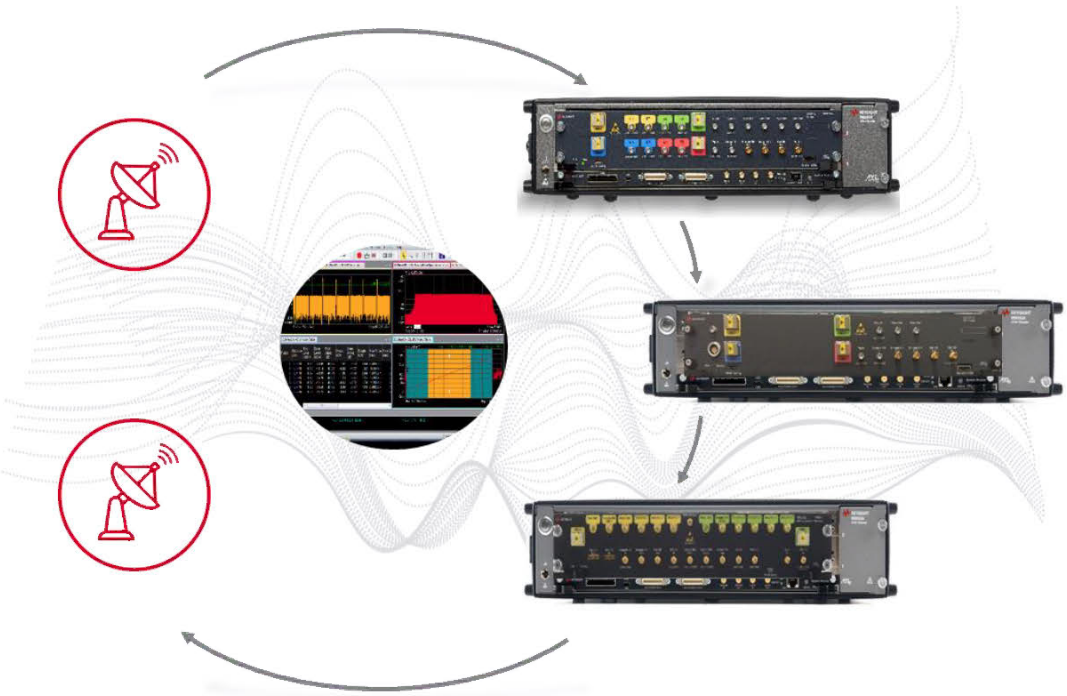
APPLICATION NOTE

Direct Radar Signal Generation and Acquisition

with Modular High-speed AWGs and Digitizers – Part 1

In this series of three application notes you will learn about the challenges that are introduced with modern radar signals *and* the instruments you can use to overcome them.



Generation and detection of radar signals have changed dramatically in the past 30 years. Today's digital signal processing capabilities offer a wide range of possibilities to simulate radar signals and include simulated objects to verify the performance of a radar system.

KEYSIGHT TECHNOLOGIES

Modern radar systems Introduction – Part 1

Since the introduction of the radar technology back in the thirties, there has been a continuous race to increase range, resolution and accuracy. The need to avoid jamming and countermeasures has resulted in extremely complex signal generation, reception and analysis scenarios. The initial scheme of a simple fixed or rotating directional antenna emitting short, unmodulated pulses has been dramatically extended through the implementation of complex intra-pulse modulation schemes. To improve resolution while extending the range signal emission was abandoned, completely or partially by methods of pulse compression. Antennas are often based on phase-array architectures where radar beams can be swept over a region of the sky or even electronically track multiple targets simultaneously without pointing directly to them. These are some of the elements defining modern RADAR systems:

Pulse Compression:

The need to overcome the contradiction between distance resolution and range led to the idea of applying pulse-compression techniques. It consists of modulation of the carrier within a radar pulse, processing the echoes at the receiver. This makes them look “compressed”, equivalent to the ones coming from a much shorter pulse. There are different ways to internally modulate pulses, both analog and digital.
The most popular analog modulation consists in a fast, linear frequency sweep, known as “chirp”. Digital modulations are based in a series of phases applied to the carrier (polyphase modulation), divided into equal duration sections (“chirps”). In both cases, the amplitude of the output pulse remains constant throughout the pulse.

Ultra-high Bandwidth (BW):

Pulse compression techniques basically interlock radar resolution with waveform bandwidth. Higher bandwidth leads to high resolution. As technology advances and new, higher speed and bandwidth DSP and RF circuitry are available, bandwidth of radar signals keeps growing. Nowadays, even commercial radars (i.e. automotive short-range CWFM radars) may have bandwidths as high as 4 GHz.

Signal Complexity:

The need to avoid jamming and other countermeasures, identify ghost targets or remove the effects of blind speeds in MTI (Moving Target Indicator) radars has led to the addition of new levels of complexity to radar signals. Staggering is a technique that changes the PRI (Pulse Repetition Interval) form one pulse to the next in a regular or random-like fashion. Another strategy is frequency-hopping, achieved by changing the carrier frequency from one pulse to the next.

Phase Array Radars:

Many radar systems depend on high gain antennas in order to identify the azimuth (2D) and elevation of the targets (3D). Tracking radars can even automatically steer the antenna to a given target by mechanically positioning the antenna towards it. As a consequence, complex mechanical positioning and control systems must be deployed while such radar systems can only track one target at a time. Things become even more difficult in radar systems attached to moving platforms such as aircrafts and ships. Most military applications require real-time tracking of multiple targets simultaneously as well. All these needs can be served with multiple element, individually controlled antennas, also known as phase-array antennas. Controlling amplitude and phase for each element results in a radiation pattern that can be steered in a wide-angle range without having to physically move the array. Even more, by simultaneously supplying different radar signals with different patterns to the same set of antennas, multiple, independent tracking systems can be implemented. The same principle can be applied to echo reception, establishing a Direction of Arrival (DOA) method.

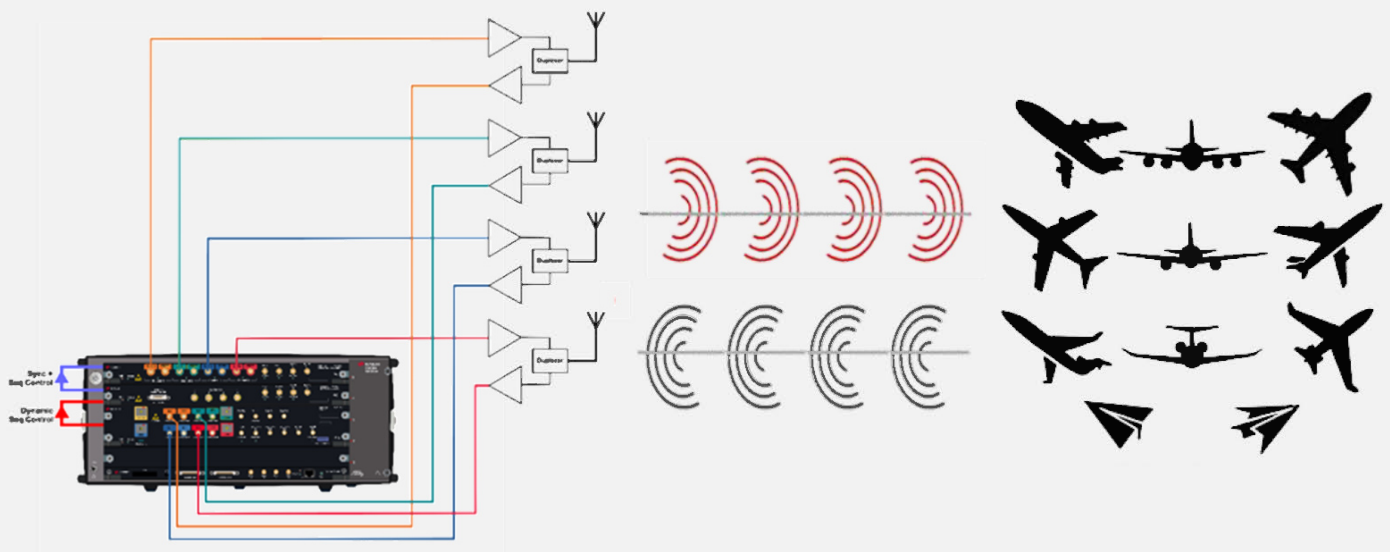


Figure 1. Time-domain instruments such as AWGs and Waveform Digitizers can be used successfully to generate and capture radar signals without the limitations in terms of modulation and analysis bandwidth found in traditional VSGs and VSAs. Here, a four channel M8195A AWG combined with four channel M8131A digitizer and M8132A DSP module can generate and capture signals from a phase array antenna at frequencies over a range of 30GHz. The system can be scaled to include tens of analysis and generation channels. The M8131A digitizer can stream waveform data to external massive storage and internally process the information. By restreaming the signals to the AWG, signals can be modified in real-time.

As in any technological environment, test gear has tried to cope with all the requirements described above. Full testing of a radar system may require multiple signal generators and signal analyzers (Figure 1). Signal generators can be used to feed the high-power, high-bandwidth output stages of radar systems or to emulate echoes to test the receiver section, including the signal processing stage. Signal analyzers are basically used for transmitter testing in the time, frequency and modulation (signal compression) domains.

The signal generation tool of choice has been the VSG (Vector Signal Generation) which can generate an IQ modulated carrier at a given range of carrier frequencies with a maximum modulation bandwidth. The most popular analysis tool has been the VSA (Vector Signal Analyzer), a spectrum analyzer capable of capturing the amplitude and phase information of a modulated carrier within a given bandwidth (known as analysis bandwidth). However, coping with the requirements imposed by modern radar systems have made increasingly difficult, if not impossible, to follow the traditional VSG+VSA approach to solve measurement needs for most radar engineers.

There are several reasons for it, but the two most important ones are limitations in analysis bandwidth and the extreme cost and difficulty to build multi-channel, phase-coherent test sets. Nowadays, the most advanced VSG in the market can generate one RF modulated carrier with up to 1 GHz modulation bandwidth. The same can be applied to VSAs although some of them can measure beyond the 1 GHz limit by using an external oscilloscope. Multiple channel or modular instruments are limited to a few hundred MHz of analysis BW. In frequency-hopping systems, signal BW is greater than modulation BW of an individual pulse, making this approach even more challenging. The limitations mentioned above, and the ever-increasing performance of time-domain instrumentation made it feasible to take a different approach: the usage of AWGs (Arbitrary Waveform Generator) for radar waveform generation and DSO (Digital Signal Oscilloscope) or waveform digitizers for analysis. These instruments were extensively used in the past. However, they were typically limited to the analysis and generation of baseband signals (the signals modulating the carriers). Today, with sampling rates well beyond 50 GSa/s and analog BW greater than 30 GHz, these instruments can even generate and analyze radar signals right at the carrier frequency. This series of application notes covers the most important aspects of using AWGs and Waveform Digitizers in the RADAR application area.

What you will learn in part two in this series of application notes:

In the second application note of this series you well learn how to use various methods to create modern radar signals. This includes multi-channel RF generation for phased antennas, sequencing of various pulse patterns and how to deal with imperfections in signal generation through waveform correction.

Modern Radar Systems at a Glance

In this first part from a series of three application notes where we explained key elements that distinguish modern radar systems form historical pure analog radars systems. These methods are pulse compression, ultra-high bandwidth in the multiple GHz range, high signal complexity by applying digital signal processing methods, and finally the application of phased array antennas, providing unmatched flexibility in antenna beam forming.

APPLICATION NOTE

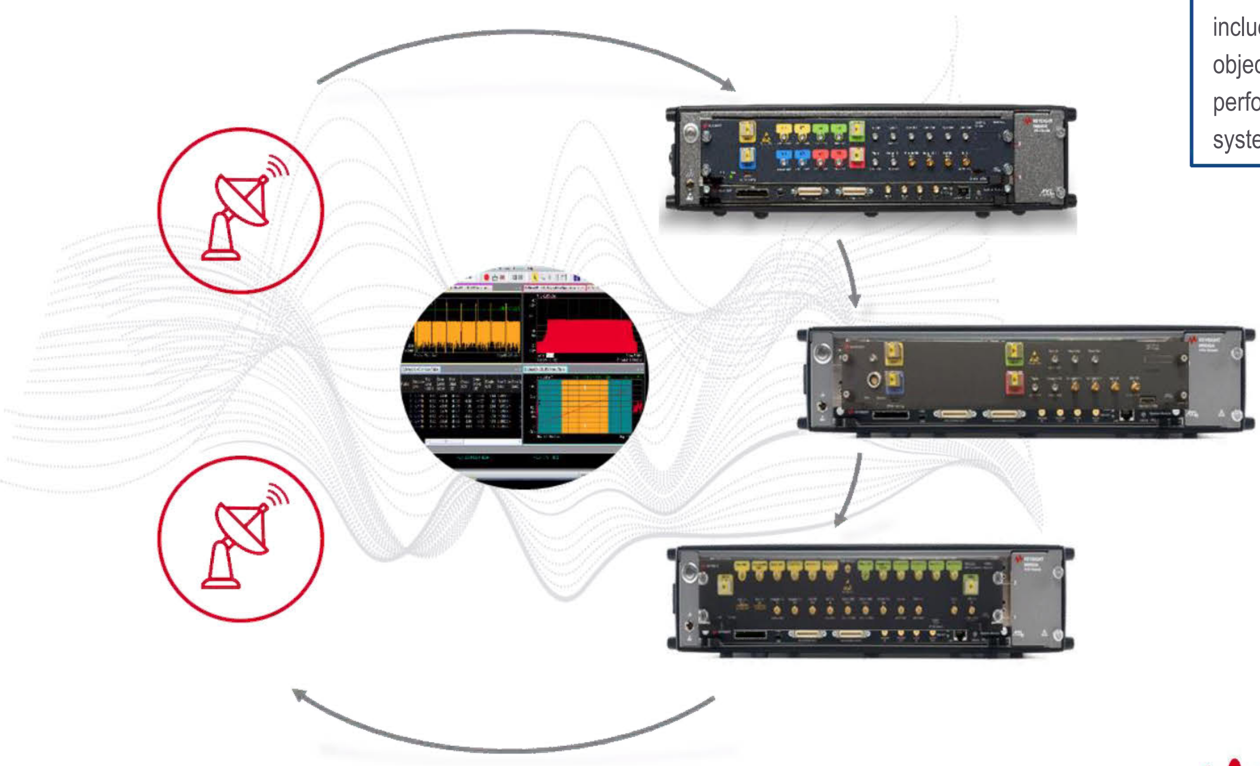
Direct Radar Signal Generation and Acquisition

with Modular High-speed AWGs and Digitizers – Part 2

In part one of this application note series we provided an overview on the challenges that are introduced with modern radar signals *and* the instruments you can use to overcome them.

In the second application note of this series you well learn how to use various methods to create modern radar signals. This includes multi-channel RF generation for phased antennas, sequencing of various pulse patterns and how to deal with imperfections in signal generation through waveform correction

Generation and detection of radar signals have changed dramatically in the past 30 years. Today's digital signal processing capabilities offer a wide range of possibilities to simulate radar signals and include simulated objects to verify the performance of a radar system.



KEYSIGHT TECHNOLOGIES

Generating RADAR waveforms with advanced AWGs

AWGs have always been part of most vector signal generators (VSA), either as an internal module or as the source of the IQ signals fed to the external modulation inputs. The block diagram of an AWG looks very similar to that of an oscilloscope with the exception that the signal flow is in the opposite direction. General-purpose AWGs generate one or more channels by loading the mathematically calculated samples into the waveform memory, which is connected to a DAC. This runs at a variable sampling clock to reconstruct the correct timing for the waveform. Waveforms that can be generated using this scheme are only limited by the quality of the DAC, the analog bandwidth of the output stages, and the limitations associated to any sampled signal. Probably, the most important consideration for any given application is the waveform bandwidth, which has to fulfil the Nyquist Sampling Theorem. The theorem states that frequency components that can be reconstructed by the DAC range from DC up to half the sampling rate (known as the First Nyquist Band). Ideal and real-world DACs produce images in the frequency-domain around multiples of the sampling frequency. For many applications, images are an unwanted effect of the digital-to-analog conversion process. However, under some conditions and for some bandwidth-limited signals, images can be selected (typically using a band-pass filter) to generate useful RF waveforms. There are basically three ways to generate a modulated RF signal involving AWGs (Figure 2):

- Baseband Generation:
  A two-channel AWG generates a pair of baseband IQ signals which is fed into an analog quadrature modulator (Figure 2, image a). The bandwidth required for each channel in the AWG is one half of the modulation BW for that signal. As modulation BW is quite limited compared to the RF carrier frequency, the requirements for the sampling rate for such AWGs is moderate (several hundred MHz).
- IF Generation:
  A one-channel AWG generates a modulated RF carrier at a lower frequency (Figure 2, image a). This signal is then upconverted to the required carrier frequency. Bandwidth requirements increase in this case as the sampling rate must be high enough to accommodate the IF carrier frequency plus half of the modulation BW. The IF carrier frequency must be at least half the modulation BW. Even selecting the lowest possible IF frequency, sampling rates must be higher than twice the modulation bandwidth.
- Direct RF Generation:
  Also known as DDS (Direct Digital Synthesis). Within this concept, a one-channel AWG generates the signal right at the desired carrier frequency (Figure 2, image b). Sampling rate requirements are typically very high as both the carrier and the modulation bandwidth must be accommodated in the Nyquist band. For signals with an RF carrier frequency much higher than the modulation bandwidth, the sampling rate must be significantly higher than twice the RF carrier when using the first Nyquist band, and much lower when using a higher order Nyquist bands. This strategy avoids the need of an external modulator or up-converter.

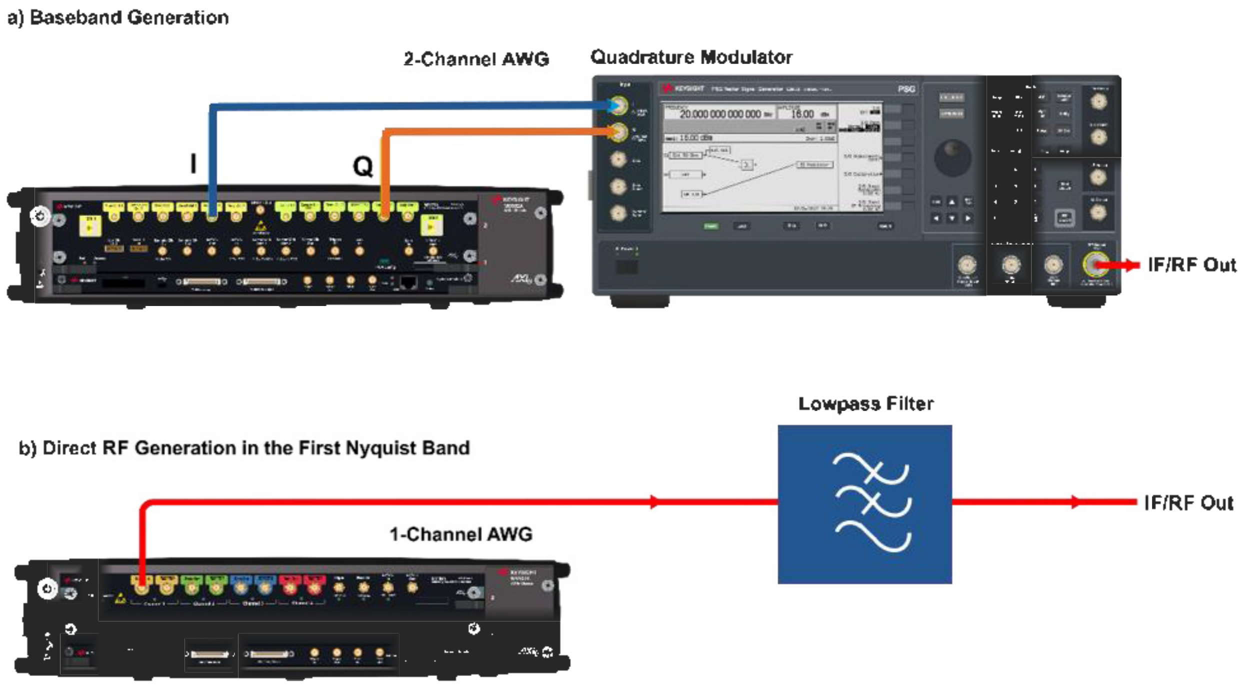


Figure 2: AWGs can generate radar (and any RF) signals following two different basic schemes. In a) two AWG channels generate an IQ pair feeding an IQ modulator to reach the target IF/RF frequency. In b) a high-speed AWG directly generates the modulated RF carrier (method often identified as DDS, or Direct Digital Synthesis) in any of the Nyquist bands of the DAC supported by the AWG analog bandwidth. In ultra-high-speed AWGs, such as the M8195A, using the second Nyquist band is impossible given the available analog bandwidth.

The latest generation of high-speed AWGs from Keysight opens the door to the direct RF generation at carriers up to 40 GHz with modulation bandwidths far beyond what is currently required. Generating signals in the first Nyquist band is always preferable given the higher amplitude, flatness and dynamic range that can be obtained there. Additionally, the analog bandwidth of high-speed AWGs (sample rate > 50 GSa/s) greatly attenuates images in the second and third Nyquist bands.

The Keysight M8195A 4-channel AWG is an AXIe module with 65 GSa/s sampling rate and a usable bandwidth greater than 32 GHz with an in band 80 dBc SFDR (Spurious Free Dynamic Range) of a 100 MHz signal. The M8195A incorporates 1MSample of internal memory in the DAC chip that can feed all four DACs at full speed. The additional high capacity internal waveform memory can be segmented and supports advanced sequencing. (Figure 3).

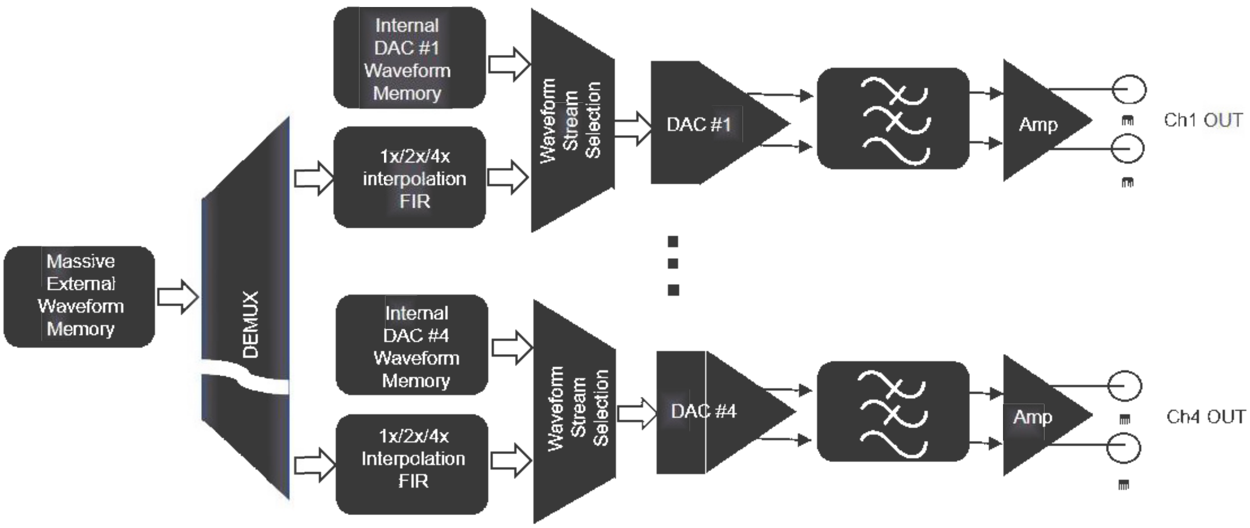


Figure 3: Simplified block diagram of the M8195A. It incorporates four synchronized DAC blocks in one ASIC. Each DAC can use the internal waveform memory (1MSample) without limitations, or a massive external waveform memory (up to 16 GSamples). The massive memory can transfer a maximum of 65 GSamples/s so it can support one channel at full speed (1X mode), two channels at half the speed (2X mode), and all four channels 1/4 the speed (4X mode). DACs always work at full speed and the DAC block incorporates an interpolating FIR filter used to correct flatness or select a given Nyquist band in the 2X or 4X modes, while removing the unwanted images.

The DACs in the M8195A always operate at full speed independent of the waveform memory mode. By applying an interpolation real-time FIR filter, the access rate of the waveform memory can be adopted to the DAC sampling rate (Figure 4). Up-sampling is accomplished by adding one (mode 2X) or three (mode 4X) zeros (zero-padding) for every actual sample coming from the massive external waveform memory (Figure 4, image b). The FIR filter then interpolates to insert the extra samples. The number of taps available for each FIR filter depends on the extended mode being used: 16 for the 1X mode, 32 for the 2X mode, and 64 for the 4X mode. As coefficients for the FIR can be freely defined, different responses can be obtained. Some of them are already pre-defined (Figure 4, images c and d) while users can load their own. For example, to compensate for frequency dependent losses including the frequency response of the AWG itself.

Internal FIR can be used for waveform up-conversion within the first Nyquist band (32.5 GHz) for the final DAC sampling rate (up to 65 GSa/s). Direct generation of Radar waveform requires modulating a carrier with a wideband signal. Figure 4d shows an example on how to generate a signal with up to 8 GHz modulation BW in the third Nyquist Band, applicable for any channel of the M8195A operating in the 4X extended mode. The right interpolation filter can isolate the image in the third Nyquist band caused by the reduced sampling rate while nulling the others. In this way, all the power goes to the desired band and there is no need for a specific analog band-pass filter at the output. In fact, for a bandwidth limited waveform, the output waveform will be the same that would be generated by the AWG at full speed (Figure 5). The difference is that the 4X extended mode permits using all four channels in extended mode while reducing the number of samples by a factor of four, increasing the maximum time-window and/or the number of segments that can be stored in memory in the same way.

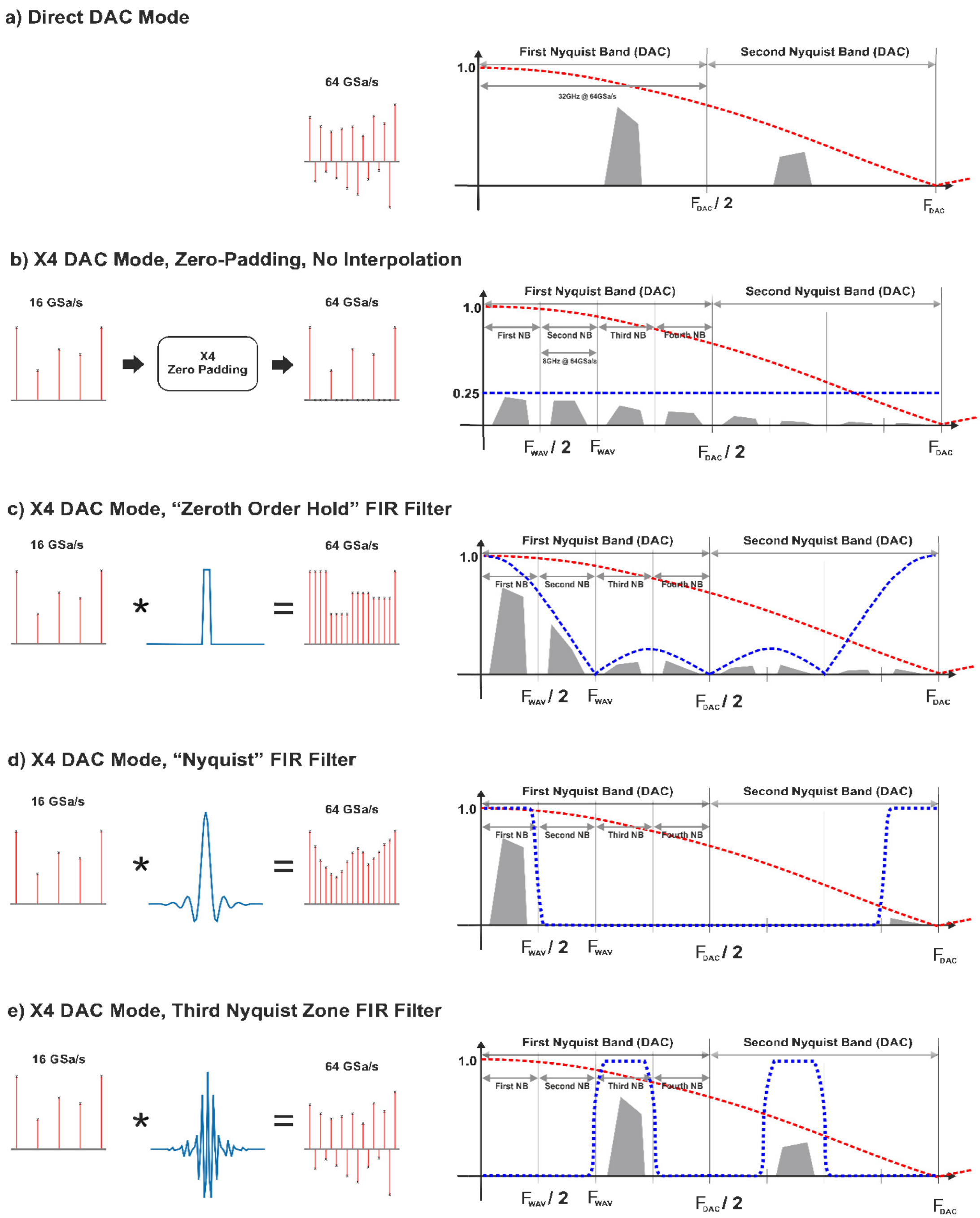


Figure 4: The interpolating FIR block attached to each DAC in the M8195A can be used to select a given image in the 2X and 4X mode. In this example, a signal of a wideband radar signal @ 20 GHz is generated directly in the 1X mode (a) @ 64GSa/s. In this mode, massive memory (and waveform memory segmentation and sequencing) is available for a single channel only. In order to use the four channels, a possible solution is generating the signal in the 4X mode and use the third Nyquist band of a 4GHz carrier @ 16GSa/s. In b), a zero-padding scheme is applied using the internal FIR. Overall power goes down by 12dB, and the unwanted images must be removed using an external analog band-pass filter. In c), the standard, predefined "Zero Order Hold" FIR filter for the 4X mode is selected. This is equivalent to use a 16GSa/s DAC. The wanted image is affected by the 16GSa/s Sinc(f) response. Although the overall power will be much higher, the amplitude of the useful image in the third Nyquist band will be lower. In d), the standard predefined "Nyquist" filter is used. As this filter selects only the first Nyquist band, the image in the third band simply disappears. Finally, in d), a "Third Nyquist Band" FIR filter is applied. In this case all the power is available for the useful waveform as it is generated in the actual first Nyquist band of the DAC running at full speed with excellent flatness. In fact, the waveform generated using this scheme will be the same as that in case a), but in this case all the four channels will be connected to the massive memory as they can work in the extended mode.

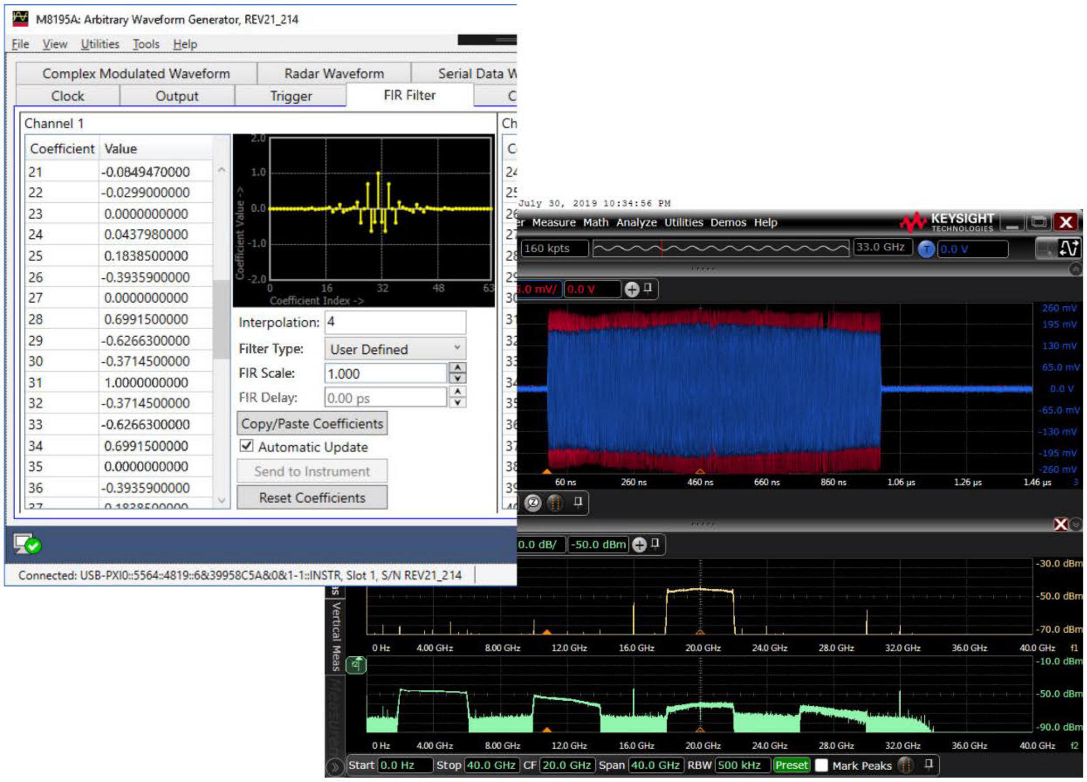


Figure 5: The M8195A's SFP shows the FIR panel with the Third Nyquist band filter coefficients defined for Channel 1 while Channel 2 is using the "Zero Order Hold" FIR Filter. These filters have been applied to the same signal, a 4GHz linear FM chirp @ 4GHz carrier (to obtain a 20 GHz carrier in the third Nyquist band). Power at 20GHz is is improved by > 15dB when the Third Nyquist band filter is applied. Additionally unwanted images are removed so there is no need for an additional band-pass filter. Channel 2 waveform in red has a slightly higher amplitude than Channel 1 (blue waveform). However, all the power in the Channel 1 signal goes to the image in the third band while most of the power in Channel 2 goes to the image in the first Nyquist band and the amplitude for the wanted image in the third Nyquist band will be much lower than that of Channel 1.

Multiple channel RF generation

Phase-Array antennas are common place in advanced radar systems. Amplitude, delay, and carrier phase must be accurately and tightly controlled for each antenna in the array to obtain the desired radiation pattern with the correct azimuth and elevation of the main lobe. There are several ways to steer the lobe. For relatively low modulation bandwidths, the same baseband or IF signal may be applied to multiple RF modulator or up-converters. The desired radiation pattern can be set by carefully adjusting the relative amplitude and phase of the carrier for each modulator or up-converter while the same modulating signal is applied to all of them. However, for many wideband Radar signals, this approach is not acceptable. The disadvantage of this approach is the relative delay between the modulating signals when the beam does not point in the perpendicular direction is not negligible in terms of the integrity of the signal. In figure 7, a 4 GHz chirp can be observed when generated by a single antenna and when generated by two antennas with a delay resulting in a 30º beam deviation with antennas located at a 10 cm distance. While response is flat in the first case, the response in the second case shows the effects of the relative delay in the in-band frequency response. Phase response and the linearity of the FM sweep will also suffer. This problem can be alleviated by generating multiple baseband or IF signals with adequate delays to feed several modulators or up-converters attached to a group of close antennas. The previously described effect grows with the number of antennas and the maximum distance between them in the same array. Even when applying this improvement, the problem of carefully adjusting amplitudes and phases for all the modulators and up-converters remains.

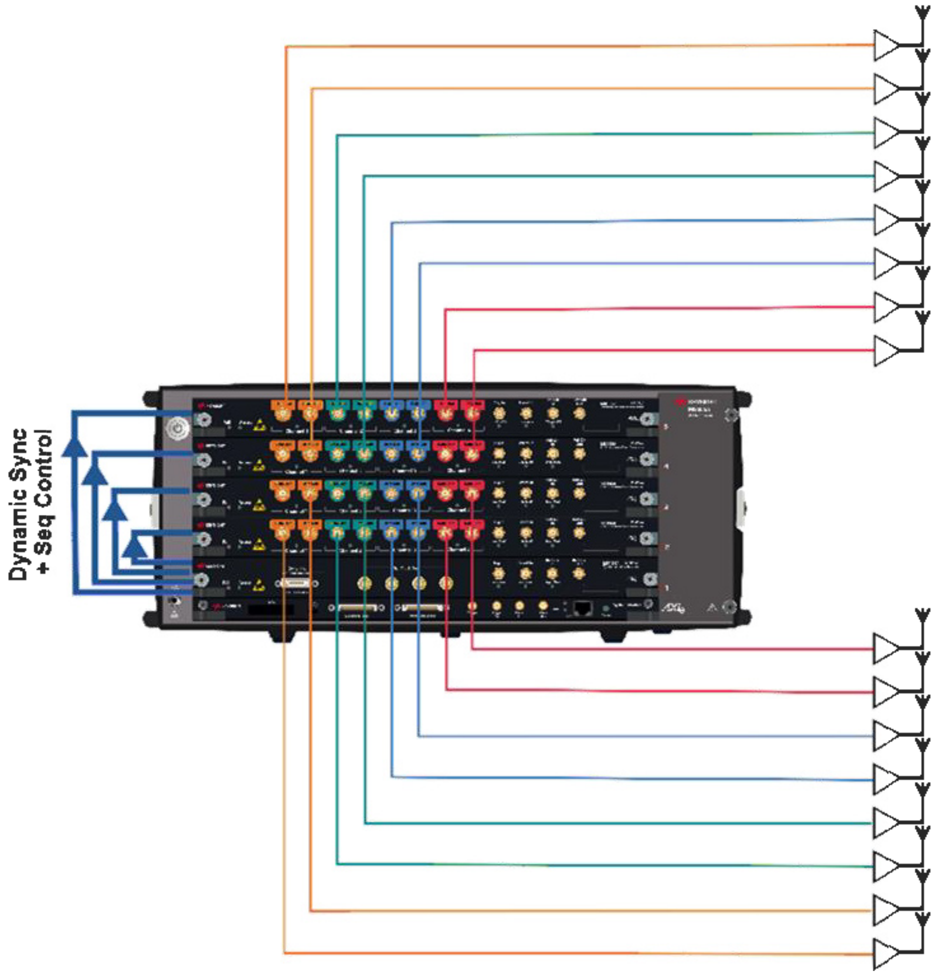


Figure 6: The M8197A synchronization module can tightly synchronize up to four M8195A modules (for a total of 16 channels) with 1ps accuracy (and 50fs resolution). It also provides a repeatable, exact trigger to achieve deterministic latency. Additionally, it can be used to apply Dynamic Sequencing to all the modules attached to it. Under the Dynamic Sequencing scheme, the next waveform segment or sequence can be selected in real-time through a parallel digital input in the front panel.

Using AWGs with multiple, synchronized channels may facilitate the emulation of phase-array radar systems in almost any situation. To do so, one channel (for DDS and IF) or two channels (for IQ baseband) must be allocated for each antenna feed. In this way, all the amplitude and timing parameters, including carrier phase, can be adjusted by just calculating the correct waveform for each antenna and setting up the corresponding output delay and amplitude. This is true even when using external modulation or up-converting devices, that, under this arrangement, can be set-up to a fixed amplitude and phase.

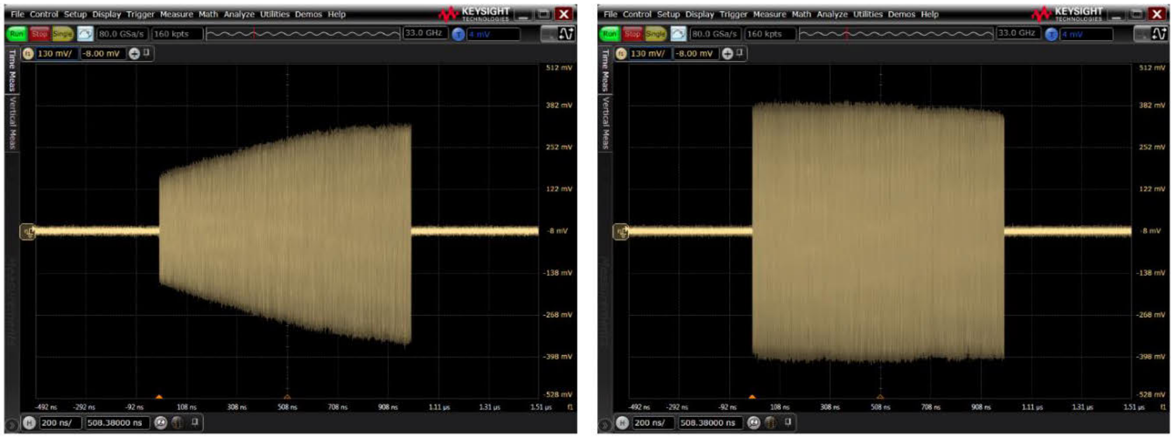


Figure 7: In phase array systems, adjusting just the carrier phase is not enough. In this example, the signal (a 4GHz linear FM chirp) from two antennas is displayed. In the left image, carrier phase for both antennas have been accurately adjusted so the combined beam points in a given direction. However, when this direction is not perpendicular to the antenna plane, and the modulating signals are synchronized for both antennas, the initial phase alignment is valid only for a very narrow bandwidth. In the right image, two AWG channels with properly delayed versions of the same chirp are superimposed, showing a near-perfect flatness over the full sweep duration.

The M8195A incorporates four AWG channels per module. However, multiple modules can be tightly synchronized using the M8197A module. Up to 16 channels can be synchronized within $1ps_{rms}$ and 50fs timing control using one chassis with one M8197A and up to four M8195A modules (figure 6). The M8197A can also trigger the four M8195A modules with a deterministic latency. The internal up-conversion capability, explained in the previous section, is a very important feature when emulating phase array radars with complex modulations, timing sequences (i.e. staggered pulses), target movements, and/or mechanical effects (i.e. antenna rotation). In order to properly support such scenarios, the combination of multiple GSamples of playing lengths, advanced sequencing for all the channels, and internal interpolating FIR filter is key.

Amplitude control is as important as signal delay and carrier phase control. The M8195A incorporates an output amplifier which allows for a 22.5 dB range amplitude control preserving the analog bandwidth of the output and the resolution of the DAC. This may be enough for most phase-array implementations. A higher adjustment range can be obtained by reducing the DAC range used by the signal. Using external attenuators is also an alternative.

The M8195A offers the possibility of directly generating such scenarios at frequencies up to 25GHz. For lower carrier frequencies, lower speed AWGs with higher resolution are also capable of generating such scenarios. The M8190A from Keysight incorporates specific DAC “RF Modes” and/or internal IQ modulators (combined with NCOs) that enable you to generate complex modulated RF signals. This is especially applicable to Radar signals at carrier frequencies well below 10 GHz in the first or second Nyquist band. It is important in multi-channel systems that phase alignment of the internal Numerical Controlled Oscillators (NCO) is precise. High granularity is required to tune the phase of each NCO independently for each channel for optimal system performance. AWGs like the M8195A or M8121A provide this feature unlike other multi-channel AWGs available.

Sequencing

Even simple radar waveforms may require very long waveform lengths. Some Radar technologies, such as MTI (Moving Target Indicator) radars, are required to keep the phase of the carrier over time for all pulses. If the PRI (Pulse Repetition Interval) is not an integer multiple of the carrier period ($1/f_c$), it will be impossible to generate a continuous, coherent waveform by simply repeating a single period stored in the waveform memory.

- The M8195A can generate up to 250ms of waveform at 64GSa/s when using the maximum waveform memory. Although this capability may be more than enough for most situations, generating a complete radar signal scenario in a unique, consecutive series of samples within the waveform memory may not be possible. In order to improve the efficiency of the waveform memory, the M8195A implements a massive memory that can be segmented providing toe possibility of generating complex radar signal scenarios. This eliminates the need for the slow process of downloading waveforms each time the waveform has been changed. Even better, the M8195A can store complex sequencing schemes instructing the generator to seamlessly select different segments.
- The M8195A can sequence any number of timeslots and jump to any step in the sequence automatically or triggered by external events (figure 8). Sequencing is useful for a series of reasons in the radar application area: Radar signals often incorporate long sections of zero samples between pulses. Sequencing may be used to define one or more pulse segments, and one or more "all-zeros" segments. Since segments can be reused (listed several times in the same sequence) and looped, extremely complex and long waveforms can be generated using just a fraction of what would be necessary in the traditional way. Reusing memory also results in the reduction of the waveform calculation and download times.
- Sequence advance can be controlled by external event signals. Sequencing may be useful to synchronize waveform generation with real-world events.
- Slow changes in the waveform (i.e. mechanical rotation of an antenna or changes in one or multiple targets being simulated) can be emulated by sequencing successive waveforms. In this way, the available 250ms out of waveform data can be extended to seconds, minutes, hours or even days.

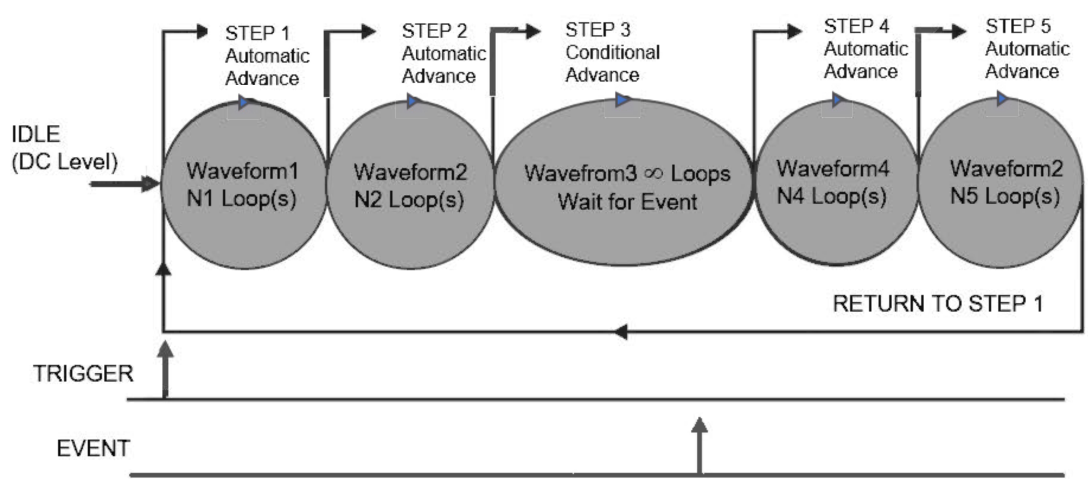


Figure 8: Massive waveform memory, memory segmentation, and advanced sequencing support the implementation of extremely complex signals with significant waveform memory savings. The M8195A supports sequences and scenarios (sequences of sequences) that can be controlled by external events. Combined with M8197A, the M8195A also support dynamic sequencing, where the next waveform or sequence to be generated is defined in real time by a digital word applied to a front panel connector.

In order to ease the implementation of such waveforms, the M8195A also supports “scenarios”. These are, in fact, sequences of sequences, adding more flexibility and resulting in huge waveform memory savings. When used along with the M8197A synchronization module, all attached M8195A modules can be dynamically controlled by external segment or sequence control lines. Under this scheme, users can control the next segment or sequence to play-back using the parallel identification word. Dynamic Control is very useful when the waveform to be generated depends on external non-deterministic conditions. These conditions can be identified by an external processing system or the internal FPGA in the M8131A to generate the correct waveform. This capability is very useful in EW (both attack and protection).

Waveform corrections

The frequency response of any ultra-wideband AWG is not flat. This is also the case for external modulators, up-converters, cables or interconnecting devices, Therefore, linear waveform corrections become necessary when high-quality wideband signals must be generated (figure 10). Given the potential differences between channels, modules, and interconnections, a channel-by-channel correction scheme must be implemented. The M8195A amplitude and phase frequency response for each channel is factory characterized at multiple sampling rates and DAC modes with 100MHz resolution in the DC to 32GHz range.

The results of this characterization process are stored in NVRAM within the module and the calibration data can be queried using SCPI commands in the IVI driver. Users can combine this information and the frequency response of any external cable or device to calculate a filter with the desired transfer function.

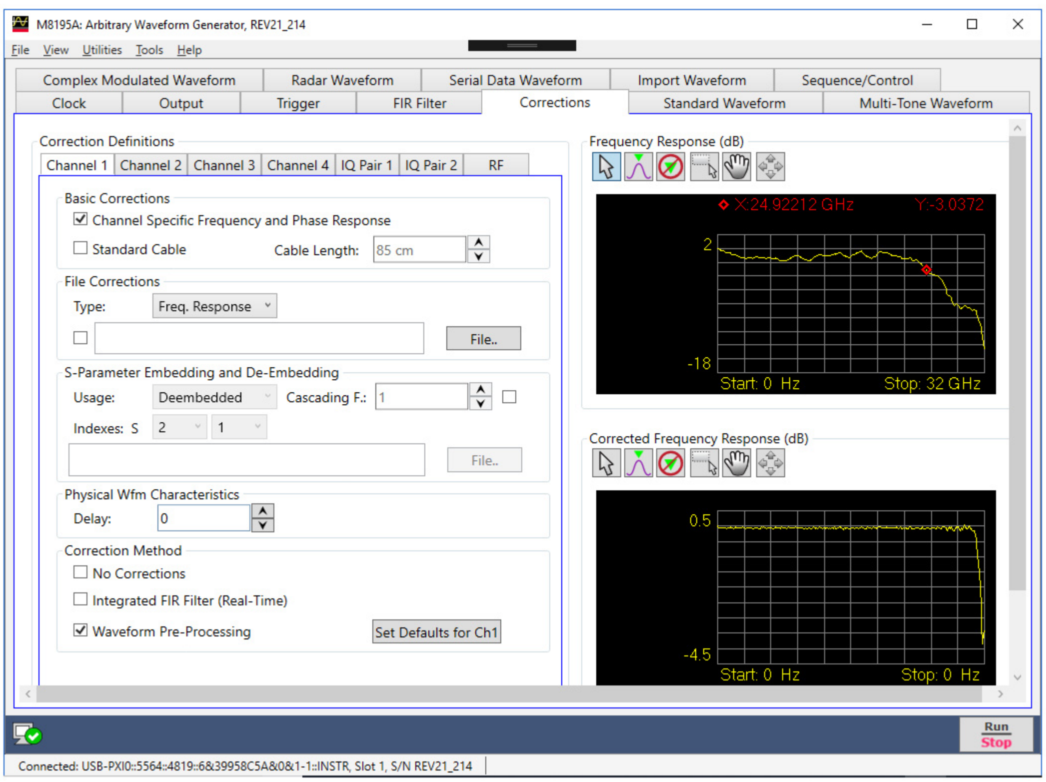


Figure 9: The M8195A SFP (Software Front Panel) can be used to setup correction filters in order to obtain flat frequency responses (magnitude and phase). Independently for each channel, it can combine correction data from the calibration data for the corresponding channel, and other sources, such as S-parameter files. The image above shows, the M8195A frequency response of Channel 1. The upper graph shows the uncorrected channel transfer function. The bottom graph shows the corrected response after applying the calculated correction filter.

For simple, low-frequency resolution corrections, the internal FIR filters may be sufficient. For more accurate, higher-resolution corrections, waveform pre-distortion must be applied. In this scheme, the undistorted waveform is convolved with the channel-specific correction filter (with tens or hundreds of taps) before downloading the waveform to each channel. The M8195A SFP incorporates an advanced correction panel. In this panel (figure 9) you can combine the internal calibrated frequency responses from each channel, standard high-quality cable attenuation, externally defined S-parameter files (in Touchstone format), user-defined corrections or responses in CSV format and the 89600A VSA adaptive equalizer complex responses to correct any baseband or IF/RF waveform. This panel can also resample any external waveform to any convenient sampling rate from arbitrary waveform generation.

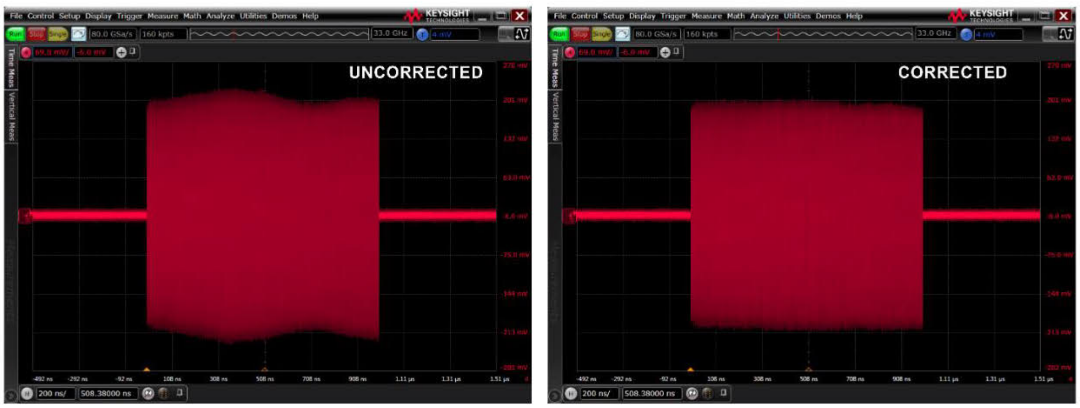


Figure 10: The effect of applying corrections can be seen in this pair of scope screen captures. The signal shown is a 4GHz chirp on a 10 GHz carrier. Improvement in pulse flatness is impressive. The same kind of improvement can be achieved for radar signals using polyphase modulations (i.e. Barker or Frank codes), where EVM improves dramatically.

Calculating radar waveforms for Arbitrary Generation

Waveforms to be generated by AWGs must be calculated in an external tool. This can be done in simulation tools, mathematical software packages, application-specific software, or waveform editing tools. They can also be extracted from real-world signals acquired by digitizers (i.e. oscilloscopes) or digital receivers. Some lower speed AWGs such as the Keysight's M8121A can stream waveform data from disk arrays or real-time processors directly to the DAC. Importing data from simulation/design tools is probably the most typical scenario when used in research. The standard M8195A SFP includes an Import Waveform toolbox where users can import data from a variety of formats including ASCII, MATLAB, binary, 89600 VSA, Keysight DSO, and encrypted Signal Studio. It supports single-channel and interleaved IQ baseband waveform arrangements. The SFP Import Waveform Toolbox adapts the waveform to be compatible with the M8195A (and any other supported AWG). First, it adapts the range of the waveforms to fit in the available DAC range, no matter the absolute scale used during creation. Second, it adapts the input waveform sample rate to the target AWG by resampling the waveform to a higher (up-sampling) or lower (down-sampling) sample rate. Proper resampling implies near-ideal interpolation and, for down-sampling, a very effective antialiasing digital filtering before resampling. The M8195A SFP provides this in a single pass while minimizing calculation time by avoiding the calculation of intermediate or not useful samples. So, users do not have to calculate waveforms in their waveform creation tools or capture them in the analysis instruments at the final desired sampling rate. The capability to import encrypted data generated by Keysight Signal Studio packages provides most tools needed to create waveforms.

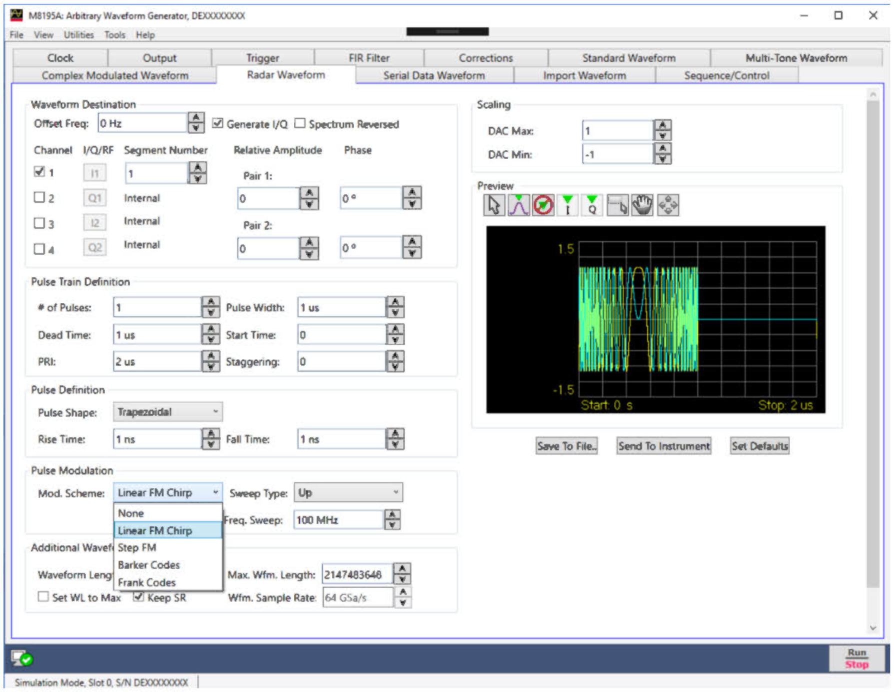


Figure 11: The M8195A SFP Radar panel allows for the out-of-the box creation of complex baseband and IF/RF radar waveform scenarios. Pulse shape, pulse train parameters and intra-pulse modulation can be defined. Signals can be stored and/or sent to any channel.

The M8195A SFP also includes a Radar Waveform generation panel (fig. 11). It can create and generate complex radar waveforms out-of-the-box. It can generate both IF/RF modulated waveforms and I/Q baseband waveform pairs to feed an external modulator. The M8195A supports the most popular intra-pulse modulation schemes for pulse compression such as linear FM (Chirp), Step FM, Barker Codes, and Frank codes. Any number of pulses with arbitrary width, PRI and staggering and user defined rise and fall times can be set up. Transfer function corrections, as explained in the previous section, are built into the application to achieve excellent flatness.

What you will learn in part two in this series of application notes:

In the final and third part of this series you will learn how to digitally capture and analyze radar signals with the option to use digital signal processing methods in order to extract core information like pulse descriptor words (PDW) and do final recording of raw data or core information like the PDW.

Modern Radar Systems at a Glance

In the first part of this series of three application notes we explained key elements that distinguish modern radar systems form historical pure analog radars systems. These methods are pulse compression, ultra-high bandwidth in the multiple GHz range, high signal complexity by applying digital signal processing methods, and finally the application of phased array antennas, providing unmatched flexibility in antenna beam forming.

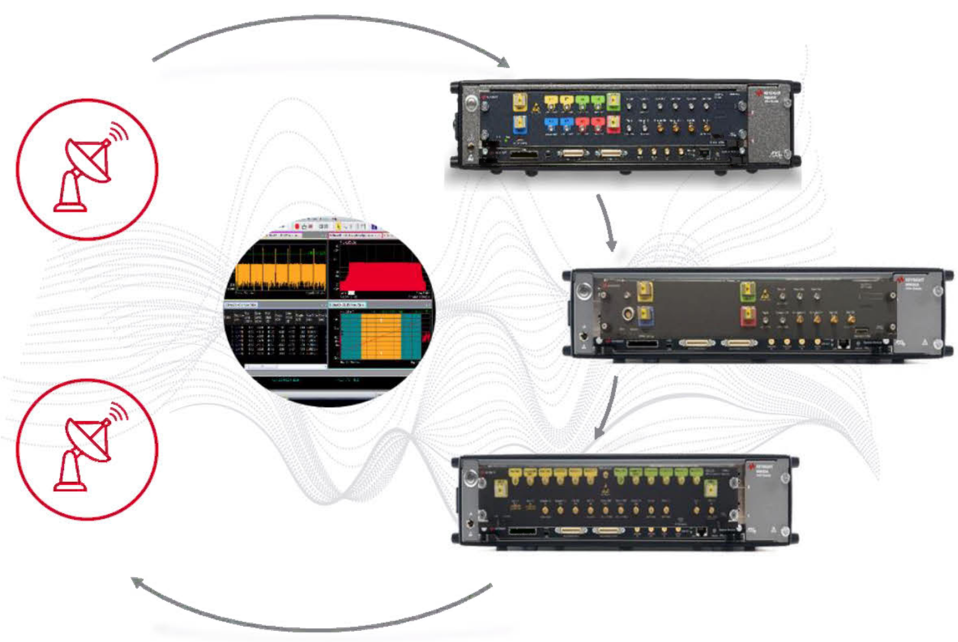
In the second part we discussed the three basic methods of modern radar signal creation. This is creating the signal in the base band with following up-conversion in analog domain or generation the IF signal directly within an Arbitrary Waveform Generator also with follow-on analog up-conversion. Finally, if you have a very broad-band Arbitrary Waveform Generator you can directly create the FR radar signal in the Arbitrary Waveform Generator and feed it via an amplifier into an antenna or even in a phase array antenna.

APPLICATION NOTE

Direct Radar Signal Generation and Acquisition

with Modular High-speed AWGs and Digitizers – Part 3

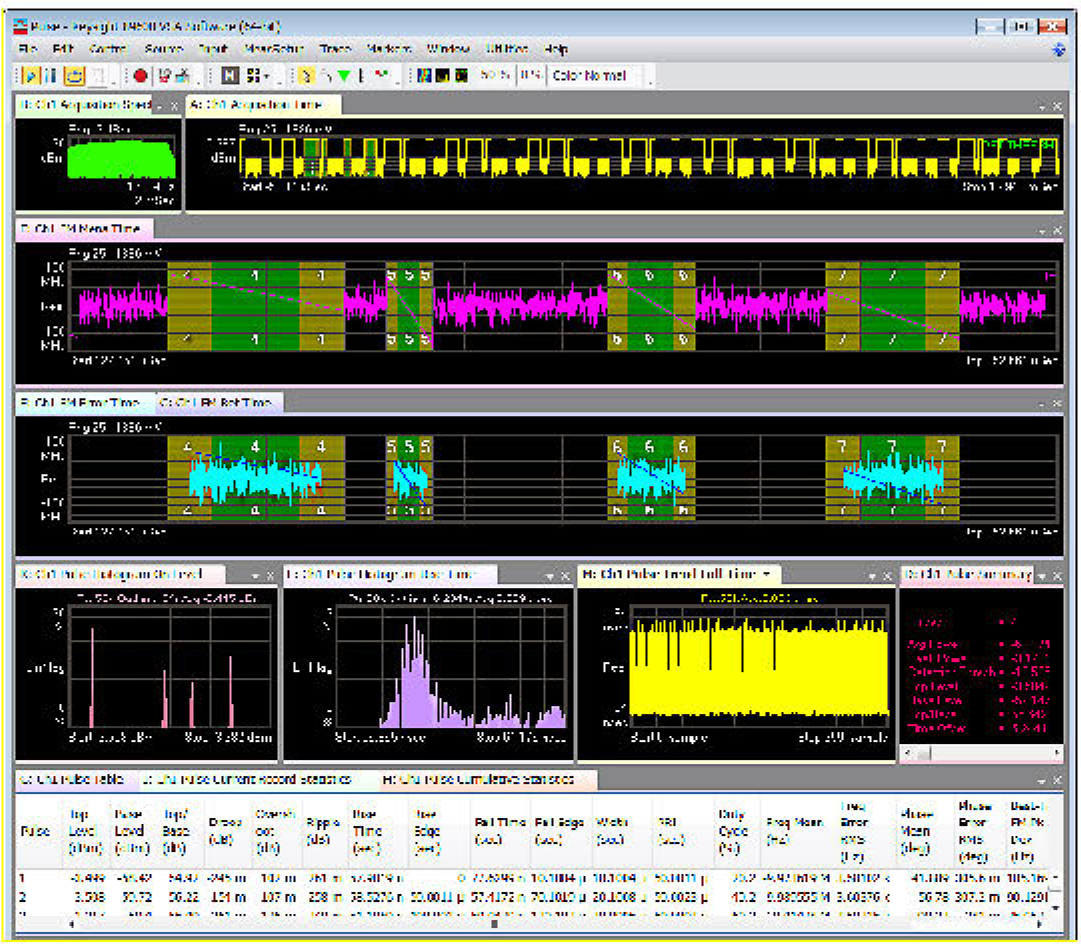
In part one of this application note series we provided an overview on the challenges that are introduced with modern radar signals and the instruments you can use to overcome them. In the second application note of this series you well learn how to use various methods to create modern radar signals. This includes multi-channel RF generation for phased antennas, sequencing of various pulse patterns and how to deal with imperfections in signal generation through waveform correction. In this third part of the application note you will learn how to detect and digitize radar. This part covers bandwidth and storage requirements as well as analysis software to deeply analyze received radar signals.



Generation and detection of radar signals have changed dramatically in the past 30 years. Today's digital signal processing capabilities offer a wide range of possibilities to simulate radar signals and include simulated objects to verify the performance of a radar system.

Radar Signal Analysis: VSA, Scopes, and Digitizers

Analyzing Radar Signals has never been an easy task. In the past, only indirect measurements in the frequency domain using analog or digital swept spectrum analyzers were possible. The trade-off between resolution bandwidth and the pulse width of the analyzed radar signal resulted in the difficulty to directly visualize the frequency and time domain characteristics of the Radar system being analyzed. Pulse compression techniques made things even more difficult. The introduction of the Vector Spectrum Analyzer (VSA) changed the situation dramatically as those devices could capture the amplitude and phase characteristics of any RF signal within the analysis bandwidth. The block diagram of a VSA is similar to that of a traditional swept spectrum analyzer with one significant difference. In swept spectrum analyzers the ADC is directly connected to the output of a receiver. Before this detection block where no phase information is available, an IF logarithmic amplifier is used to extend the analysis dynamic range. VSAs do not incorporate an IF log amplifier and directly feed the IF signal to the ADC with sufficient sample rate and measurement bandwidth to fully characterize any RF signal within the IF bandwidth of the device. The ADC in VSAs operates as an internal digitizer. Dynamic range is therefore influenced by the RF front end noise and the linearity, as well as the ADC’s effective number of bits (or ENOB). Depending on the demodulation of the IQ components, instantaneous power can either be visualized in the time-domain or in the frequency domain by applying an FFT.



Radar signal analysis beyond 1 GHz, especially in multi-channel systems such as phased-array antennas or MIMO systems, is often a challenge due to cost and alignment of such analysis systems. Depending on the system requirements regarding cost and bandwidth three approaches are available (Figure 12):

- For bandwidths below 5 GHz and one channel a high performance VSA is the most appropriate solution. It provides an excellent sensitivity and high dynamic range.
- For bandwidths above 5 GHz two approaches are viable:
  - First approach uses the VSA as an analog downconverter that feeds its IF signal directly into an oscilloscope. In this case the VSA must be able to operate with the significant higher input frequency.
    This approach is also viable for single or low channel systems.
  - Second option is to work with a high-speed digitizer or oscilloscope that uses either direct digitalization and DSP post-processing, or one of the previously described down conversions. This is especially the best approach for multi-channel high bandwidth systems.

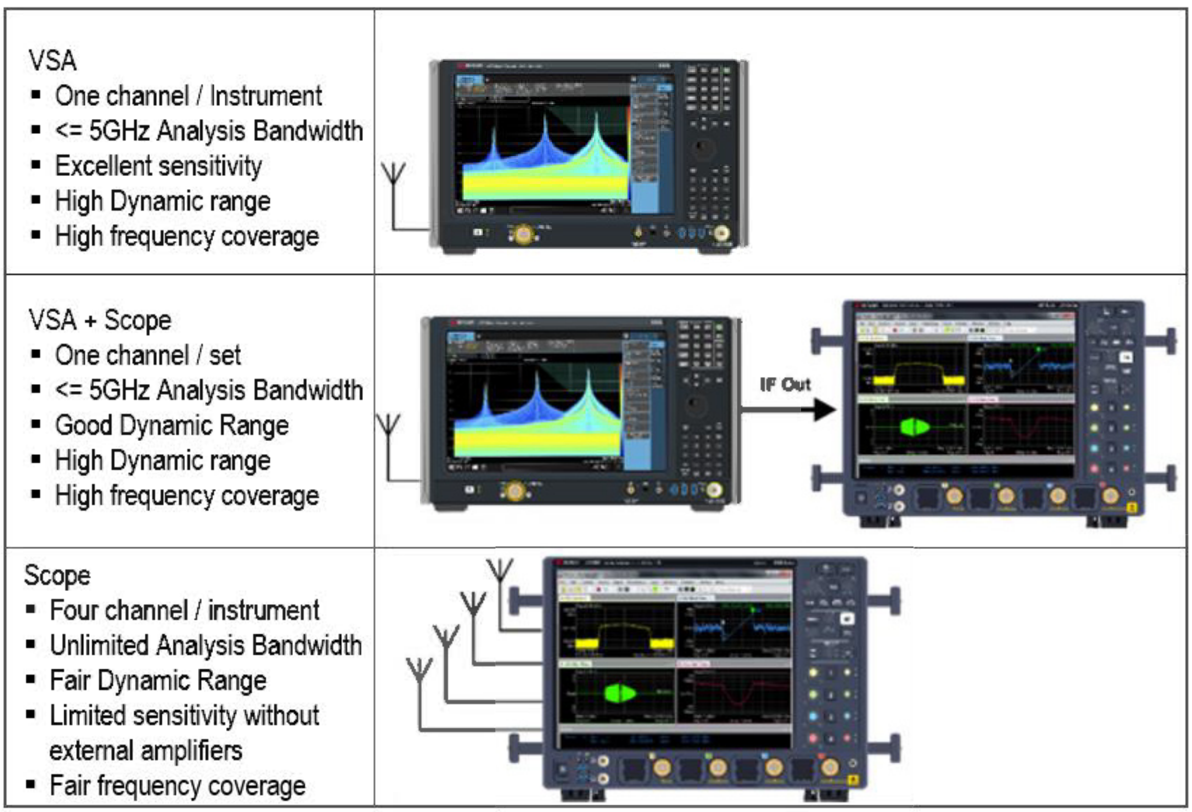


Figure 12: Different ways to analyze radar signals using one or more pieces of T&M equipment.

a) Traditional VSA (Vector Spectrum Analyzer).

b) The combination of a VSA and a Real-Time Digital Storage Oscilloscope with a higher analysis bandwidth.

c) A high-bandwidth oscilloscope can directly analyze complex modulated RF signals in multiple domains simultaneously with virtually unlimited analysis bandwidth.

Digitizers for RF Applications

Even when sampling rate or analog bandwidth are not a problem for the successful acquisition of an IF/RF signal, the large amount of waveform data generated in the process may be a challenge. In VSAs, the IF signal is digitized by two ADCs with identical sample rate, at least twice the IF bandwidth as required by the Nyquist Sampling Theorem. The two ADC paths represent the In-phase and Quadrature parts of the complex signal. When analysis bandwidth is lower than the maximum given by the Nyquist Theorem, a combination of a low-pass filter at each I/Q component and a down-sampling process can further reduce the amount of data created by the digitizer. In a Digital Sampling Oscilloscope (DSO) or digitizer, the complete IF/RF signal must be digitized, requiring a sampling rate at least twice the maximum frequency coverage of the original signal.

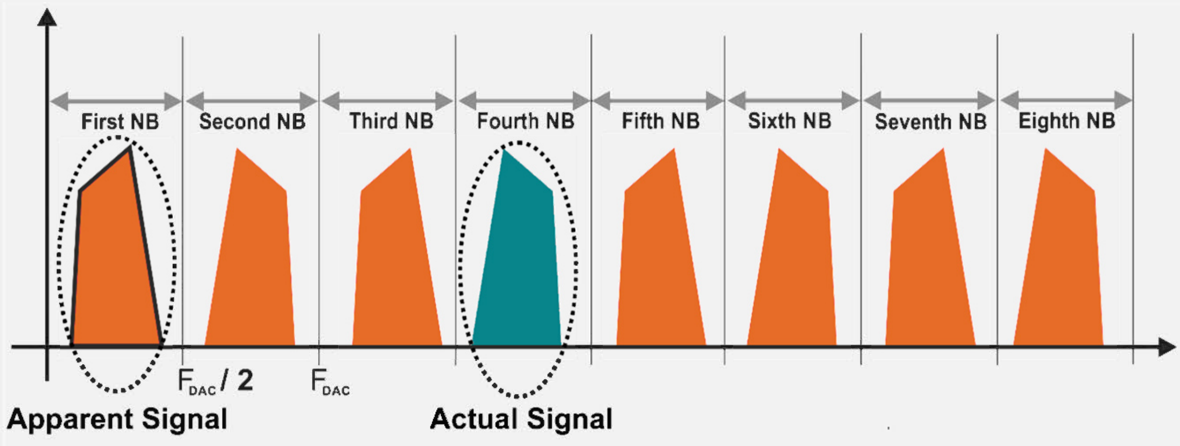
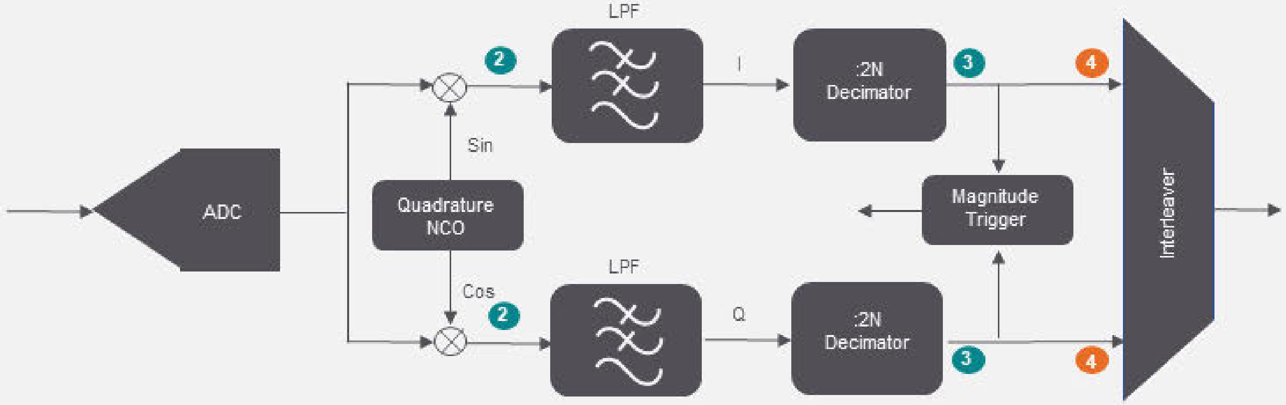


Figure 13: ADCs can successfully digitize signals beyond the Nyquist frequency if bandwidth is limited and lower than half the sampling rate. Sampling rate must be selected so the signal of interest is in the center of any of the Nyquist bands. In this example the target signal sits in the middle of the fourth Nyquist band. The digitized signal shows up as if it would be in the first Nyquist band. For even numbered Nyquist bands, the spectrum of the signal in the first Nyquist band (in fact, an alias) will be reversed. This concept requires the analog bandwidth of the digitizer to be high enough to cover the baseband signal frequency.

In order to ease the problem described above, there are several approaches available to you. ADCs are typically used to digitize any signal between DC and half the sampling rate. This band is called the First Nyquist Band. Any frequency component beyond this band will show up in the first Nyquist band as aliasing, interfering with the signal there. Therefore, a good digitizer implementation requires a low-pass filter at the input to fulfill the Nyquist criteria. However, aliasing can be exploited as a way to down-convert any bandwidth-limited signal beyond the first Nyquist band (Figure 13). If the signal of interest is located in the middle of the second Nyquist band (between SR/2 and SR), after acquisition it will show up as if the signal was located in the middle of the first Nyquist band with an inverted spectrum. This is similar for signals in the third Nyquist band, but the spectrum would not be reversed. This method can be extended to any Nyquist band, as long as the input bandwidth covers the frequency range of the input signal, and no other signals in other Nyquist bands are present. This can be achieved by applying a sufficiently steep band-pass filter, effectively acting as an antialiasing filter in this environment.

The key takeaway is that it is possible to capture high frequency signals with ADCs operating at significantly lower sample rates than the Nyquist Theorem would require. This concept is often known as under-sampling.

Data reduction can also be implemented through digital down-conversion (DDC) processing (Figure 14).



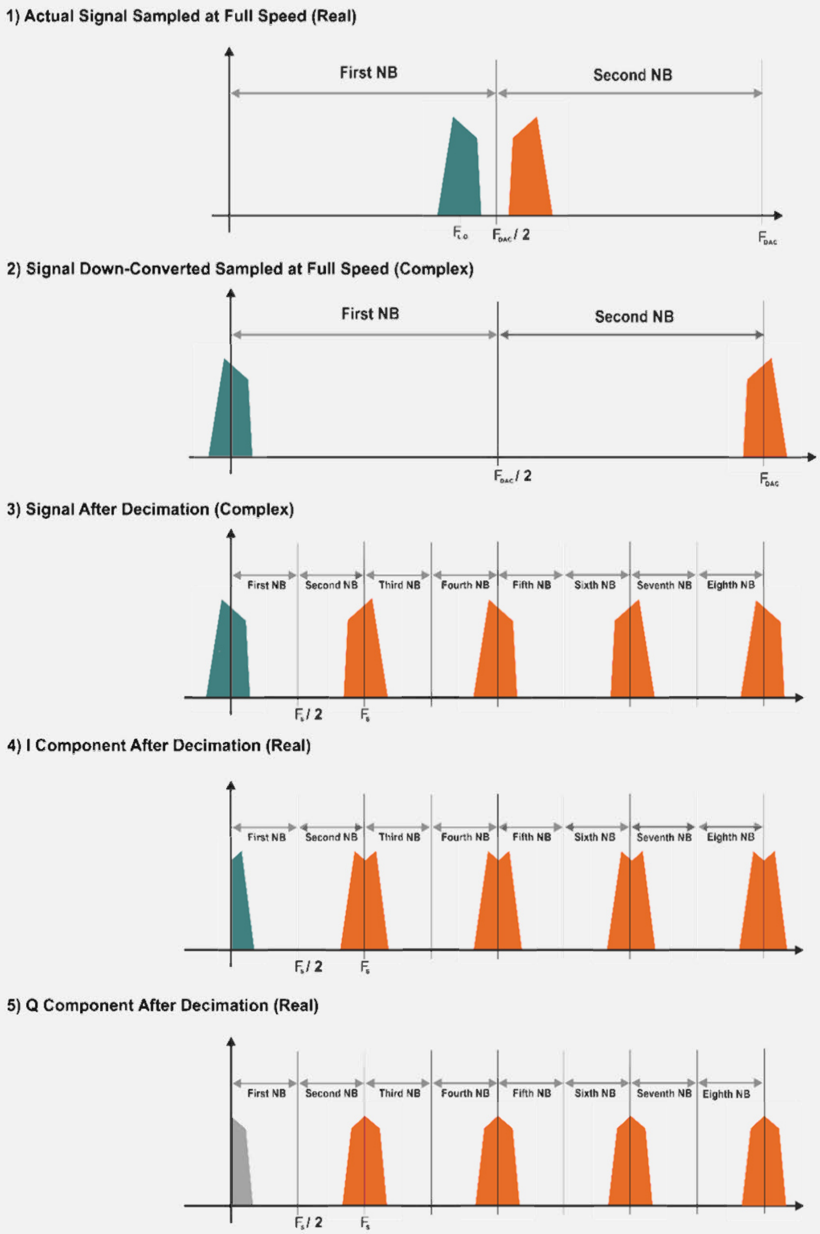


Figure 14: A different way to reduce the sampling rate and the data rate at the output of a digitizer block is Digital Down-Conversion (DDC). The digitized input signal is down-converted to DC (through a quadrature demodulator), low-pass filtered, and decimated. This process reduces the effective sampling rate without loss of information and improves the SNR due to its processing gain (factor 0.5 additional bits every time the sampling rate is divided by 2).

In this case, a bandwidth limited signal is mixed with a sine and cosine of a Numerical Controlled Oscillator (NCO), the center of the band of interest is shifted to the difference frequency between the original signal and the NCO and their sum. After that, a low-pass digital filter needs to be applied to reject the unwanted parts of the spectrum. Things become simpler when the down-sampling ratio is an integer number N, as resampling is simplified to select 1 out of N samples (and discarding the other N-1 samples) and no interpolation is required. Most DDC implemented in digitizers do not down-convert to a given IF. Instead, they down-convert to DC. The final outcome will be a pair of real sample streams, carrying the information of the I (real part) and Q (imaginary part) components of the down-converted signal. Those two streams (I and Q) can be interleaved into a single one at twice the sampling rate (so the Nyquist sampling theorem still applies). This process can be applied after signal acquisition or in real-time by some DSP after the ADC. Although mathematically both processes are equivalent, their impact in data reduction is huge. Post-processing of already captured data does not actually reduce the waveform acquisition memory requirements, but it gives the flexibility of processing the original signal multiple times (i.e. to isolate different signals). Real-time processing on the other hand can dramatically reduce the flow of samples at the output of the digitizing section, so less waveform memory will be necessary to store a given time window. A lower data rate also simplifies transmission both internally (to the acquisition memory) or externally (to an external processing or storage device when continuously streaming). Another important effect of this down-conversion scheme is the processing gain obtained through it. Processing gain is achieved in additional bits of resolution resulting from the signal bandwidth reduction. **Basically, 0.5 bits of vertical resolution are added every time the output sampling rate is divided by two** (Figure 15).

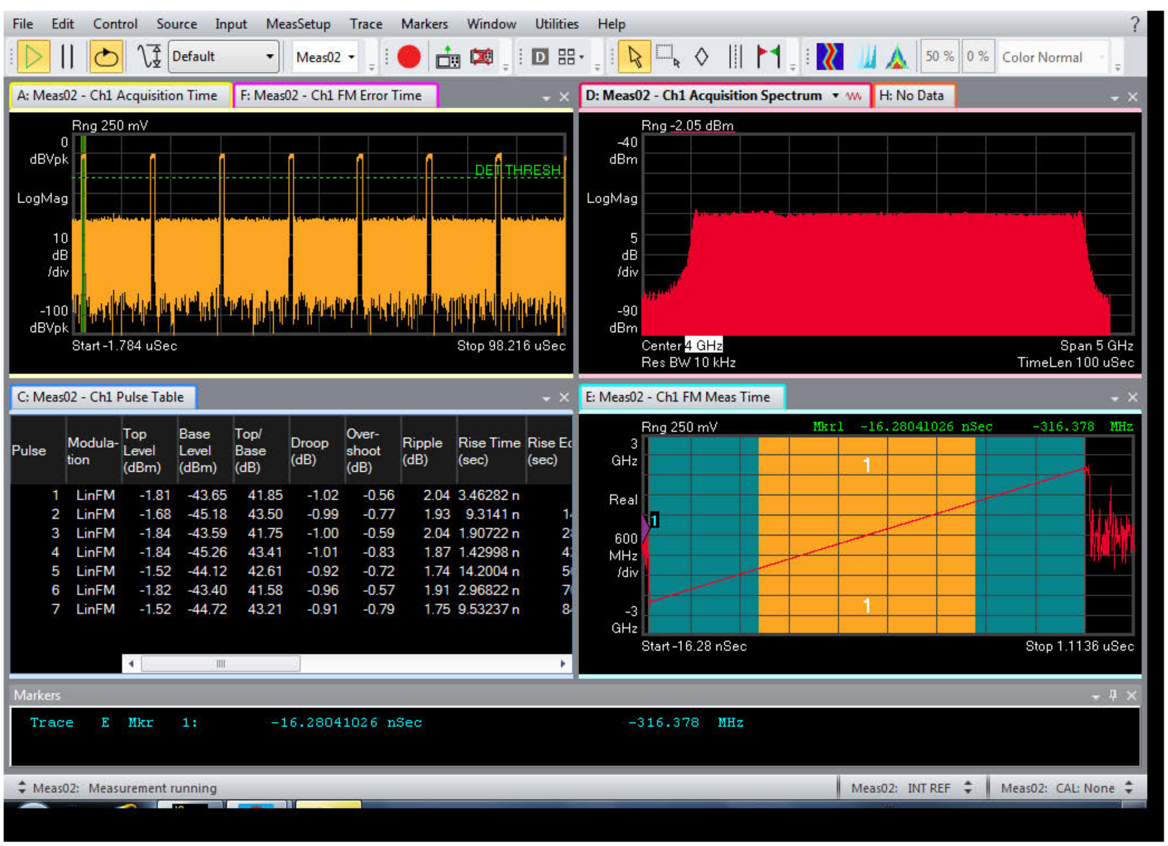


Figure 15: This screen capture has been created using a M8195A generator working in the 4X extended mode, captured using the M8131A in the 16 GSa/s using 4-channels, and analyzed using the 89600 VSA SW running on a PC and controlling the M8131A in real-time. The goal is generating and analyzing a 4 GHz chirp centered at 12 GHz. As both instruments are working at 16 GSa/s, direct generation and analysis would be impossible. However, generating the signal in the M8195A second Nyquist band using the internal FIR. An interpolator creates a high-quality, high-power, good dynamic range LFM chirp. The M8131A is capturing the chirp by under sampling the actual waveform, located in its second Nyquist band. In this case, the center frequency is 4 GHz.

Waveform Capture, Seamless Streaming, Continuous Storage

Many times, a thorough analysis of complex Radar or EW scenarios require extremely long captures without losing any events. The simplest way to do this is digitizing the complete radar signal for the duration of the experiment. No matter how long the internal acquisition memory is, when it is full, it is necessary to transfer the content to an external storage or processing device (i.e. a computer). As transfer time is usually much longer than acquisition time, the loss of events appearing during transfer is inevitable. In order to avoid this loss, there are several possible strategies (Figure 16):

- Waveform data reduction by under sampling and/or DDC as explained in the previous paragraph.
- Acquisition memory segmentation and timestamping: As many real-world signals (i.e. radar) show relatively short bursts of activity separated by long periods of inactivity, data reduction can be obtained by only storing the active periods and discarding the rest. This can be implemented by acquisition memory segmentation. Segmented memory can be used to store data only from active signals, e.g. each pulse can be assigned to a separate segment. In doing so the timing information between the pulses gets lost, therefore a timestamp for each pulse or segment is required to recover the full timing sequence of all pulses. Advanced digitizers can store a timestamp for each segment. Timestamps are derived from a sample counter connected to the sampling clock and initialized for each sequence acquisition.
- Internal real-time processing through DSP and FPGA: In many situations, waveform data is the intermediate step to get the final information of interest. For example, in an electronic intelligence (ELINT) environment, the important information may be the location, duration, and modulation of the pulses transmitted by the radar of a potential aggressor. The waveform will be used to extract information described as Pulse Description Word (PDW) and store the PDW in a table. Although the size of each PDW may be quite short, the amount of waveform data necessary to extract the information may be much larger. Some digitizers incorporate internal FPGAs. Functionality of the FPGAs may be defined, total or partially, by the digitizer manufacturer. In the ELINT example, the internal FPGA could be used to detect and characterize pulses and store (or transfer) the PDW.
- Streaming to external processing and storage devices: When the internal acquisition memory is not enough, a solution may be by-passing it and directly transfer the digitized samples to an external storage device. Most digitizers modules are based on computer busses like PCIe . Even the most advanced current implementation with nearly 16 GBytes/s transfer speed might not be able to handle the data rates produced by real-time sampling digitizers. For these devices, you may also be able to use multiple point-to-point optical links that potentially transfer speeds in the Tbit/s range.

The M8131A Digitizer

The Keysight M8131A is a good example of a state-of-the-art digitizer optimized to work in the RF environment with an outstanding analysis bandwidth. It can sample up to 32 GSa/s on 2 channels or 16 GSa/s on 4 channels with 10 bits resolution into a 2 GByte internal acquisition memory. It incorporates the right features, level of performance and functionalities to address the capture and analyze wideband RF signals. Other features are:

- Excellent SFDR of 66 dBc at 1 GHz.
- High analog bandwidth (12.5 GHz) with a choice for the input type for each channel: single-ended with a variable range (40 mVpp-400 mVpp) or differential with a fixed range and lower noise.
- Real-time channel by channel frequency response correction to maximize flatness based in characterization data obtained in the factory. The correction settings can be modified by users to deembed the behavior of external cables and devices.
- Capability to capture waveforms in the second Nyquist band when working in the 16 GSa/s, 4-channel mode with differential inputs.
- Digital Down-Conversion for all the channels with center frequencies (CF) independently defined for each channel. The decimation factor can be selected between multiple powers of 2. Processing gain results in an improvement of 12 dB in the SNR (or 2 bits) when capturing a waveform with 800 MHz analysis bandwidth in the 16 GSa/s acquisition mode (16x decimation) or 6 dB (1 bit) when analyzing a waveform with 8 GHz analysis BW in the 32 GSa/s mode (4x decimation).
- Excellent analysis BW: up to 12.5 GHz for IF/RF signals (one channel) and 25 GHz for IQ baseband signals (2 channels).

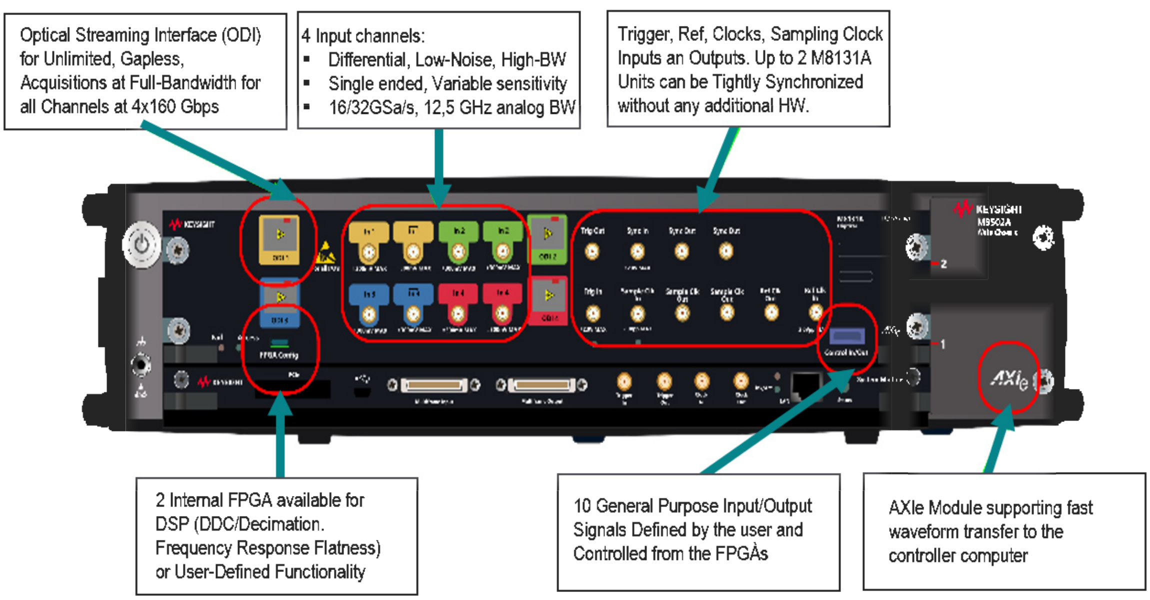


Figure 16: Full bandwidth, seamless streaming for all the channels is one of the unique features of the M8131A. It can be used for external storage or signal processing. For additional signal processing capabilities, the M8131A signal processing can included into the system with signal processing module and external storage and an AWG to retransmit the processed signal.

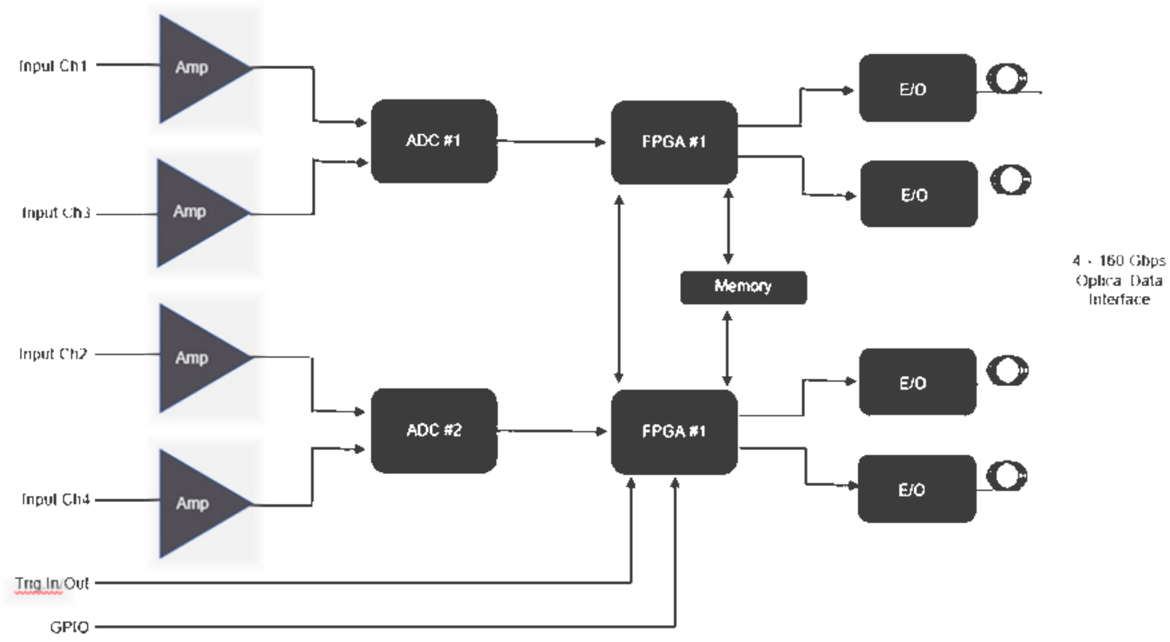


Figure 17: The M8131A is a high-performance, high sampling rate 4 channel digitizer with full-bandwidth seamless streaming through standard ODI optical links (top). The diagram (bottom) shows the basic blocks, including the shared ADC (one for every two input channels), the associated FPGAs, and the streaming optical outputs.

The M8131A has been designed from scratch to support massive amounts of data as required by the radar, EW or ELINT environments. In addition to the large internal acquisition memory (2 GByte), full speed streaming to external devices is supported for all the channels through an ODI (Optical Data Interface) interface as defined by the AXIe Consortium. Four ODI interfaces on the front panel can stream with 160 Gb/s each. Internal waveform memory can be segmented, and the module supports external and internal trigger sources. Segmented acquisitions (with no rearm dead time) are time-stamped with one-sample resolution so the original timing of the signal can be recovered. In addition to the traditional, scope-like, level trigger, it also supports “magnitude trigger” when using the internal DDC. In this case, the trigger event is generated by the instantaneous magnitude (or power) of the input signal and is especially suited for pulse detection and acquisition in the segmented acquisition mode.

Some of the already described M8131A functionalities (i.e. DDC, frequency response corrections) are implemented in the internal FPGAs. The FPGA can be connected to the PCIe bus, the ODI interfaces, and a series of connections in the front panel such as a 10-line GPIO including several synchronization and trigger inputs and outputs. The FPGA is powerful enough to support functionalities such as Pulse Description Word (PDW) extraction, DOA (Direction Of Arrival) angle determination of phase array systems, or real-time spectrum analysis.

The combination of an M8131A digitizer with a mass storage, a signal processing module like the M8132A and an arbitrary-waveform-generator to retransmit modified signals, all in real-time, provides a very powerfully tool for object simulation in radar test systems or in other application like 5G.

Integrating multiple M8131A units is one of the huge advantages of the instrument's AXIe architecture. Multiple modules, each with 4 channels, can be integrated in one or multiple AXIe mainframes. The availability of synchronization and trigger signals into and out of the modules provides synchronizing of several modules without the need for additional hardware.

The M8131A is compatible with the leading VSA software. The 89600 VSA software (Figure 19) can fully control the analyzer and simultaneously handle all the functionality of the module. The 89600 SW offers specific support for any telecom or radio standard. The Radar Analysis Bundle offers analysis of both RF and baseband signals from the M8131A channel. It can operate with pulsed radar signals with automatic identification of pulses and intra-pulse modulation identification. Continuous-wave frequency-modulation (CWFM) signals are also available (popular in the automotive environment). The availability of extremely wide analysis bandwidth (> 12 GHz) allows for characterization of automotive radar CWFM signals or frequency-hoping radar signals.

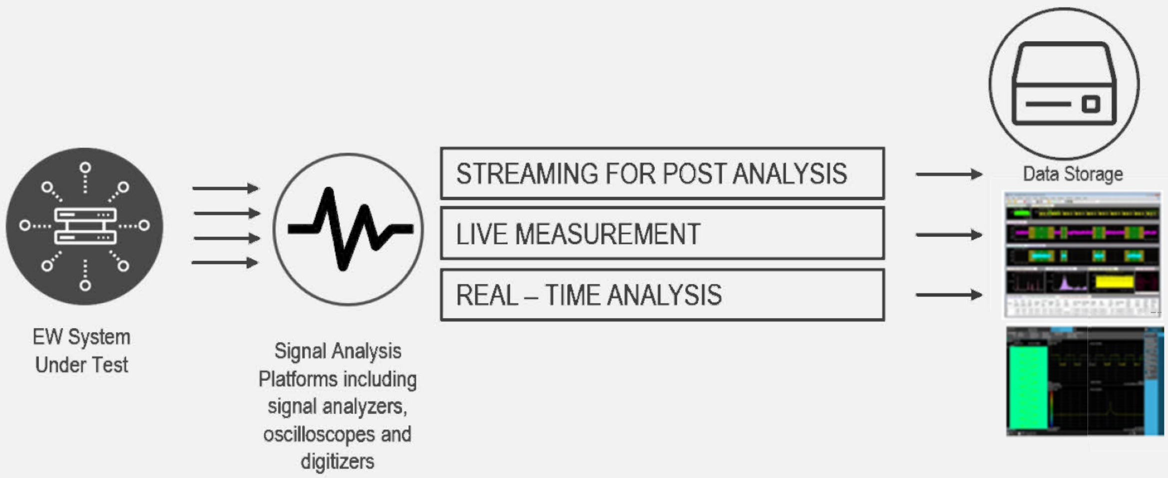
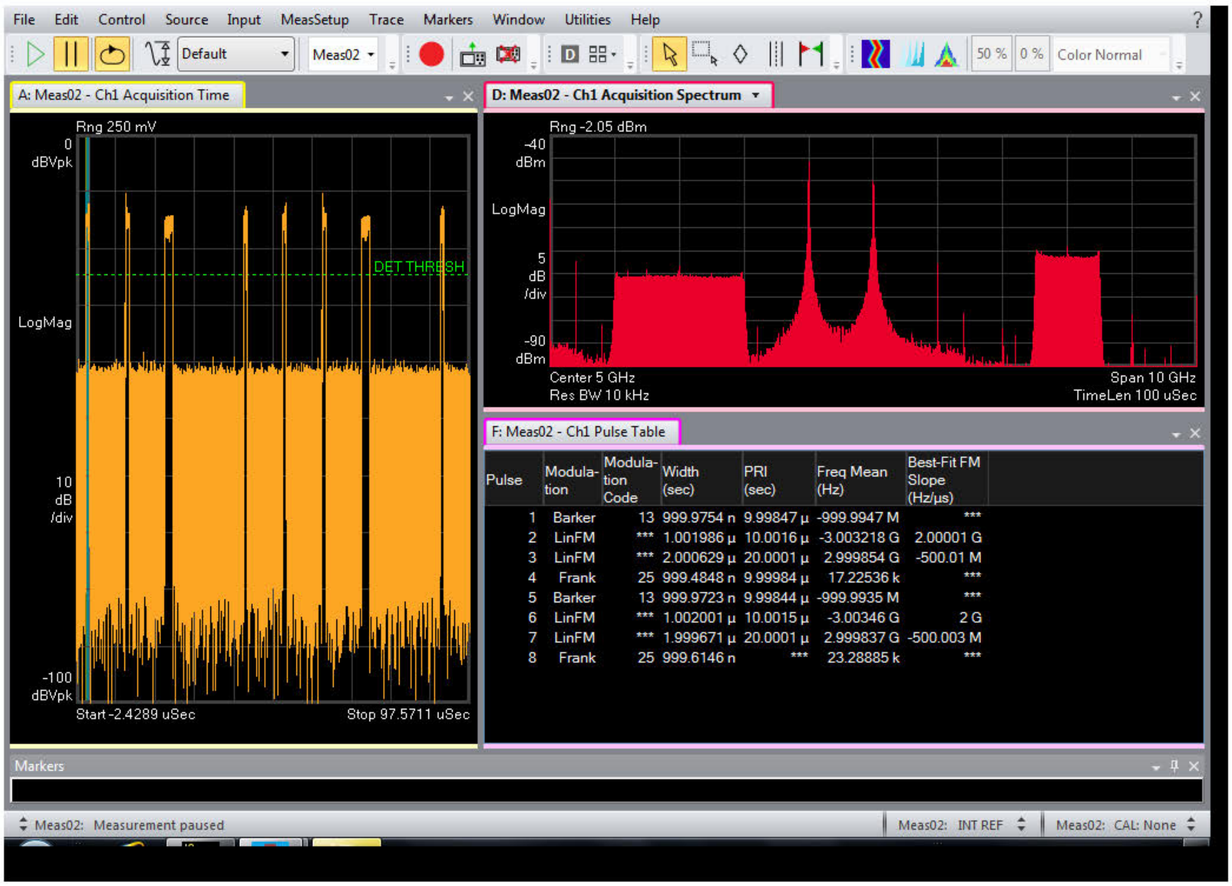


Figure 18: Real time radar signal analysis.

Conclusions

The M8195A and the M8131A open the door to affordable, easy-to-integrate, multi-channel radar signal generation and analysis. When used in combination, it is even possible to create closed-loop systems with deterministic latency. The generation and analysis bandwidths allow handling one or multiple wideband radar signals simultaneously, including frequency hopping signals. Advanced triggering, segmented acquisition and gapless streaming are offered by the M8131A digitizer. Large internal, segmented waveform memory and advanced sequencing in the M8195A AWG offers the ability to create extremely long duration radar and EW scenarios. Finally the AXIe module form factor offers the ability to integrate many channels into one system and provides analysis and emulations of phase array or MIMO radar systems.



Pulse	Modulation	Modulation Code	Width (sec)	PRI (sec)	Freq Mean (Hz)	Best-Fit FM Slope (Hz/µs)
1	Barker	13	999.9754 n	9.99847 µ	-999.9947 M	***
2	LinFM	***	1.001986 µ	10.0016 µ	-3.003218 G	2.00001 G
3	LinFM	***	2.000629 µ	20.0001 µ	2.999854 G	-500.01 M
4	Frank	25	999.4848 n	9.99984 µ	17.22536 k	***
5	Barker	13	999.9723 n	9.99844 µ	-999.9935 M	***
6	LinFM	***	1.002001 µ	10.0015 µ	-3.00346 G	2 G
7	LinFM	***	1.999671 µ	20.0001 µ	2.999837 G	-500.003 M
8	Frank	25	999.6146 n	***	23.28885 k	***

Figure 19: High bandwidth AWGs and digitizers offer unparalleled performance in terms of analysis bandwidth and signal generation and analysis flexibility. Here, the M8195A is generating a sequence of frequency hopping, dissimilar pulses over an 8 GHz bandwidth. The M8131A digitizes the waveform and it is analyzed by the 89600 VSA SW radar pulse analysis option. The different pulses are properly identified and characterized, including the automatic identification of the intra-pulse modulation applied to its pulse, sweeps for LFM-modulated pulses, etc

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In the first part of this series of three application notes we explained key elements that distinguish modern radar systems form historical pure analog radars systems. These new methods are pulse compression, ultra-high bandwidth in the multiple GHz range, high signal complexity by applying digital signal processing methods, and finally the application of phased array antennas, providing unmatched flexibility in antenna beam forming.

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In this final third part of the series of application notes we focused on capturing radar signals with modern high bandwidth digitizers or real-time oscilloscopes. We discussed the bandwidth requirements and challenges when digitizing a radar signal and showed tools like VSA to deeply analyze the digitized radar signals. Especially with modular small form factor digitizer phased array antenna radar detection system can be easily realized.

A set of AXIe modules consisting of M8131A digitizer, M8132A signal processor with customer programmable FPGA and the M8121A arbitrary waveform generator is available to detect, manipulate and re-sent radar signals in most flexible way.