modulation schemes used in satellite communication like QPSK, QAM, APSK, as well as custom modulation which may be of interest in satellite applications. Custom constellations can be defined by creating your own IQ maps; for example, users can define a custom 32 APSK signal by specifying the number of constellation states for each ring, as well as magnitude (for spacing) and phase of each ring.

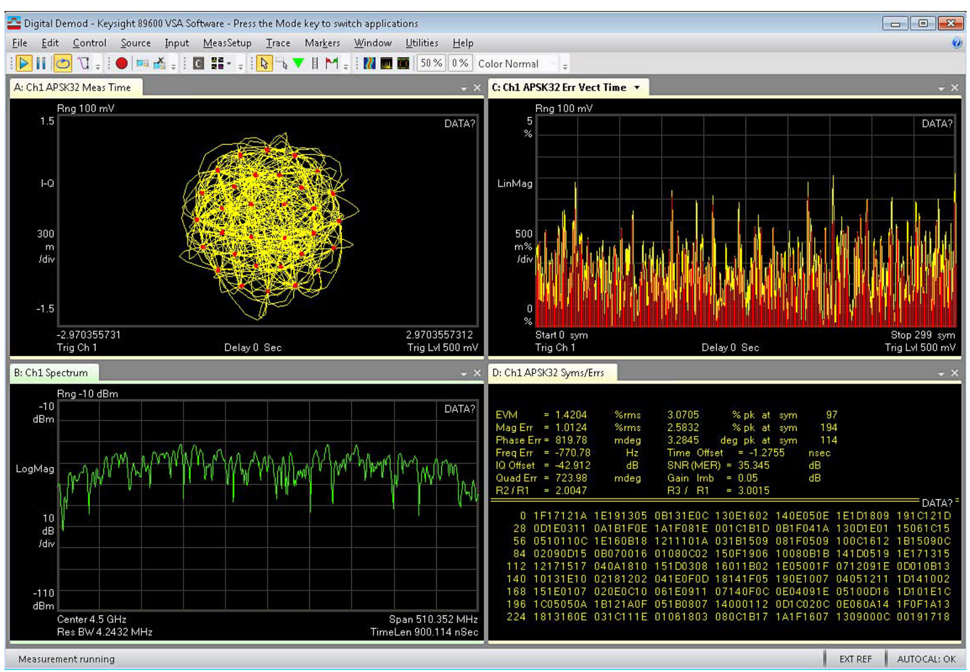

Figure 18. Digital demodulation in the 89600 VSA software enables detailed analysis of the corrected, custom 32 APSK signal.

Powerful Real-Time Signal Analysis (RTSA) for Interference Detection

With the increasing number of satellites in orbit and the growing complexity of the electromagnetic environment on Earth, interference detection for the satellite system has become a serious problem facing both satellite operators and regulation institutions. Traditional satellite monitoring systems —which are based on frequency sweeping technology—work well with interferers that are present on the transponder for a significant amount of time. However, for unintentional interferences, such as air to air radar signals with low duty cycles, the sweep rate will limit the monitoring systems ability to detect the signals.

Figure 19 illustrates the concept of frequency sweeping. The RBW filter and sweep trajectory—shown in green —are plotted against time, while 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. As shown in Figure 19, several signals are missed in this mode.

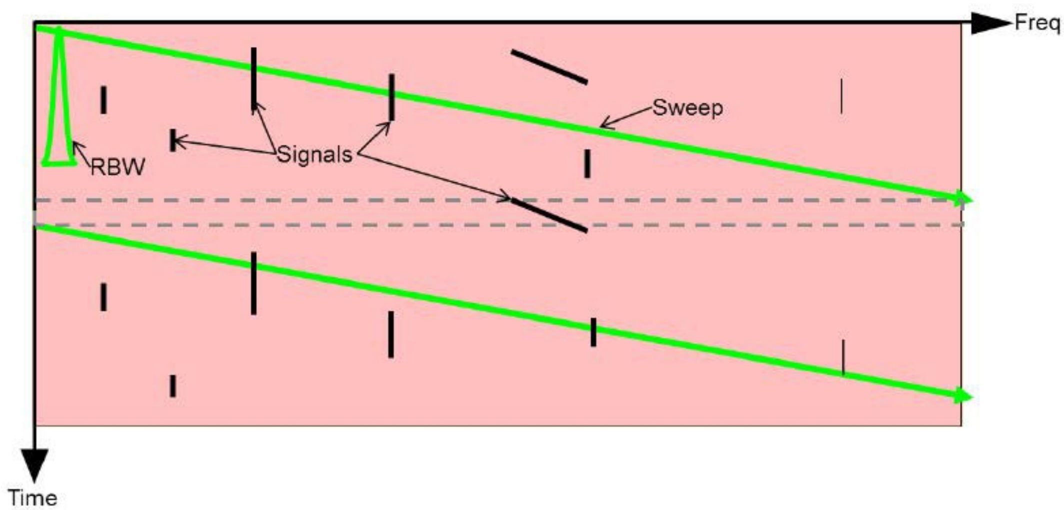

Figure 19. Example of traditional sweep.

However, in Real-time spectrum analysis (RTSA) 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 20). With improvements in digitizers and DSP technology, this technique can cover a gap-free span of 2 GHz in standalone signal analyzers like N9032B PXA and N9042B UXA. The gap-free nature of RTSA mode--available for the X-Series, handheld FieldFox, or compact PXIe analyzers--makes it ideal for detecting transient signals. To display all this data, traces which can show the signal behavior over time are a critical part of real-time analysis. Persistence and spectrogram displays provide insight into the time, frequency, and amplitude behavior of signals.

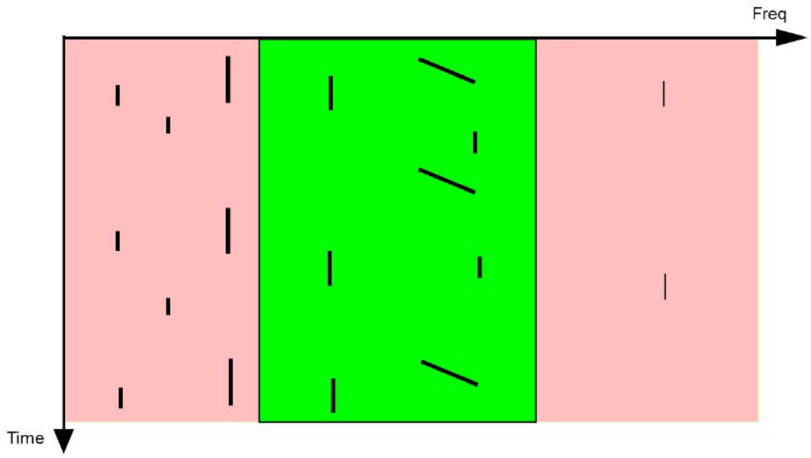

Figure 20. RTSA data capture and analysis mode.

Below (Figure 21) is an example of monitoring 12 satellite channels while there is interference from radar signals (1/10 duty cycle) nearby. The interference signals are captured and displayed on the screen clearly. Additionally, you can focus on the signal of interest with effective triggering mechanisms such as frequency mask trigger (FMT) and/or time qualified trigger (TQT). Used together with 89600 VSA, it is easy to capture the interference signal, play the signal back, then perform an in-depth analysis on it.

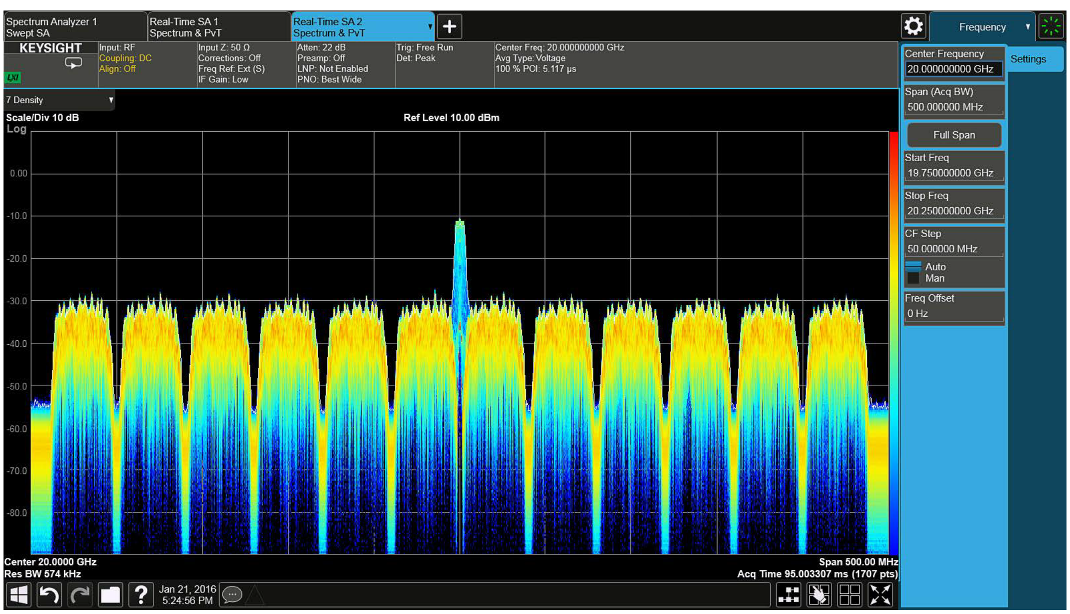

Figure 21. RTSA for interference detection.

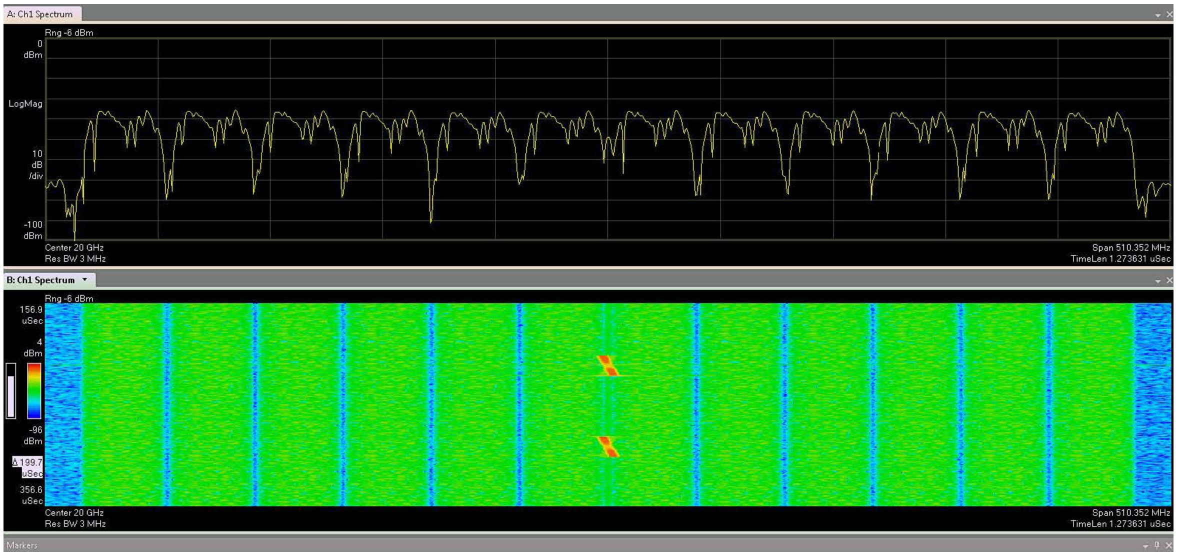

Figure 22. Capture, playback and analyze the interference signal.

Conclusion

X-Series signal analyzers are the benchmark for accessible performance that puts users closer to the answer by easily linking cause and effect. Across the full spectrum – from CXA to UXA – users will find the tools they need to design, test, and deliver their next breakthrough.

With measurement options that range from excellent to exceptional, the multi-touch X-Series signal analyzers accelerate innovation in satellite components and systems. The available software options include X-Series measurement applications that provide proven, ready-to-use measurements and the 89600 VSA software that enables comprehensive demodulation and vector signal analysis. As satellites become more complex with wider bandwidths and more potential for interference, the X-Series signal analyzers can help link cause and effect, bringing you closer to the answer.

Resources

- X-Series Measurement Applications Brochures
  X-Series Measurement Applications | Keysight
- N9032B PXA X-Series Signal Analyzer Data Sheet
  N9032B PXA X-Series Signal Analyzer, Multi-Touch | Keysight
- N9042B UXA X-Series Signal Analyzer Data Sheet
  N9042B UXA X-Series Signal Analyzer, Multi-touch | Keysight
- Signal Analyzers X-Series Brochure
  Signal Analyzers X-Series | Keysight