GaN or GaAs, TWT or Klystron - Testing High-power Amplifiers for RADAR Signals using Peak Power Meters

Measuring and characterizing pulsed RF signals used in RADAR applications present unique challenges. Unlike communications signals, pulsed RADAR signals are "on" for a short time followed by a long "off" period. During "on" time, the system transmits anywhere from kilowatts to megawatts of power. The high-power pulsing can stress the power amplifier (PA) in a number of ways both during the on/off transitions and during prolonged "on" periods. As new PA device technologies are introduced, the latest one being GaN, the behavior of the amplifier needs to be thoroughly tested and evaluated. Given the time domain nature of the pulsed RF signal, the best way to observe the performance of the amplifier is through time domain signal analysis. This application note explains why the peak power meter is a must-have test instrument for characterizing the behavior of pulsed RF PAs used in RADAR systems.

RADAR Power Amplifier Technology Overview

Before we look at the peak power meter and its capabilities, let's look at different technologies used in high-power amplifiers (HPA) for RADAR systems, particularly GaN on silicon carbide (SiC) and why it has grabbed attention.

The second part of the 20th century saw the rise and dominance of semiconductor technology in electronics, and the ushering out of the Vacuum Electron Devices (VEDs), commonly referred to as tubes. Aside from rock bands' love for the "warm" sound of the tube amplifier, one area in which VEDs maintained their dominance has been PAs that operate up to megawatts of output power at very high frequencies (1 GHz to 100 GHz) found in RADAR systems. Most commonly used VED technologies in RADAR applications today are Traveling Wave Tubes (TWT), Klystrons, Magnetrons, and Gyrotrons. TWT amplifiers (TWTA) provide what the RADAR systems need the most: multi-octave bandwidths, multi-kilowatt peak power output, support of high frequencies, as well as ruggedness and reliability. Compared to TWTAs, Klystron power amplifiers (KPA) offer better efficiency. About four decades ago, semiconductor-based PA solutions called solid state power amplifiers (SSPA) started making modest inroads as an alternative technology for certain RADAR applications. Silicon-based laterally diffused metal oxide (LDMOS) offered a few hundred watts of output power, ruggedness, and reliability. Its upper frequency limited to about 3 GHz (S-Band) at high output powers curbed its applicability in RADAR. Gallium arsenide (GaAs), a wide-bandgap semiconductor, overcame the high frequency deficiency of LDMOS, reaching above 100 GHz, yet its lower operating voltage has limited its output power capability. High-power GaAs amplifiers have often required paralleling of multiple devices to reach desired power levels at the expense of loss in efficiency. GaAs found common use in RADAR but still was not a viable alternative in most high-power RADAR applications. About two decades ago when GaN was introduced, it created much excitement since it offered hundreds of watts of output power at very high frequencies; it also provided the ruggedness required in RADAR applications. In the earlier years of GaN, the concerns over reliability due to lack of a suitable substrate to get the heat out of the die were addressed by placing GaN on a SiC wafer substrate. While GaN provided the heat capacity, SiC provided three times better thermal conductivity. The enhanced thermal performance improved the reliability and ruggedness.

While TWTAs and KPAs are here to stay for the foreseeable future (e.g., a TWTA is being used on the James Webb Space Telescope), GaN has established itself as a suitable lower cost alternative in the long run for RADAR applications.

Peak Power Meter for Pulsed RADAR Measurements

The most critical analysis of the pulsed RF signal takes place in the time domain. Since peak power meters measure, analyze, and display the power envelope of an RF signal in the time domain, they are an essential tool for measuring, analyzing, and characterizing anomalies and behavior of high-power amplifiers used in pulsed RADAR applications. Figure 1 shows a simplified block diagram of a benchtop peak power meter.

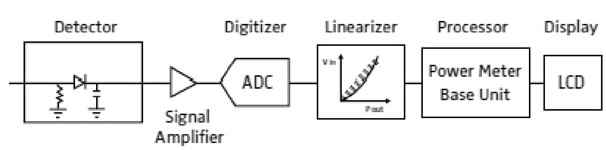

Figure 1. *Block diagram of a peak power meter.*

The front end of a power meter is the RF envelope detector housed in a power sensor. The detector removes the RF carrier and generates an analog waveform representing the envelope of the RF input signal. The most critical specification of the detector is its response time to a pulsed RF signal or its rise time. If the detector does not have the bandwidth to track the envelope of the signal, accuracy of all measurements, including peak, pulse, and average power, is compromised (Figure 2).

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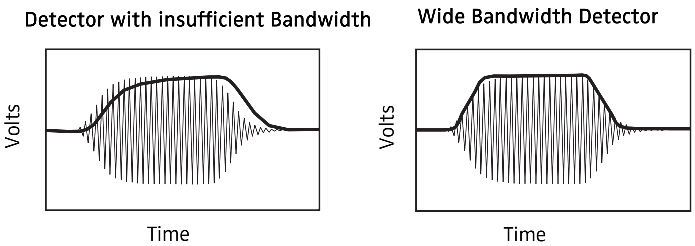

Figure 2. Impact of rise time and bandwidth capability of the sensor for accurately measuring and displaying the pulse RF signal.

The detector output is then digitized by an analog-to-digital converter (ADC). The digitized samples are processed by the digital signal processor for linearization and measurement analysis. The processed waveform is displayed in the time domain as power-versus-time along with automated pulse and marker measurements. In Maury Microwave peak power meters from the Boonton RF Power Analysis product line, the vertical axis displays the power (or voltage) in watts, volts, or dBm with the ability to change the scaling and vertical center. On the horizontal axis, the timebase can be set as low as 5 ns per division (50 ns span) to zoom in to a specific portion of the waveform, such as the rising or falling edge, to observe fine details. These peak power meters use the Random Interleave Sampling (RIS) technique; this yields 100 ps resolution on repetitive waveforms. Figure 3a shows a time domain diagram of the conventional sampling and interpolation method. Figure 3b shows the RIS method. Figure 3c shows how the resolution is improved going from conventional to the RIS-based method on a 4500C peak power analyzer.

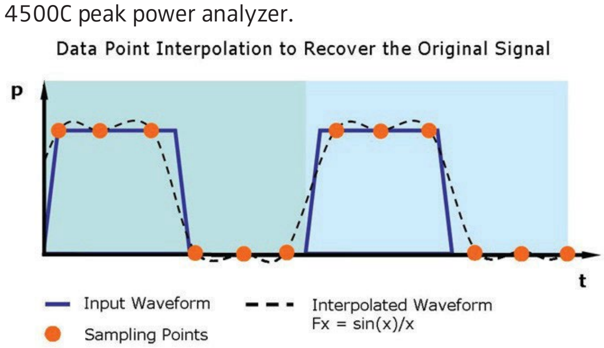

Figure 3a

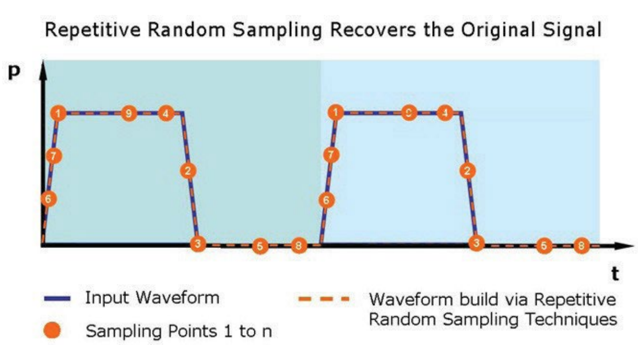

Figure 3b.

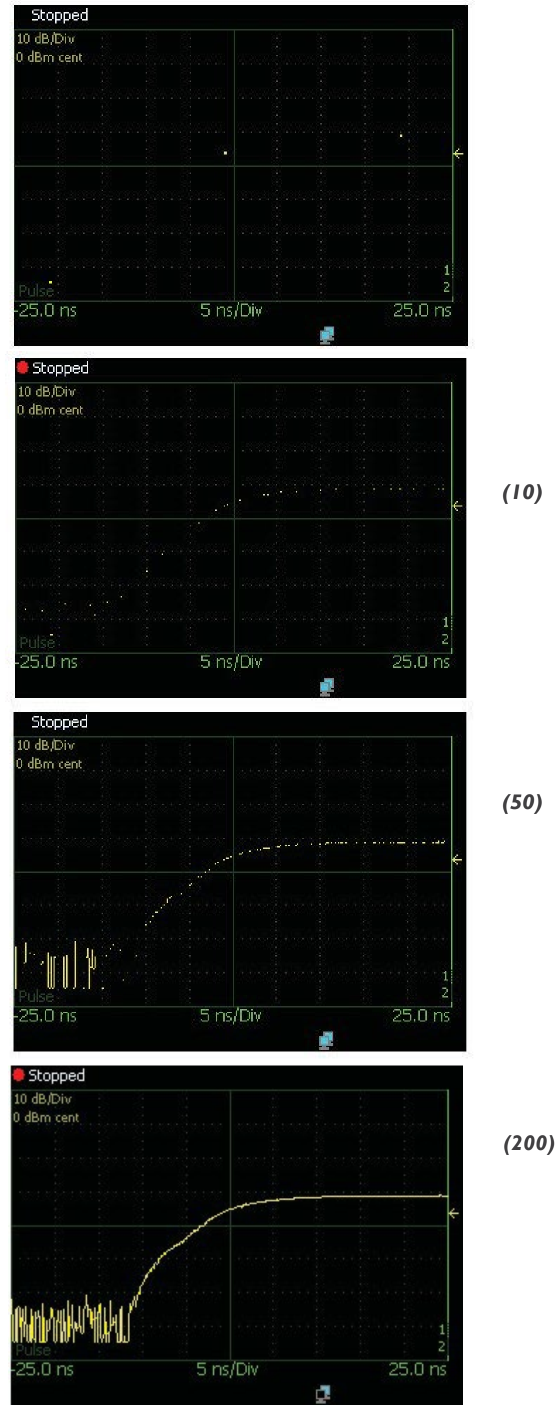

Figure 3c. These four screenshots show how a waveform is built through repetitive sampling techniques. The first sweep (top) shows an initial set of three data points, equally 20 ns apart. The remaining three show 10, 50, and 200 sets of additional data. This method achieves the highest resolutions, allowing the user to zoom in on fast signals

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Peak power meters can be triggered by the incoming RF signal or by an external gating (baseband) trigger signal applied to auxiliary inputs. Real-time Power Processing™ featured in the RTP5000 Series USB peak power sensors allows the sensor to perform up to 100,000 measurements per second, capturing each pulse and glitch event. Advanced triggering features of Maury Microwave peak power meters, like trigger holdoff, delays the re-arming of the trigger, which is useful when working with identification friend or foe (IFF) or other RADAR signals.

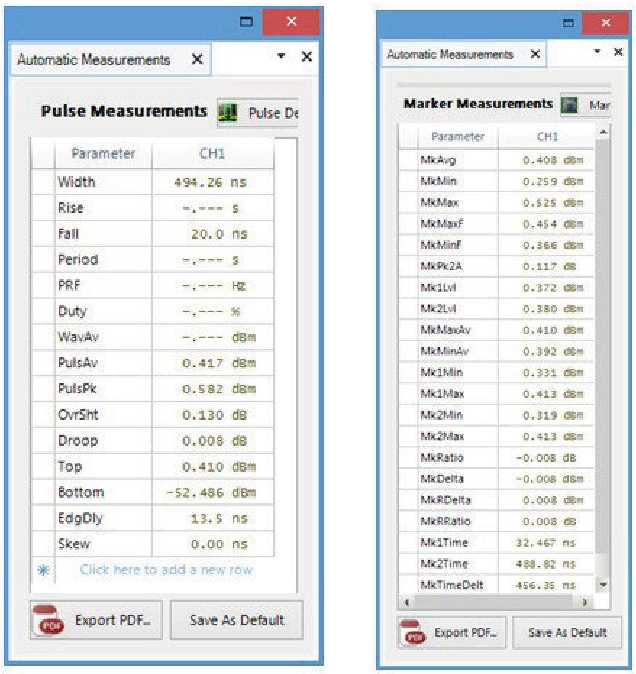

Figure 4. *Automated pulse and marker measurements using the RTP5000 Series USB peak power sensor.*

In terms of measurement capabilities, peak power meters perform numerous manual, automated marker, and automated pulse measurements. Automated pulse measurements (Figure 4) provide measurement values of a number of critical parameters that help characterize the performance of the power amplifier and the RADAR system. Rise and fall time indicate the amplifier's ability to output a pulsed RF signal with the necessary signal integrity. Overshoot pinpoints potential ringing problems. Droop shows the amplifier's power supply limitations or the impact of thermal effects with prolonged pulse widths.

Pulse width, period, pulse repetition rate, and duty cycle measurements provide other time domain characteristics of the signal. There are also a number of automated marker measurements (Figure 4 on the right) that enable time-gated measurements. These measurements are performed between two markers and provide average, peak, min, and max power readings, as well as peak-to-average ratio, delta marker of power level, and delta time marker measurements.

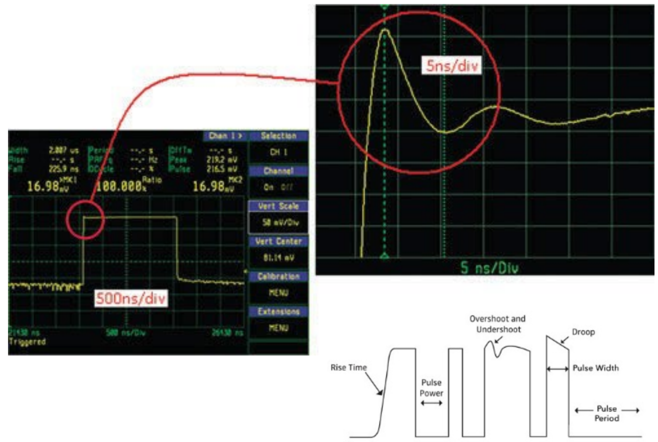

Figure 5. *Some of the pulse characteristics that can be measured using a peak power meter.*

A significant advantage power meters have over other measurement instruments is the size of the power sensor. It is small and light enough to be directly connected to the measurement port without the need for an RF cable, which can degrade measurement accuracy due to impedance mismatch and cable loss, especially at higher frequencies.

For automated test environments, all Maury Microwave peak power meters can be remotely accessed via various interfaces such as USB, LAN (TCP/IP), RS232, and GPIB, depending on the model.

Test Setups for Making Pulsed RADAR Measurements

Although there are numerous pulsed RF amplifier architectures, two types are considered in this application note. The first is an amplifier; the input is CW and the output is pulsed RF. A gating signal modulates the incoming signal to achieve the desired pulse RF signal (Figure 6).

In Figure 6, a dual-channel meter measures the input signal power at P1 and the reflected power at P2 in the time domain for return loss calculation, as well as monitoring anomalies of the reflected signal. At P3 the output of the amplifier is monitored and measured. A second dual-channel power meter is used to measure the output of the amplifier to calculate parameters, such as gain, as well as monitor the reflected power of the load. The gating signal that modulates the RF input signal can also trigger the power meter enabling delay and latency measurements.

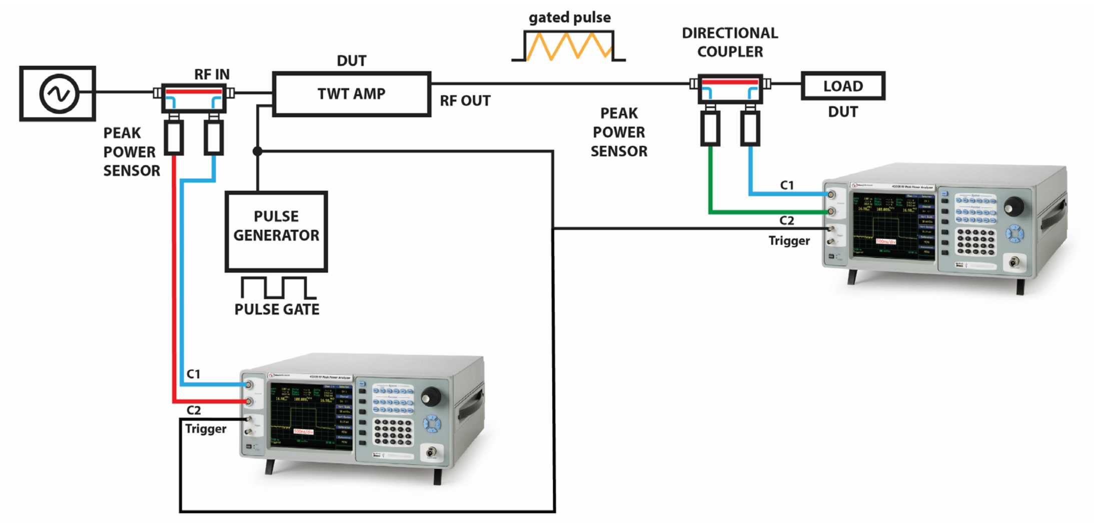

Figure 6. *Test setup for time domain pulse measurements. The input signal is CW and the output signal is pulsed RF. A gating signal modulates the incoming CW signal*

The highest performance Maury Microwave benchtop peak power analyzer, model 4500C, is equipped with waveform math capabilities and is capable of displaying gain and return loss in the time domain. The instrument is also equipped with two scope channels. When the gating signal to the amplifier triggers the peak power meter, both the gating signal and the output of the amplifier can be displayed on the peak power meter, enabling critical timing measurements as well as detecting if any amplifier anomalies are caused by the gating signal.

While benchtop models support one (single) or two (dual) channels, the RTP5000 Series USB peak power meters can measure and display up to eight channels on a single GUI window. Using three or four USB sensors, amplifier input and output power, reflected input power, and reflected load power can all be measured and displayed on the same trace window or in an automated test setup via remote programming.

The second test setup includes an amplifier where the output is an amplified (and potentially distorted) version of the pulsed RF input signal (Figure 7) with no external gating signal supplied to the amplifier. The setup is ideal for analyzing not only fully assembled amplifiers but also subassemblies, such as the driver stage or the final stage of the amplifier or even a semiconductor power transistor. The setup uses three USB peak power sensors and a directional coupler to make scalar-like gain and return loss measurements of the amplifier.

Since the power rating of a typical sensor is about +20 dBm, the output of the PA is attenuated to protect the power sensor while making the output power measurement. Before measurements can be taken a thorough calibration procedure is required at the frequencies in which the amplifier is going to be tested to account for losses in the signal path. The losses that need to be calibrated out in the test setup of Figure 7 and calculations required to compute gain and return loss are provided below.

L1: Loss from signal generator output to the FWD port of the directional coupler.

L2: Loss from signal generator output to the power amplifier input.

L3: Loss from amplifier output to the 40 dB attenuator output.

L4: Loss from amplifier input into the REV port of the directional coupler.

Once the losses are measured, input, output, and reflected power measurements can be made:

P1: Power reading at FWD port of the directional coupler.

P2: Power measured at the 40 dB attenuator output.

P3: Power measured at REV port of the directional coupler.

PA input power = P1+L1-L2

PA output power = P2+L3

PA input reflected power = P3+L4

All Maury Microwave peak power meters and USB power sensors are capable of adding an offset to the measurements so the math above can be done by the meter once the losses are measured and entered into each channel as an offset.

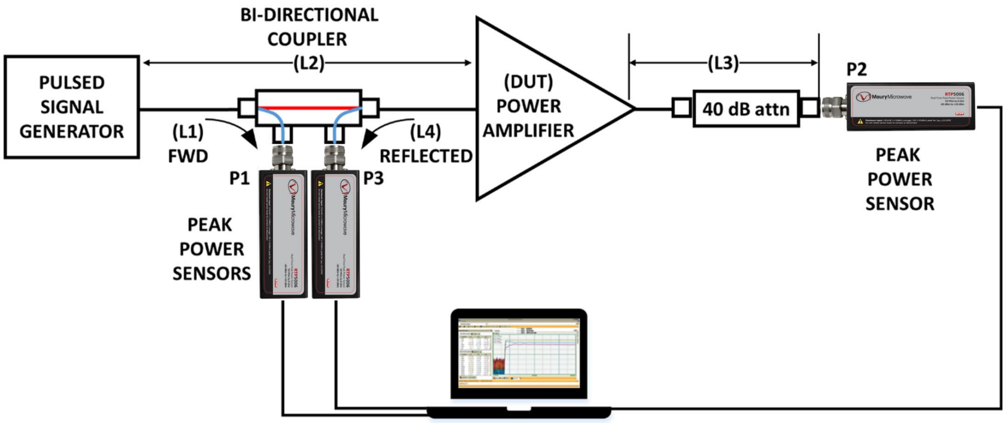

Figure 7. Test setup showing time domain scalar-like gain and return loss measurements using three sensors and one directional coupler.

The input, output and reflected power measurements can be used to compute gain (S21) and input return loss (S11).

PA gain (dB) = PA output power (dBm) – PA input power (dBm)

PA input return loss (dB) = PA input power (dBm) – PA input reflected power (dBm)

The 4500C can perform these measurements in the time domain using waveform math.

It is important to note that in both test setups, Figure 6 and Figure 7, the directional couplers need to have excellent directivity in order to make accurate power measurements, especially for return loss calculations. Unused ports of the couplers must be terminated with 50 ohms during measurements.

Figure 8. The screenshot captures the input, output and reflected waveforms of the pulsed RF signal. The blue trace (CH2) is output of the DUT (note overshoot and ringing) and the purple trace (CH3) is the reflected signal from the input port of the load on the output of the DUT.

Measurements

Figure 8 shows three waveforms measured with the test setup in Figure 7 using the RTP5000 Series peak power sensors. The input waveform is displayed on CH1, reflected waveform on CH3, and the output on CH2. Note that automated measurements performed on all three channels are displayed to the left of the trace display window. The measurements can be transferred to a spreadsheet to perform the necessary gain and return loss calculations, as well as other parameters of interest. In an automated test environment, the same measurements can be accessed through remote programming to perform gain and return loss computations as well.

When evaluating new technologies such as GaN, monitoring power droop across the pulse width is critical as it can be an indicator of the limitations of the thermal properties of the GaN device and its package. Time domain peak power measurements can be taken at the output of the amplifier (Figure 9).

Droop measurement capabilities are shown in Figure 9 using the Maury Microwave RTP5318 USB peak power sensor. Power droop can be measured either using the automated pulse measurements or using automated marker measurements as well as horizontal markers. The automated marker measurements can display the droop by placing markers at the desired points on the waveform and using the MkRatio measurement. Alternatively, reference lines can be placed on the vertical axis at the desired high and low points of the pulse to measure the droop. Automated pulse measurements are computed automatically based on pulse definition irrespective of marker or reference line placements.

Conclusion

Regardless of the technology used in a RADAR's power amplifier, high-resolution and highly accurate time domain power measurements are critical to understand amplifier performance and behavior. Peak power meters and USB peak power sensors are essential measurement tools for time domain power analysis to test RADAR power amplifiers for R&D, quality, manufacturing, field support, and system calibration applications.

Maury Microwave Peak Power Meter Solutions

Products in the Boonton RF Power Analysis product line feature over seven decades of expertise in power meter design and development, almost as long as RADAR systems have been around. Just as RADAR power amplifier technology has evolved so has power measurement technology. Maury Microwave peak power meters and USB peak power sensors are used today, as they have been for decades, in a wide range of civil and military RADAR systems and have become the instrument of choice in RADAR signal testing.

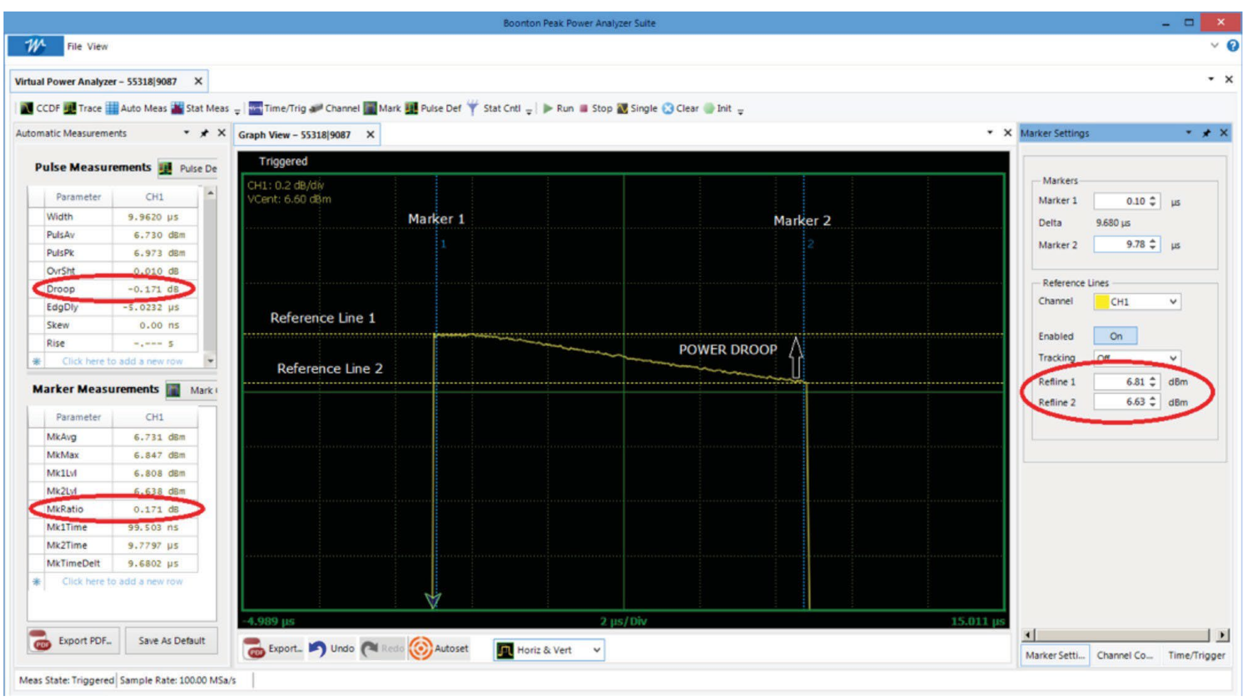

Figure 9. Droop measurement using an RTP5318 USB peak power sensor. Blue vertical lines 1 and 2 are markers placed for automated marker measurements. Yellow dashed horizontal lines are reference lines. Automated pulse measurements are computed automatically based on pulse definition irrespective of marker or reference line placements.

The 4500C is the top performance benchtop peak power analyzer. It is the instrument of choice for capturing, displaying, analyzing, and characterizing RF power in both the time and statistical domains for pulsed RF applications. 4500C, and its predecessors, has been deployed for weather, civilian and military aviation, and electronic warfare RADAR system testing. Waveform math and memory channels as well as two scope channels to monitor external trigger signals on the same display as the incoming RF envelope signal are unique to the 4500C.

The RTP5000 Series USB peak power sensors deliver benchtop performance in a USB form factor. The sensors are able to make 100,000 triggered measurements per second, making it ideal for capturing high PRI/PRR/PRF RADAR signals without missing a pulse or glitch event. Industry-leading 3 ns rise time enables it to handle the most challenging RADAR signals. 195 MHz video bandwidth makes it ideal for making time-gated power and crest factor measurements for broadband communications signals like Wi-Fi 6E and 5G cellular.

The PMX40 RF power meter is a companion to the RTP5000 Series USB peak power sensors. It provides design engineers and technicians the utility of a traditional benchtop instrument, the flexibility and performance of modern USB RF power sensors, and the simplicity of a multi-touch display built with award-winning technology featured in the Boonton RF Power Analysis product line. As a benchtop meter, the PMX40 provides a standalone solution for capturing, displaying, and analyzing peak and average RF power in both the time and statistical domains. The PMX40 is compatible with the RTP5000 Series, the RTP4000 Series USB real-time true average power sensors, and the CPS2008 USB true average connected power sensor. Up to four Boonton USB power sensors may be connected to the PMX40 to make independent or synchronized multi-channel measurements of CW, modulated, and pulsed signals.