Keysight Technologies

Overcoming the Challenges in Satellite Testing and Interference Detection

Application Note

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights

Introduction

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

This application note focuses 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. For the converter, its 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 replay. Traditionally, most transponders use the so-called “bent pipe” style (Figure 1), where the signal is received by the satellite and converted to the downlink frequency and then re-transmitted. There is no change to the nature of the transmissions between the earth stations. This style has limited processing and flexibility. The earth station must organize the transmissions to make sure the transponder resources are used efficiently. However, there is a trend in modern satellites toward using onboard processing, which is called a digitally regenerative payload (Figure 1). The signal is demodulated, decoded, re-encoded, and modulated on the satellite. 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 also has the ability to transmit wide dynamic ranges with low RF signal-to-noise ratios. However, digitally regenerative payload design is considerably more complex than the traditional analog bent pipe.

In the digital payload where digitally modulated signals are present, test signals also become more complex. While continuous wave (CW) tones can be used to test some of the components, such as power amplifiers (PAs), CW tones cannot be used to test the complete payload. Here modulation analysis becomes more important, which will be covered in later sections.

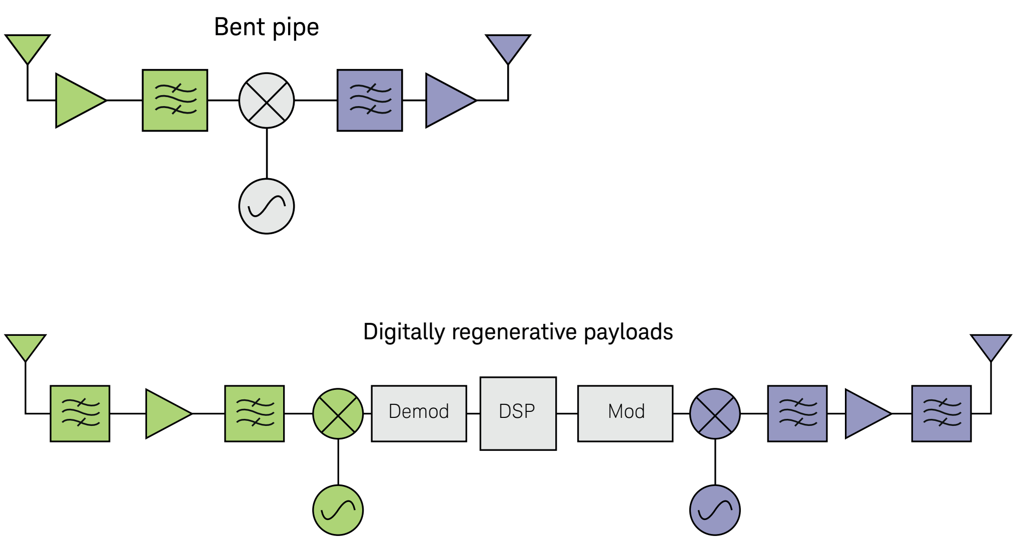


Figure 1. Traditional (top) and modern (bottom) satellite transponder architecture

Wideband Satellite Component Test

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

Wideband PA test

There are some significant challenges that come along with designing and testing wider bandwidth transponders. When many channels are sharing a single transponder, there is potential for interference between the channels. A significant contributor is non-linear distortion within the power amplifier in the transponder. This can lead to 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.

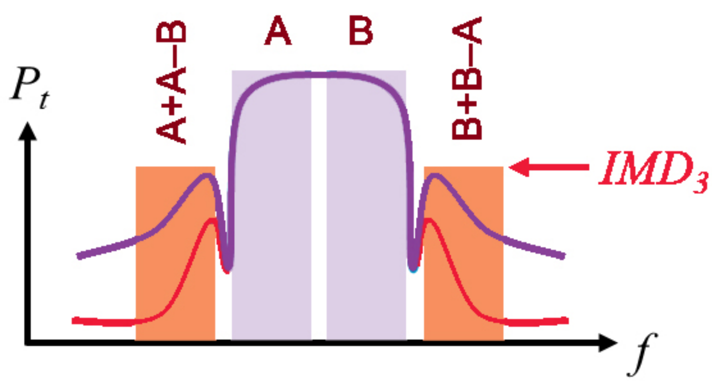


Figure 2. Non-linear distortion in PA creates interference in adjacent channels

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.

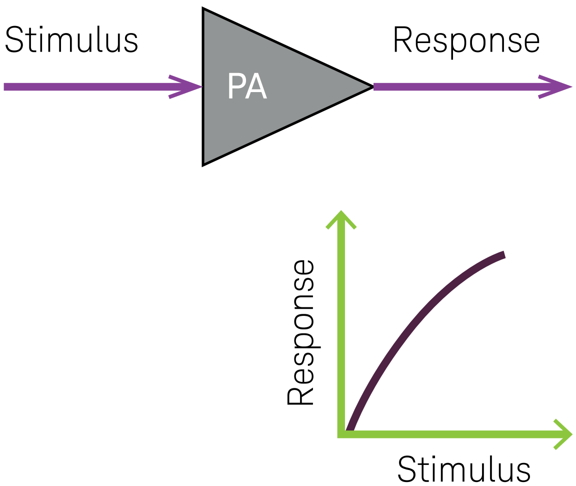


Figure 3. Stimulus and response PA test

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, if the modulated signal is 144 MHz and the 3rd order non-linear impacts will be used in the signal conditioning, the N9030B-B5X would provide 510 MHz of analysis bandwidth, which is enough to capture the 144 MHz wide modulated signal along with the 3rd order spectral regrowth components.

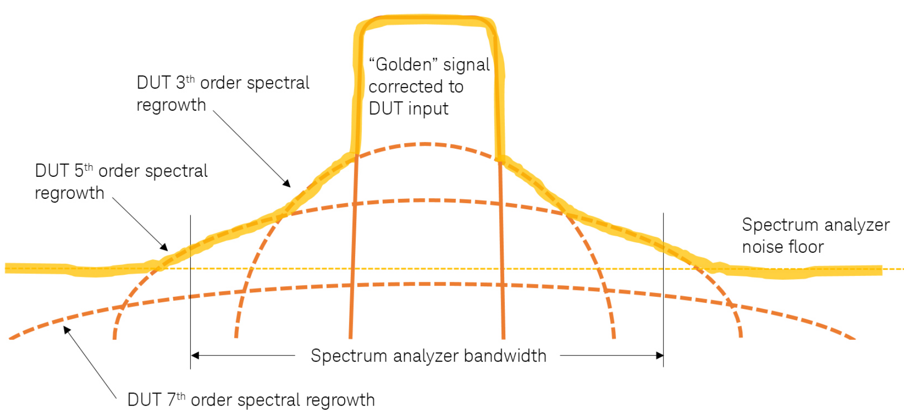


Figure 4. Power spread for PA non-linearity effects

Through a simple stimulus-response measurement, you can see AM/AM, AM/PM, gain compression, and delta error vector magnitude (EVM) (Figure 1).

- 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.

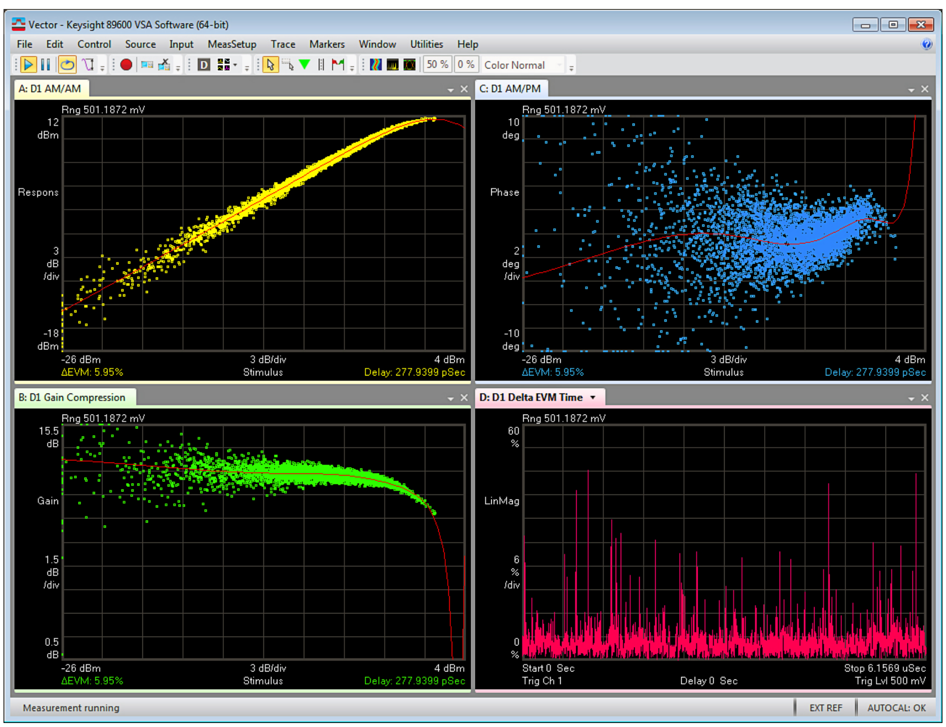


Figure 5. Examples for satellite PA measurements

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 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

To transmit information without distortion, it requires a linear system for phase, which is defined as linear phase response over the transmission bandwidth. Group delay flatness is a measure of the phase linearity and is therefore an important parameter in determining the transmission quality of a system.

Group delay is measured based on phase measurements and is defined as the negative-slope of the transmission phase with respect to the frequency (Figure 6).

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

Where Φ is phase, ω is frequency.

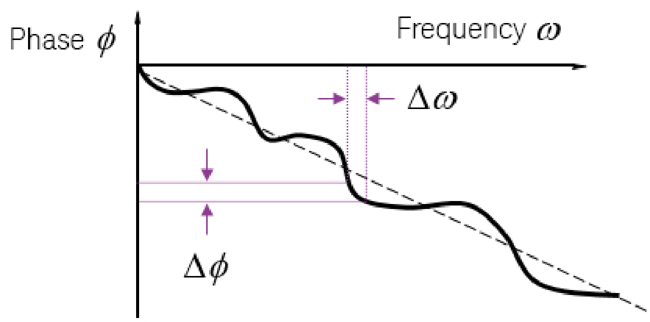


Figure 6. Group delay concept

There are many methods to measure group delay. Traditionally, the group delay measurement can be performed with a network analyzer using two tone methods. In this application note, a new approach is discussed which is based on using a wideband multi-carrier signal as stimulus and a signal analyzer to capture the response of the device under test (DUT).

The wideband multi-carrier signals can be generated using an arbitrary waveform generator (AWG). Modern AWGs are capable of generating several GHz of analog bandwidth and a vector signal generator can be used as an external RF upconverter to move the stimulus signal to the center frequency of interest. In the 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.

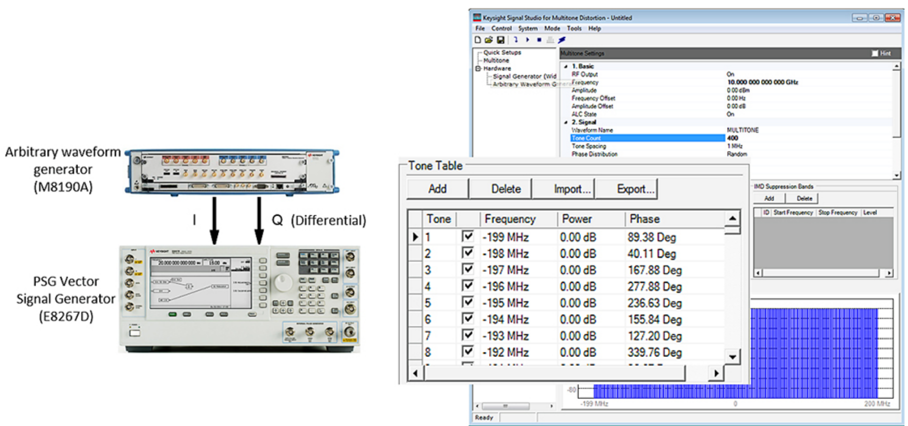


Figure 7. Multi-tone signals generated using an M8190A AWG and E8267D PSG vector signal generator with N7621B Signal Studio for multitone distortion

On the receiver side, 89600 VSA software with option BHL (channel quality measurements) enables you to make group delay measurements using a signal analyzer. The software provides the frequency converter corrections to enable tests for frequency converting DUTs. The definition of the multi-tones can be recalled for faster measurement configuration.

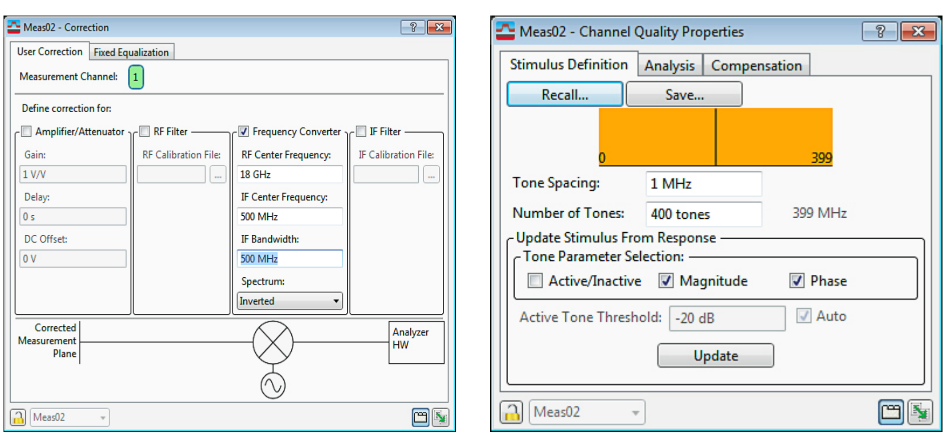


Figure 8. Frequency converter correction feature (left) and stimulus definition recall feature (right)

The measurement procedure for group delay is actually 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.

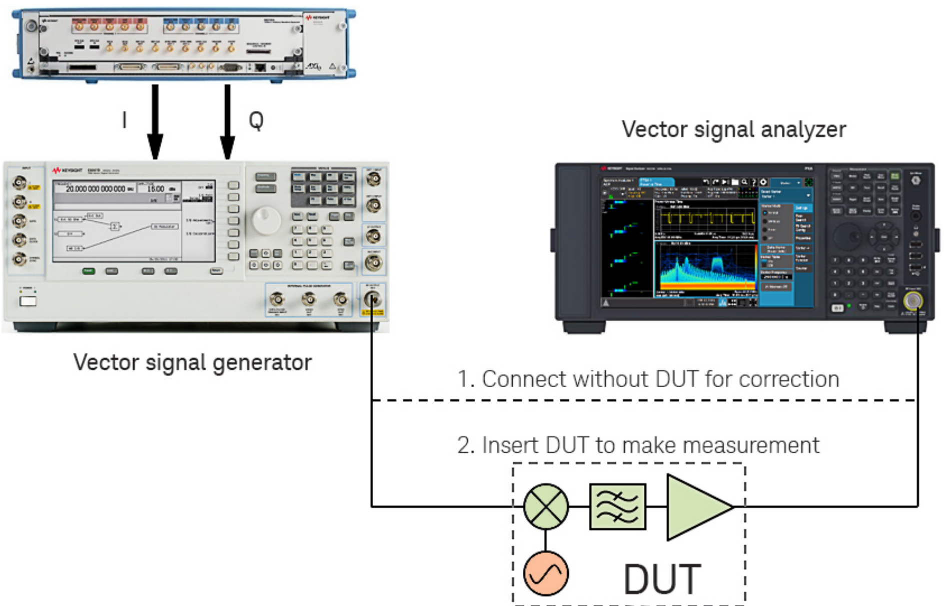


Figure 9. Group delay measurement, two steps

An example of the measurement results is shown below with frequency magnitude response, phase, and group delay traces (Figure 2).

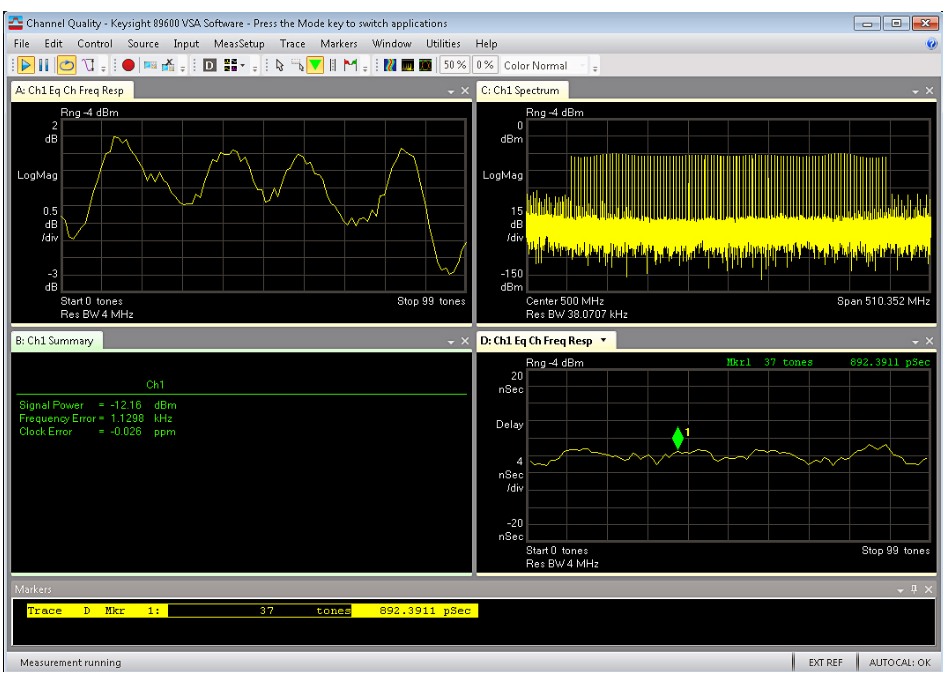
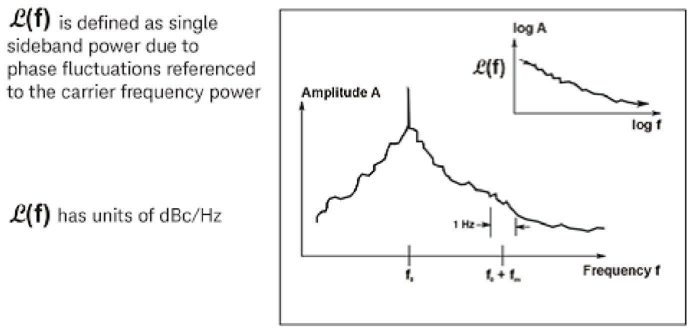


Figure 10. Group delay measurement example on converters

Phase noise test

In the frequency conversion system, the phase noise of the local oscillation (LO) 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 phase noise unit of measure 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.



$$\mathcal{L}(f) = 10 \log \left(\frac{\text{Power 1 Hz bandwidth}}{\text{Total power in full BW}} \right)$$

Figure 11. Phase noise definition

The 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 way, however, this method requires the phase noise of the instrument itself be much lower than the LO under test. N9030B PXA has superior phase noise, which can be used for common phase noise measurements (–136 dBc/Hz @ 1 GHz carrier, 10 kHz offset typical.)

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 “Measuring Noise and Noise-like Digital Communications Signals with Spectrum and Signal Analyzers” publication number 5990-5729EN.

N9068C phase noise measurement application built into the signal analyzer provides one-button phase noise measurements. It automatically optimizes the measurement in each offset range to give the best possible measurement accuracy.

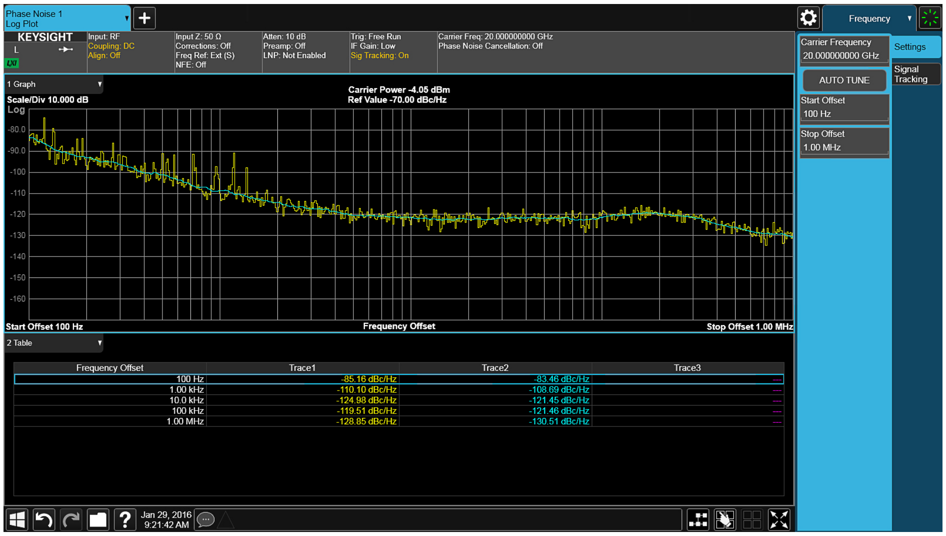


Figure 12. Phase noise measurement example

Low nosie amplifier 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 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 measurement.

There are two main approaches for making noise figure measurements, Y-factor method and cold source method. Y-factor is the most commonly used method, used with 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, AN 57-1” and “Noise Figure Measurement Accuracy – The Y Factor Method, AN 57-2”. In this application note, the focus will be measurement uncertainties.

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

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

Where,

- F_1 is the noise factor of the DUT
- F_2 is the noise factor of the noise figure instrument
- 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.

It can be seen that 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 13 shows the trend of measurement uncertainty. A noise figure uncertainty calculator is used for the simulation, and all the other parameters remain the same in the simulation. It can be seen that with the decrease of instrument noise figure, the measurement uncertainty becomes lower.

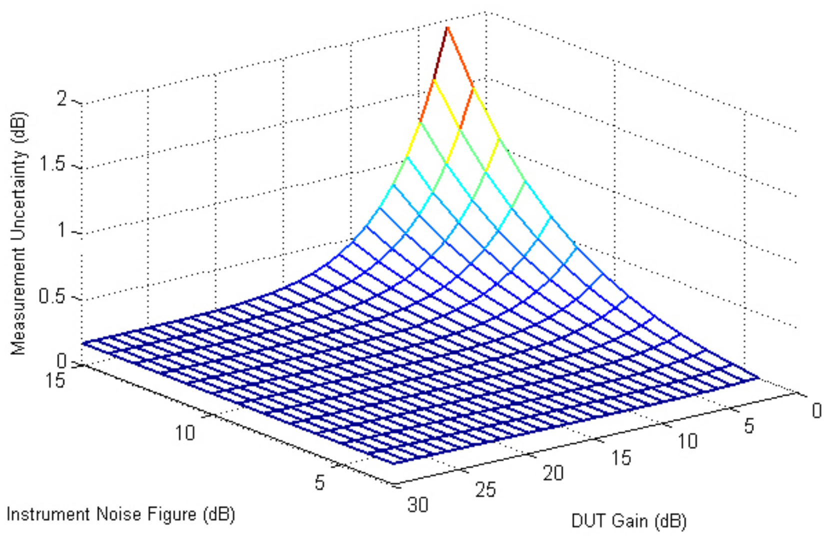


Figure 13. Measurement uncertainty results versus instrument noise figure and DUT gain

Keysight offers external USB preamplifiers to be used with signal analyzer to significantly decrease the effective instrument noise figure as shown in Figure 14.

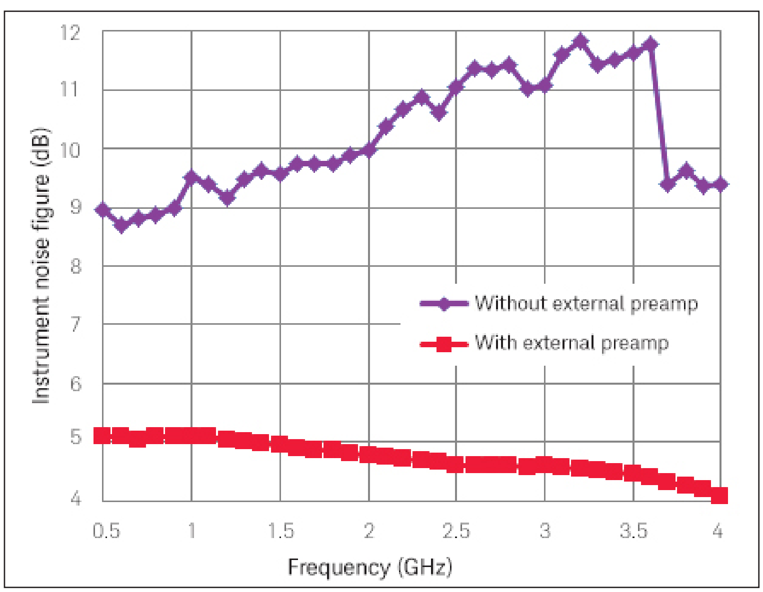


Figure 14. Effective instrument noise figure without external preamp (blue line) and with external preamp (red line)

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

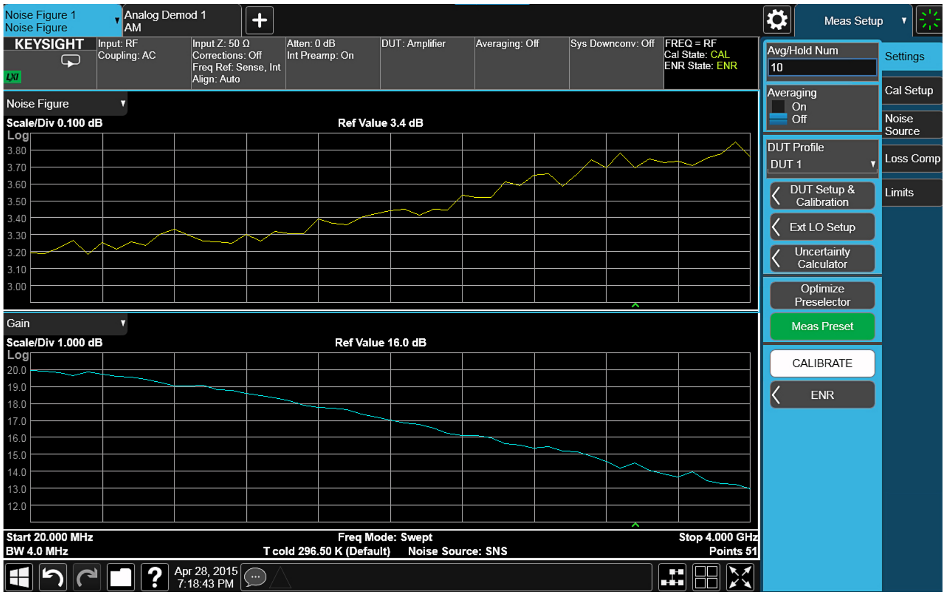


Figure 15: Noise Figure Measurement on LNA

Modulation analysis of standard and custom modulation types

One ongoing challenge for satellite operators is to transmit 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, it becomes increasingly difficult to view a time-domain waveform or frequency waveform and understand or trouble-shooting problems in signal quality. Modulation accuracy measurement is the best choice to characterize the modulated signals at the system level.

EVM is a key metric in modulation accuracy tests. It is the difference between a reference vector and the actual received signal vector (Figure 16) and it can measure performance on an operational link that contains all impairments (including AM/AM, AM/PM distortion of PA, group delay of converter, phase noise of LO, and noise figure of LNA, etc). Together with other modulation analysis results and constellation displays, it can tell the root cause of the problem or where the signal is degraded. Figure 17 gives some examples. If the constellation is more rectangular than square (upper-left example), there is gain imbalance and it indicates 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).

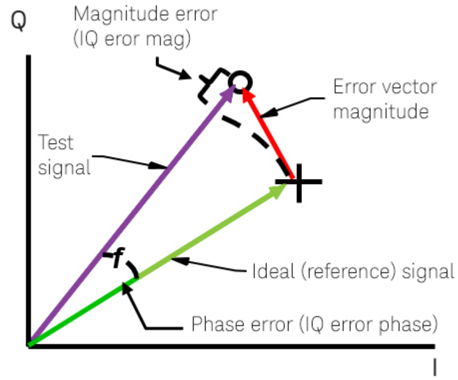


Figure 16. EVM concept

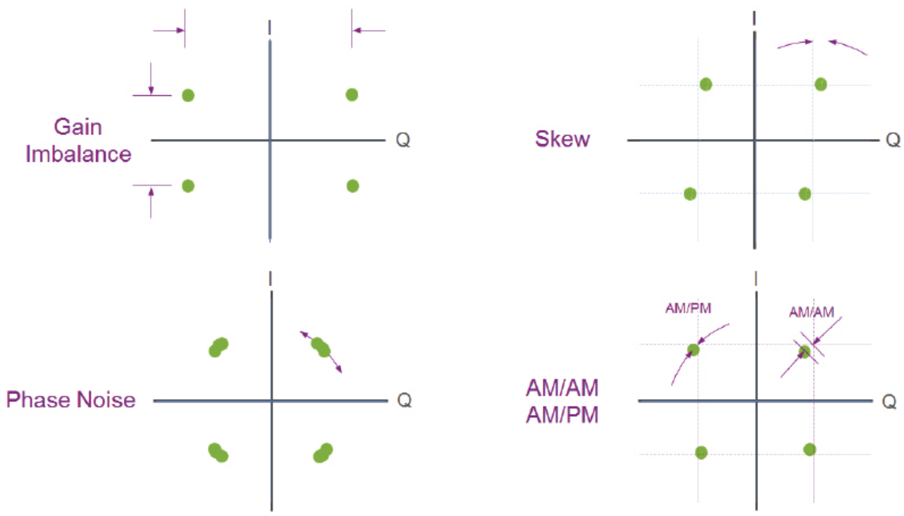


Figure 17. Each type of deviation provides clues about the underlying I/Q impairments that are affecting signal quality.

89600 VSA software together with 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, a custom 32 APSK signal by defining the number of constellation states for each rings as well as ring magnitude (for spacing) and ring phase.

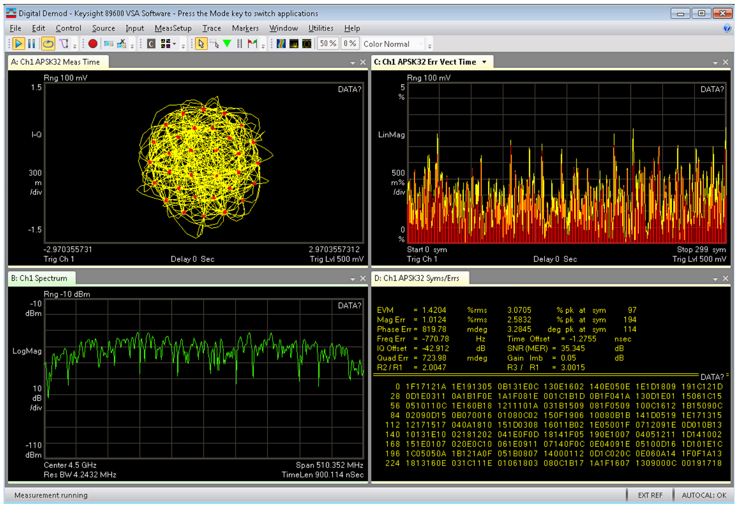


Figure 18. Digital demodulation in the 89600 VSA software enables detailed analysis of the corrected, custom 32 APSK signal.

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

With the increasing number of satellites in orbit and the growing complexity of electromagnetic environment on the earth, interference detection for the satellite system becomes a serious problem facing satellite operators and regulation institutions. The 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. But for the 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 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 be neither detected nor displayed. It can be seen that in this mode, several signals are missed.

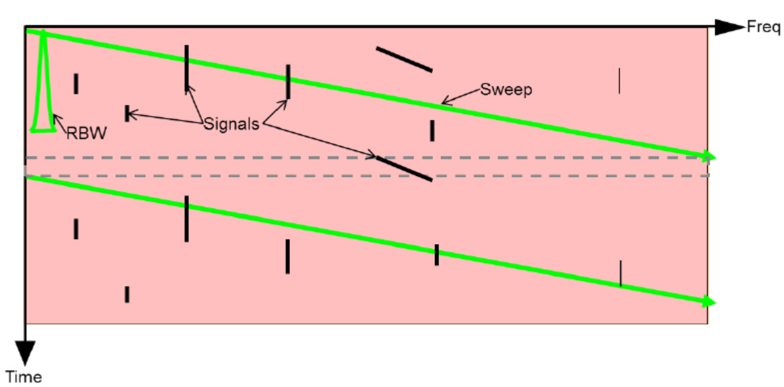


Figure 19. Example of traditional sweep

However, in 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). Due to the restriction of the FPGA capability, the bandwidth of RTSA is limited compared to the traditional frequency sweep method. For example, the bandwidth of RTSA is usually limited to less than 160 MHz for most instruments, and the frequency sweep range can cover upto tens of GHz. With improvements in digitizers and DSP technology, this technique can cover a gap-free span of 510 MHz in standalone signal analyzers like N9030B PXA. To display all of 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 time, frequency and amplitude behavior of signals. The gap-free nature of RTSA mode makes it ideal for detect transient signals.

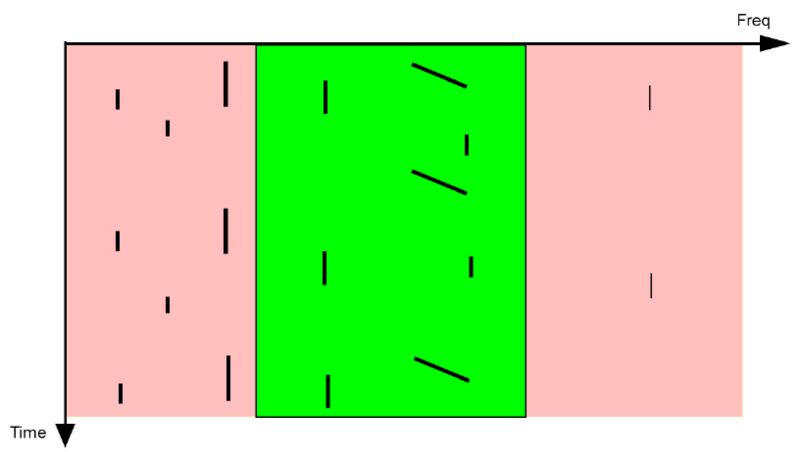


Figure 20. RTSA data capture and analysis mode.

Below (Figure 21) is an example of monitoring 12 satellite channels while there is an interference from radar signals (1/10 duty cycle) nearby. The interference signals are captured and displayed on the screen clearly. And you can also choose the 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 it back and go through deep analysis on it.

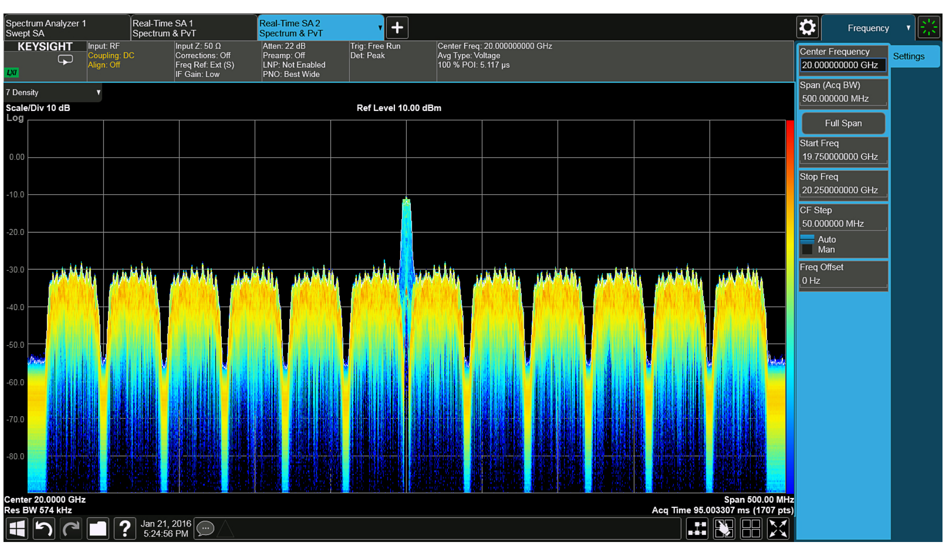


Figure 21. RTSA for interference detection

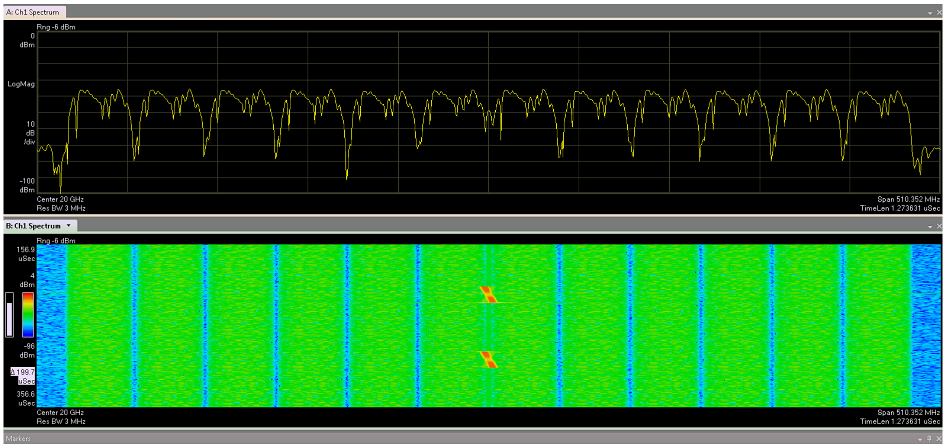


Figure 22. Capture, play back and analyze the interference signal

Conclusion

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

With measurement options that range from excellent to exceptional, the multi-touch PXA accelerates 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 PXA can help you link cause and effect and put you closer to the answer.

References

Literature

X-Series signal analyzers – Brochure, literature number 5992-1316EN

N9030B PXA X-Series signal analyzer, multi-touch - Data Sheet,
literature number 5992-1317EN

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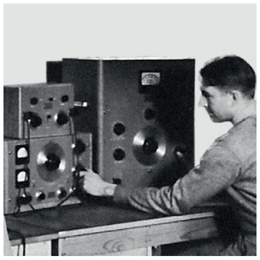
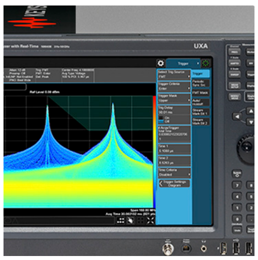


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Published in USA, December 1, 2017
5992-1505EN
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