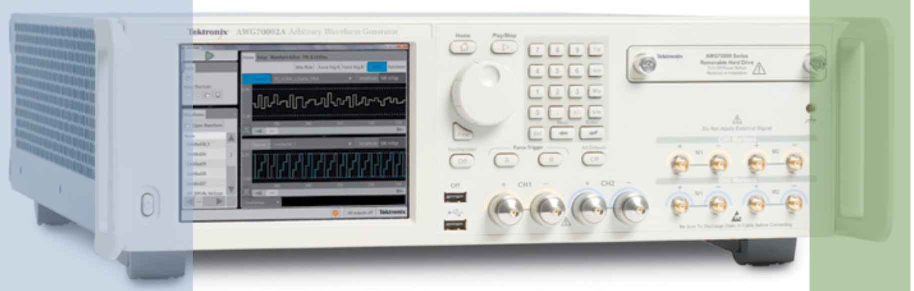


RADAR Signal Generation with High Performance AWG

Application Note

Tektronix®

Figure 1.

The Tektronix AWG70000 (Figure 1) Series Arbitrary Waveform Generator (AWG) can reach sampling rates as high as 50GS/s with 10 bits vertical resolution, 20 GHz usable bandwidth, 16GSample waveform memory size, and excellent SFDR (Spurious Free Dynamic Range) characteristics. Such level of performance allows for the direct generation of fully modulated RF/µW signals required by modern RADAR. Most of these requirements are impossible to handle by lower performance AWGs or traditional vector signal generators (VSG). The purpose of this paper is to show how the characteristics and performance level of the AWG70000 series influence the ability to support different RADAR technologies and the way the instrument's flexibility can be used to compensate for internal /external device imperfections and to emulate real-world targets and conditions.

1 Introduction

The generation of RADAR signals is one of the most challenging tasks for a signal generator. The combination of carrier frequency, modulation bandwidth, and, in most cases, their pulsed nature results in a series of requirements difficult to match by existing instrumentation. The increasing complexity of RADAR systems, the growing application of complex modulation techniques such as OFDM or UWB, and the signal quality requirements for a successful test impose severe restraints to stimuli equipment applied to RADAR testing. The need to emulate multi-antenna RADAR systems as those based in phase-array antennas or, more recently, MIMO architectures, implies the need to generate multiple signals with tightly controlled timing and phase alignments.

Traditionally, RADAR signal generation has been implemented through a combination of some sort of baseband signal generator and a RF/µW modulator, often sharing the same piece of equipment. The Tektronix AWG70000 series of arbitrary waveform generators (AWG) can be successfully applied to these architectures, although their level of performance allows for the direct generation of RADAR signals with carriers up to 20GHz (beyond the K_u band) with a much higher signal quality, cost effectiveness, and repeatability than traditional solutions. This paper is devoted to describe how the AWG70000 series generators can be applied to a wide range of RADAR signal generation requirements.

2 Generation of RADAR Signals

2.1 Specific RADAR and EW Signal Characteristics

Carrier frequencies used in RADAR systems cover almost all the usable radio-electric spectrum. From very low frequencies required for long range and over-the-horizon surveillance RADAR up to millimeter wave used in some high-resolution, small size military and civilian RADARs. The vast majority of radar systems, though, operate at frequencies less than 18GHz (Ku band). The Radar equation implies that range is maximized as power increases while spatial resolution improves as pulses become narrower (Figure 2). As these two requirements are contradictory, pulse-compression techniques are widely applied in order to match both. Regarding signal characteristics, these are the main two groups:

- Pulsed RF: The signal consists in periodic burst of an RF carrier, modulated or not (simple pulse radar systems). The rate at what pulses are generated is known as PRF (Pulse Repetition Frequency) and their period as PRI (Pulse Repetition Interval).
- CW (Continuous Wave) Radars: the RF signal is continuous and range is established through some time markers carried by the transmitted signal. FM modulation is a popular way to measure distance, as the instantaneous frequency coming from the target will depend of its distance.

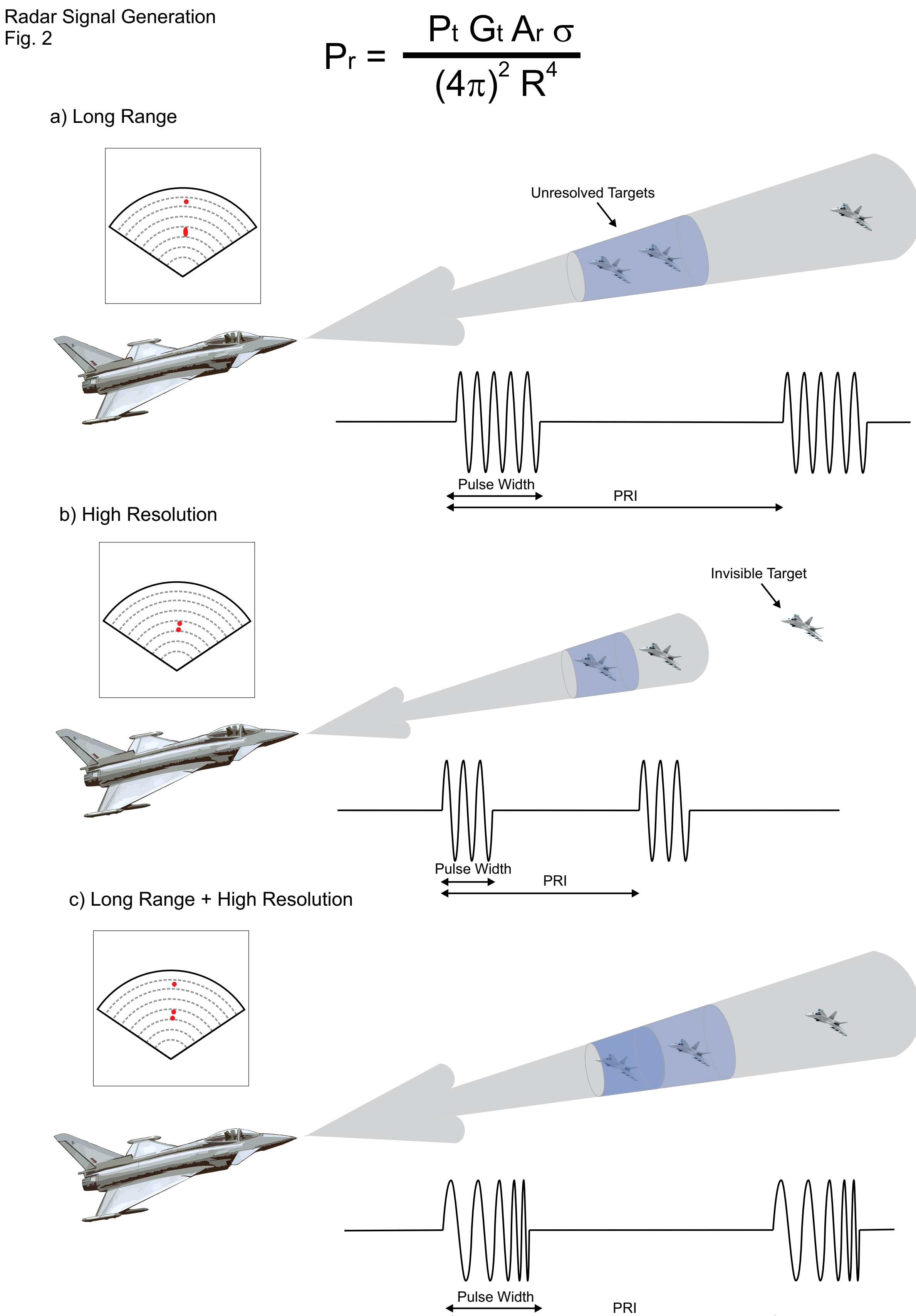


Figure 2. The radar equation (top) implies a trade-off between range, which requires long pulses (a), and spatial resolution, which requires short pulses (b). Pulse compression techniques (c) allow for long range, high-resolution radar systems as echoes are "compressed" at the receiver. Pulse compression implies complex intra-modulation within pulses.

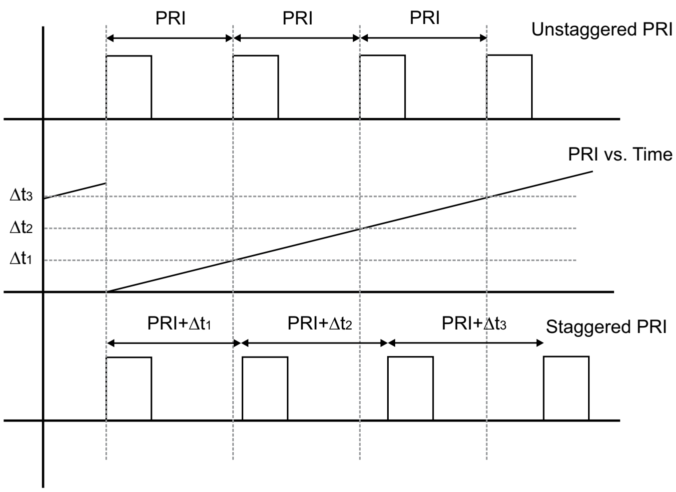


Figure 3. Staggered PRF changes the timing between pulses over time. By doing that, blind speeds can be removed and targets beyond the radar's nominal range can be detected while obtaining a signal more resilient to countermeasures or jamming. Staggering profiles may be rather complex and its correct emulation through an AWG requires long waveform memories to keep all the sequence. Here, a simple linear profile is shown.

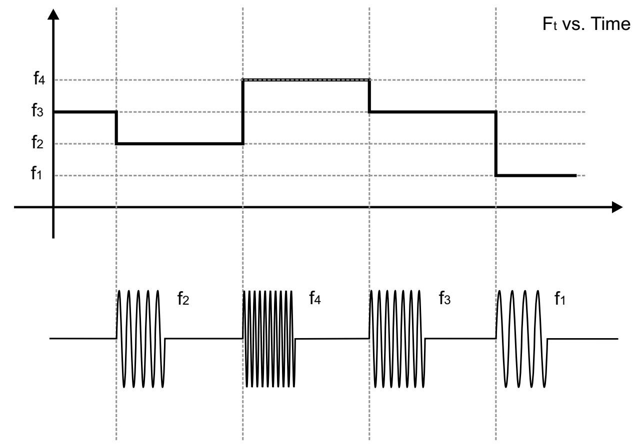


Figure 4. Frequency agile radar systems change the emitting frequency over time in a pulse-by-pulse basis. Frequency sequences look random and non-repetitive to intentional jammers so it is very difficult to set up effective countermeasures. Frequency agility may be applied by simply switching some local oscillator at the transmitter or by controlling the frequency offset of IQ baseband signals applied to a quadrature modulator. In the first case, frequency switching behavior may be an issue. In the second, modulation bandwidth of the modulator must cover the complete frequency range covered by the radar.

For pulsed RF radars, PRF may be fixed or it can vary over time (Figure 3) for a variety of reasons:

- Resolve echo ambiguity: Unambiguous ranging of targets is limited by the PRI. Targets located beyond that distance can be mistakenly positioned according to the timing to the nearest transmitted pulse. A way to identify this situation is by changing the timing of consecutive pulses so their position against near pulses will change.
- The "Doppler Dilemma": Radar systems use the Doppler Effect to measure target velocity and/or reduce the effects of clutter. The physics of the Doppler Effect produce "blind speeds" for specific target velocities. Changing the PRF can change the location of "blind speeds" and detect previously invisible targets. Some radar systems switch between a high PRF optimized to obtain blind speed higher than the expected target velocities and a slower one optimized for range.
- Protection against jamming: Variable PRI, often combined with complex stagger sequences, allows an easier identification of echoes caused by a given radar and others created by radars operating in the same frequency or by intentional jamming. Some stagger sequences are specifically designed to confuse DSP-based jammers.

Also for pulsed RF radars, the transmitting frequency (Figure 4) may be fixed or variable (frequency agility). Variable transmitting frequency takes the form of frequency hopping patterns. These patterns are rather complex, non-predictable, and typically non-repeating (or repeating over extremely long periods of time). Carrier frequency can even change for each transmitted pulse.

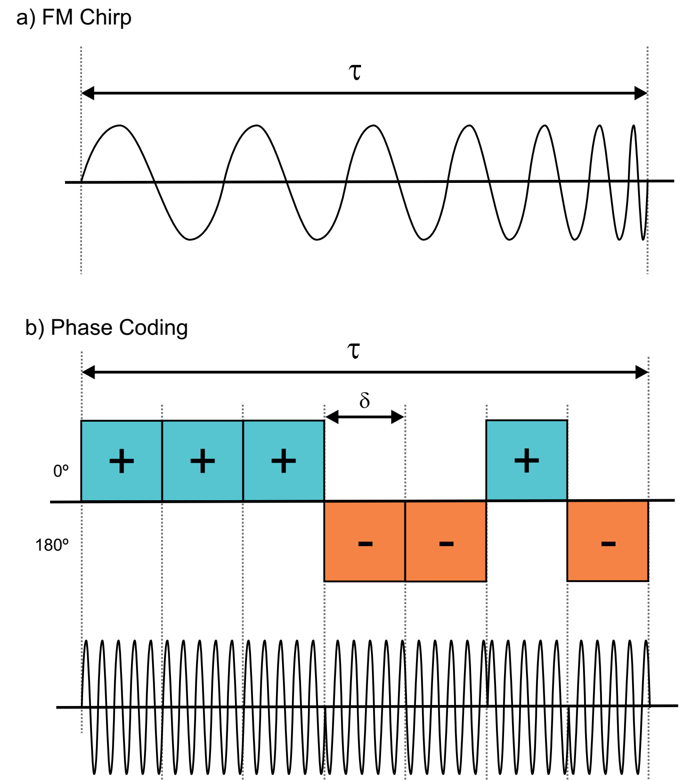


Figure 5. Pulse compression requires intra-modulation of the radar pulses. The most popular techniques involve some sort of fast frequency linear or non-linear sweep, called FM Chirp (a), or phase modulation using a binary sequence with low autocorrelation when not perfectly aligned such as Barker codes. Barker sequence of length 7 is shown in (b).

Pulse compression techniques can increase ranging by transmitting longer pulses (so average power is increased for a given peak power) while echo processing at the receiver can result in a much better spatial resolution by "compressing" the pulse through some correlation or dispersion processing. There are two main pulse compression methodologies:

- FM Chirps (Figure 5a): These consist in fast frequency sweeps. These sweeps may be linear (LFM) or non-linear (NLFM). Non-linear FM has some advantages regarding bandwidth thus resulting in better sensitivity and lower noise levels at the receiver.
- Phase modulation (Figure 5b): Each pulse is made by a series of shorter pulses where the carrier phase is controlled by some low autocorrelation binary sequence of symbols. While the average power is controlled by the total duration of the sequence, spatial resolution depends on the duration of each symbol. Binary-phase-coding, where carrier phase changes between 0 and 180 degrees, although Barker code sequences is a very popular example. Polyphase pulse compression applies the same basic idea but the carrier phase takes more than two values.

Some advanced techniques already applied to broadcast and mobile communications such as OFDM or MIMO are also being developed for Radar usage.

An important issue for some radar systems is carrier phase coherence. In some systems, such as the higher-performance coherent MTI (Moving Target Indicator) architecture, phase coherence must be preserved between consecutive pulses.

Returning echoes, no matter the phase characteristics of the transmitted pulse, will consist of a superposition of signals with a variety of relative phases. There will be multiple target echoes with arbitrary delays, multiple echoes from the same target with different time of arrival due to multi-path, all kind of clutter and frequency shifts caused by the Doppler Effect due to either the transmitter and/or the target relative speeds. The instantaneous amplitude and phase for a given echo will be also controlled by the target shape and size. In other words, no matter how complex the transmitted signal is, the reflected signal will be much more complex.

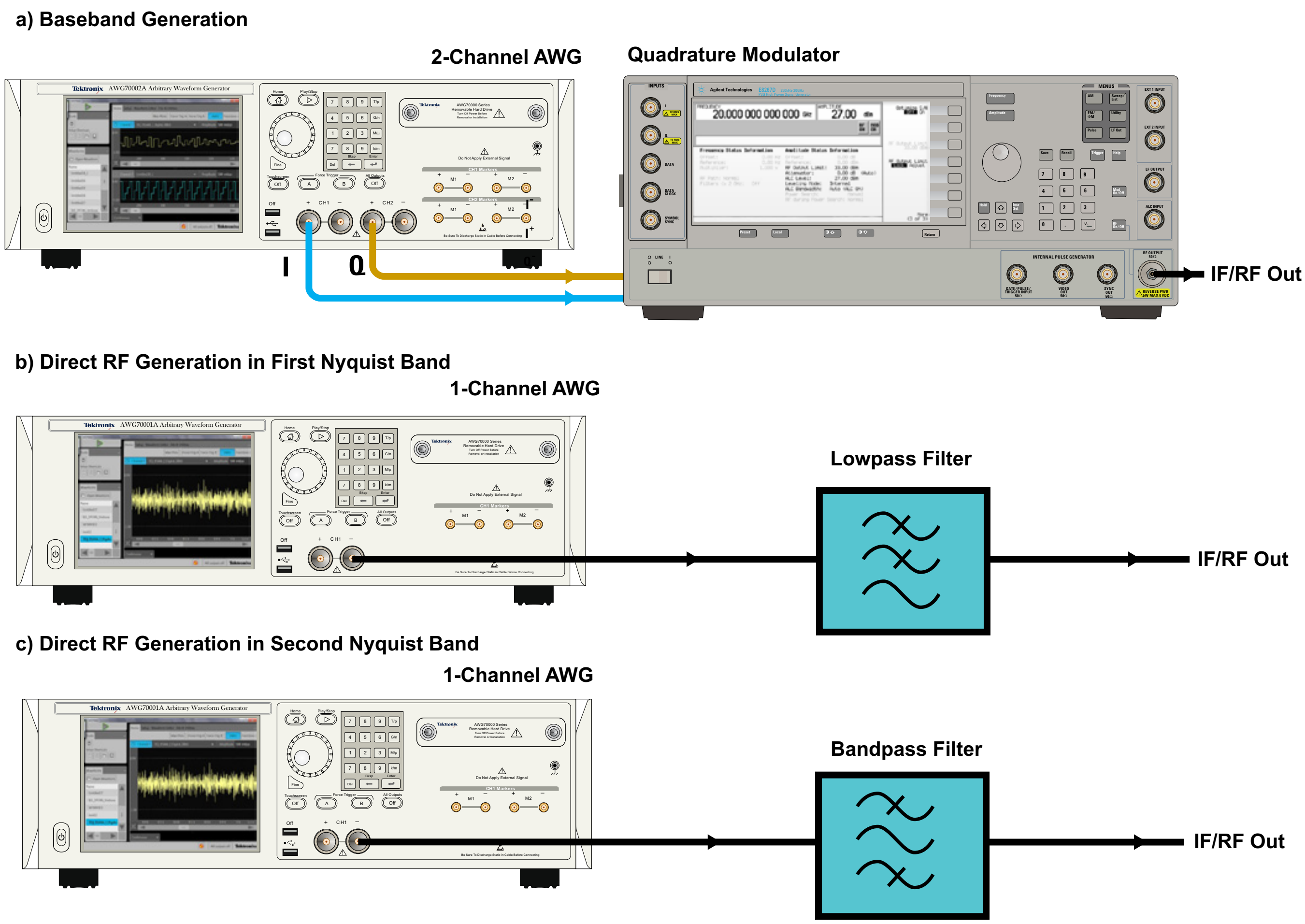


Figure 6. AWGs can generate modulated carriers through different methods. Baseband generation (a) requires a two-channel AWG and an external quadrature modulator. Sampling rate requirements depend only on the modulation bandwidth which is limited by the modulator itself. Direct RF generation (b) results in a ready-to-use modulated RF carrier. It requires a single-channel AWG while sampling rate requirements depend on both the carrier frequency and the modulation bandwidth. As modulation bandwidth is always a fraction of the carrier frequency, modulation bandwidth is virtually unlimited. A variant of direct RF generation uses the signal image located in the second Nyquist band (c) so the requirements for sampling rate are relaxed. However, the amplitude of the image, the steep roll-off of the AWG frequency response at these frequencies, and the limited modulation bandwidth supported may dramatically reduce the usability of the generated signal.

2.2 RADAR Signal Generation Architectures

AWGs can generate RADAR signals through basically three different methods (Figure 6):

- Baseband generation: The AWG generates the time-domain signal to be applied to a RF modulator. For simple signals where pulses are generated by controlling the envelope of some carrier, a one-channel AWG is applied to an amplitude modulator (AM). For more complex signals requiring complex digital modulation or fast frequency sweeps (chirp) both the amplitude and the phase of the carrier must be instantaneously controlled. In this case, the most flexible and easiest solution to implement is a quadrature modulator that requires two baseband signals, the In-Phase (or I) and the Quadrature (or Q) components. These two baseband signals can be generated through AWGs with 2 channels or by using 2 synchronized single-channel generators.
- IF (Intermediate Frequency) generation: The AWG generates in this case a modulated signal at a relatively low carrier frequency. In some cases, this signal can be applied directly to some signal-processing block in the receiver or the transmitter. In others, performed at the final RF/µW frequency, it is necessary to use an up-converter block to reach the final carrier frequency.
- Direct RF generation: The AWG will generate the modulated carrier at the final RF/µW frequency so no additional signal-processing blocks other than filters or amplifiers are required.

All methods have both advantages and drawbacks. Baseband and IF generation can be implemented with moderate performance AWGs, for most signals, a few GS/s are enough. However, in both cases, modulation bandwidth of the final RF/µW signal will be limited by the characteristics of the modulator or up-converter. As an example, commercially available, instrument-grade quadrature modulators are capable of generating signals with up to 2GHz bandwidth what may be not sufficient for some RADAR applications. Even worse, wideband quadrature modulation is extremely sensitive to I/Q imbalance or quadrature errors so accurate alignment after careful calibration is required to obtain good quality signals. On the other hand, direct signal generation require extremely fast AWGs as sampling rate must be, at least, 2.5 times higher than the maximum frequency component of the signal. Traditionally, obtaining good-quality signal in terms of spurious-free dynamic range (SFDR) has been difficult with ultra-high speed AWGs, given the limited DAC resolution (6 bits). However, the latest generation of Tektronix high-speed AWGs, the AWG70000 series, offers 10 bits vertical resolution at speeds up to 50 GS/s, opening the door to quality signal generation beyond the K_u band (12-18GHz).

2.3 Baseband Signal Generation

At first sight, the generation of baseband signals seems to be a relatively easy task, as modulation and up-conversion are performed by an external device. The modulation device may be a simple amplitude modulator (AM) for basic pulsed RF signal generation. However some baseband signals (i.e. Barker Codes used in pulse compression) require suppressed carrier, which is not supported by most AM modulators, as the instantaneous phase can take two values (0° and 180° or BPSK). Finally, baseband generation of FM chirps, QPSK/QAM, and, in most cases, UWB OFDM signals require a quadrature modulator as both the instantaneous amplitude and phase of the carrier must be controlled. Emulation of realistic radar echoes incorporating the effects of the target characteristics, multi-path, Doppler shifts, noise, and jamming always requires quadrature modulation as there are both I and Q components thus a two channel AWG is mandatory for baseband generation (Figure 6a).

Generating good quality wideband modulated signals using this scheme is not an easy task. Frequency responses of both baseband generators and RF modulators are not flat and group delay is not constant over the bands of interest when signal bandwidths are high. Regarding AWGs, even a perfect instrument incorporating ideal DACs will show a zeroth-order hold response:

$$H(f) = \mathrm{sinc}(\varpi f/Fs) = \sin(\varpi f/Fs)/(\varpi f/Fs),$$
$$Fs = \text{Sampling Frequency}$$

The above response will introduce linear distortions to the RF pulses, altering the shape of the transitions and modifying the rise and fall times. Additionally, the analog frequency response of the AWG, cabling, and the modulator frequency response will add to the distortions. Unwanted images resulting from the sampled nature of signals generated by AWGs can also affect signal quality, as they will show up as unwanted sidebands in the RF domain. Finally, the limited time resolution available in any AWG may result in unexpected levels of pulse-to-pulse jitter.

The good news is that AWGs can generate either undistorted or distorted signals and distortion mathematically applied to waveforms stored in the generator's memory may be designed to compensate for external distortions. After careful calibration of the overall frequency response it is possible to design a compensation filter, which takes care of improving flatness and group delay response. Typically, the compensation filter takes the form of a pre-emphasis filter as it will correct the generation system' overall low-pass frequency response. As high frequency components are boosted, the low frequency components of the signal must be attenuated in order to keep a peak-to-peak value that fits in the available DAC dynamic range.

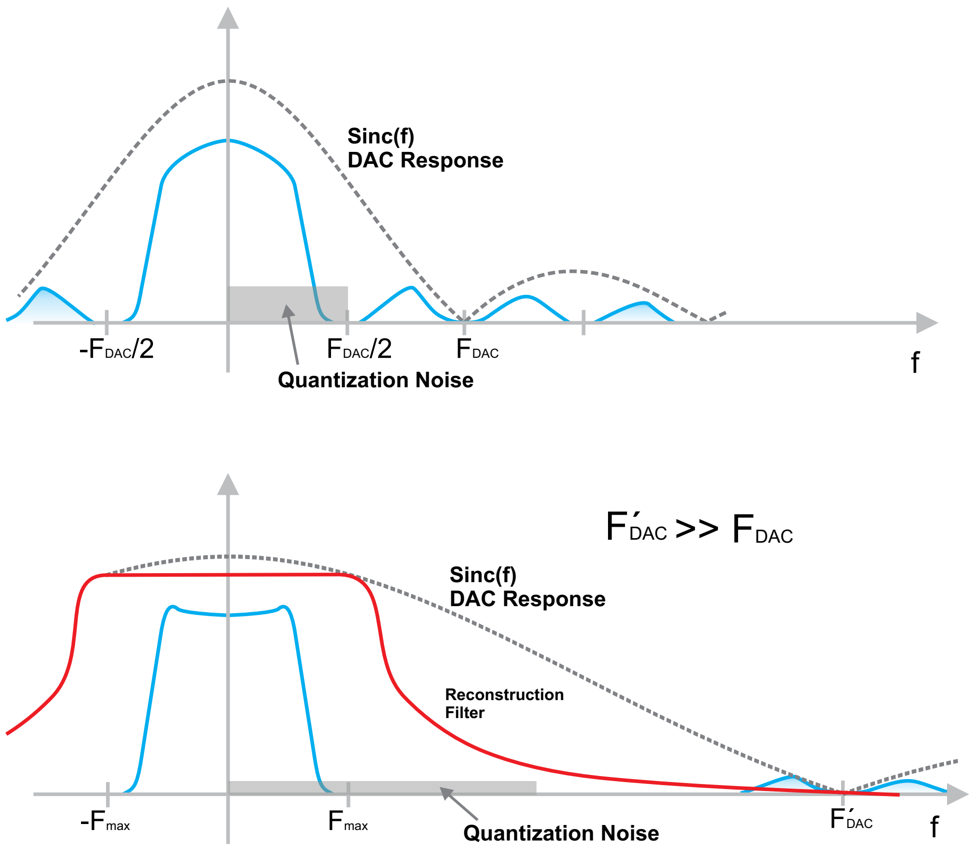


Figure 7. Generating a limited bandwidth signal at a much higher sampling rate that the one required by the sampling theorem (Fs=2xBW) is a technique known as oversampling. This technique improves the quality and usability of the signal as it improves SNR (and effective bits) and flatness while relaxing the requirements for reconstruction filters.

Maximum sampling rate greatly influences signal quality. Generally speaking, it is a good practice to set the AWG sampling rate well over the minimum nyquist requirement for a given signal by the Nyquist sampling theorem, operation known as oversampling (Figure 7). Higher sampling rate increases signal quality for various reasons:

- Flatter frequency response: The influence of the sinc(ϖf/Fs) response is reduced as sampling rate increases. For a 4 GHz BW signal generated at 12 GS/s by an ideal AWG, the impact in the flatness will be 1.65dB, while the same signal generated at 25GS/s will result in a 0.37dB flatness.
- Image rejection: The first image will be located at a higher frequency and, as a consequence, the gap between the wanted signal and the unwanted images will grow. This results in lower-order reconstruction filters with gentler roll-offs and much more linear phase response with a good image rejection level.
- Lower quantization noise: Although quantization noise is basically a function of the DAC' vertical resolution, the quantization noise power density will decrease as sampling rate increases as the same power is spread over a higher bandwidth. Oversampling is, in fact, equivalent to increasing the vertical resolution by a number of bits $\Delta n = 10 \times \log_{10}(\text{Oversampling Factor})/6.02$. As a reference, the AWG70001A running at 50GS/s will be equivalent in terms of raw vertical resolution to a 12-bit AWG running at 12GS/s.
- Lower pulse-to-pulse jitter: Positioning of very fast edges (rise/fall times equal or lower than one sampling period) with pulses it depends completely on the sampling period, so a faster sampling rate results in a more accurate edge location. Unless the pulse repetition rate is an exact submultiple of sampling rate, positioning errors will result in a pulse-to-pulse jitter with a peak-to-peak amplitude equivalent to the sample period. Accurate edge positioning, well below the sampling period, is only possible when rise/fall times of the edges are equal or larger than two (2) sampling periods (The signal frequency content must meet the Nyquist criterion). The previous requirement results in 170ps rise/fall times for a 12GS/s generator, 80ps for a 25GS/s unit and a mere 40ps for a 50GS/s AWG, such as the Tektronix AWG70000 series.

The only relevant drawback of oversampling is memory requirements as the number of samples required to store a given time window is proportional to the sampling rate. This is one of the reasons why very long record lengths are so important to very high-speed AWGs. As a reference, the AWG70000 with 16 GSamples waveform memory can generate at 50GS/s almost twice the time window competing instruments running at 12GS/s can, with only 2 GSamples of waveform memory.

For quadrature-modulated radar signals such as FM-Chirps, two baseband signals, the I and Q components, must feed the external modulator. These two components must be generated independent and synchronously through a 2-channel AWG or by using two one-channel AWG properly synchronized. Ease-of-use and timing alignment for two-channel AWGs make them preferable to solutions based on two one-channel instruments, provided sampling rate is sufficient. The Tektronix AWG70002A (2 channels @ 25GS/s), with minimum channel-to-channel jitter, offers an excellent combination of bandwidth (10GHz RF Freq response leading to 20GHz modulation bandwidth), convenience, and cost efficiency for the generation of IQ baseband signals. Quadrature modulation is, though, very sensitive to channel-to-channel mismatches in all domains. Differences between the I and the Q components may come from mismatches in the amplitude/phase frequency response for the two AWG channels, cabling and interconnections, as well as imbalances and errors within the quadrature modulator itself. Even frequency agile radar systems may be simulated through quadrature modulation as baseband signals may be positioned anywhere within the external modulator modulation bandwidth with instantaneous frequency switching and no PLL-induced transients. Again, the capability to generate such signals depends on the external modulator modulation bandwidth, which uses to be rather limited in terms of radar signal requirements.

As a good oversampling ratio and high analog bandwidths improve the overall signal quality in any AWG, it also improves uniformity between channels. Operating the AWG to generate a relatively low frequency signal results in better flatness and phase linearity so equality between channels is also improved. Additionally, remaining amplitude or delay differences can be removed by simply modifying the overall signal amplitudes and carefully adjusting the channel-to-channel delay. High oversampling ratios also result in lower amplitude images while these are located farther away from the signal of interest so they can be easily filtered out before reaching the modulator. Given the wideband nature of RADAR signals, the high oversampling ratio that can be reached with the Tektronix AWG70002A 2-channel instrument, its excellent RF Frequency response (>10GHz) and its spurious performance, the quadrature modulator use to be the weak link. Wideband quadrature modulators response is far from flat and internal I/Q imbalances may be much higher than those from excellent quality AWGs such the AWG70000 series.

Quadrature imbalance and error results in unwanted images showing up at the RF signal (Figure 8) and located at symmetric frequency locations respect to the carrier. Those unwanted images increase noise and reduce modulation quality. The amplitude of the image will depend on the phase and amplitude errors for a given modulation frequency and it will be a function of it. As an example, a LFM Chirp generated under conditions of quadrature error and imbalance, will consist of the expected linear sweep in the frequency domain plus an unwanted sweep in the opposite direction which amplitude and phase at a given frequency will depend on the I/Q amplitude and phase mismatch for that particular frequency. Again, AWGs can generate a differentially corrected signal. Correction must be based on an extra calibration step of the overall generation system where the quadrature error and imbalance as a function of the modulation frequency (positive and negative) is obtained and the resulting differential correction filter is found. Once obtained perfect balance and phase between the I and the Q components, an additional overall amplitude/phase calibration must be performed. Actual calibration procedures can take care of both calibration steps simultaneously and better results may be obtained by iterating calibration to an already pre-corrected signal. Shifted SSB (Single Side Band) multi-tone signals may be a good calibration signal as they allow for the estimation of both the wanted carriers and the unwanted image carriers over the whole modulation bandwidth. The calibration data will be valid for a given signal generation conditions and for a limited period of time. Typically, a complete joint generator-modulator calibration will be valid for a period of up to 24 hours, mainly due to drifting parameters in the wideband quadrature modulator. Calibration is a time-consuming process that requires additional equipment, typically a high-end real-time oscilloscope, a wideband vector signal analyzer, and the corresponding software.

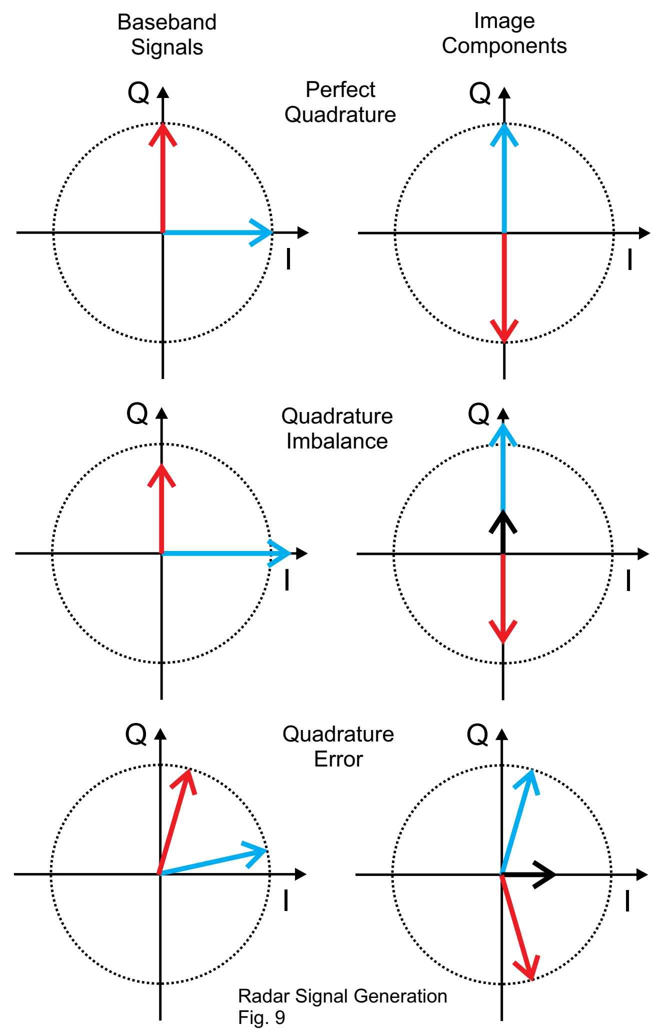


Figure 8. Matching between the I and the Q signals is critical for modulation quality when an external quadrature modulator is involved. Differences may come from the AWG, the interconnections, and the quadrature modulator itself. This is especially true for wideband modulations as mismatches will be a function of the modulating frequency. Careful calibration and differential correction of the signals may reduce the level of the unwanted images caused by quadrature error or imbalance. Direct RF generation does not suffer of this problem as quadrature modulation is implemented numerically.

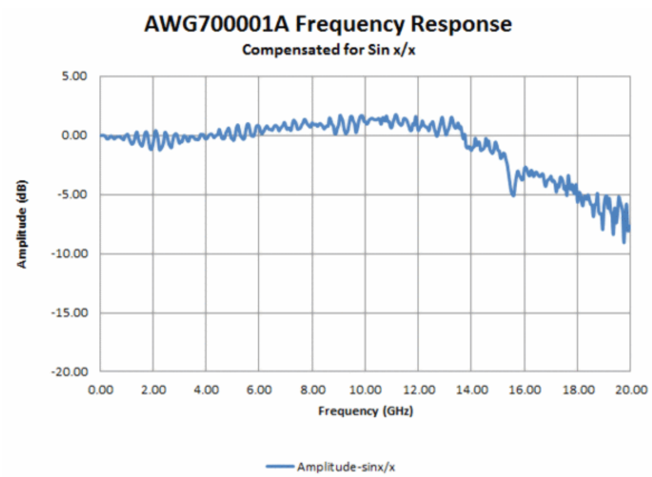


Figure 9. AWG70001 frequency response after removing the influence of the DAC's Sinc(f) response. The low attenuation of frequencies as high as 20 GHz permits the direct generation of modulated carriers at those frequencies.

2.4 Direct Carrier Generation

Ideal AWGs can produce any signal from DC up to half the sampling rate ($F_{max} = F_s/2$). With a high enough sampling rate it is then possible to generate directly a modulated RF signal (Figure 9). Previously, relatively low sampling rate and poor spurious-free dynamic range (SFDR) limited the capability of high-speed AWGs to generate carriers of only a few GHz. The Tektronix AWG70000 series, with its 50GS/s and improved SFDR performance, breaks the limitations allowing the direct generation of wideband signals with carriers up to 20GHz and virtually unlimited modulation bandwidth. Direct generation offers an important set of advantages over the traditional baseband/external modulator combination:

- Baseband generation and quadrature modulation are performed mathematically. As a result, there is no unwanted quadrature imbalance or errors. This approach results in higher quality and more repeatable test signals.
- Only one channel is required.
- No additional equipment is required. Given the cost of wideband modulators, this translates into important cost savings especially when multiple synchronous signals are required (i.e. for MIMO Radar or Phase Array emulation).
- Direct, virtually unlimited, agile frequency radar signal emulation.
- One single AWG can generate multiple dissimilar carriers or wideband noise so more realistic test scenarios can be obtained with a single instrument.
- Simplified calibration procedure as only the much more stable AWG amplitude/phase frequency must be established and no external modulators are involved.

Although advantages are overwhelming, actual implementations of this architecture can show some drawbacks as well. One important issue is record length requirements. For a given record length (RL), the maximum time window (TW = RL/Fs) that can be implemented is inversely proportional to sampling rate (Fs). As sampling rates for direct RF generation tend to be higher than those for baseband signal generation, the same record length translates to shorter realizable time-windows. This is why maximum record length is an especially important factor for high-speed AWGs. The AWG70000 series with its 16GSample waveform memory is capable of storing much longer time-windows than the closest competitor running at less than 1/6th the sampling rate. Record length is crucial for a realistic emulation of complex radar systems incorporating staggered pulse sequences, frequency hopping patterns or time varying echo characteristics caused by target movement or antenna vibration. The Tektronix AWG70001A 50GS/s generator can generate a non-repeating signal of up to 320ms at its maximum sampling rate so the effects of antenna vibrations of just 3Hz or aircraft displacements around 100m can be emulated.

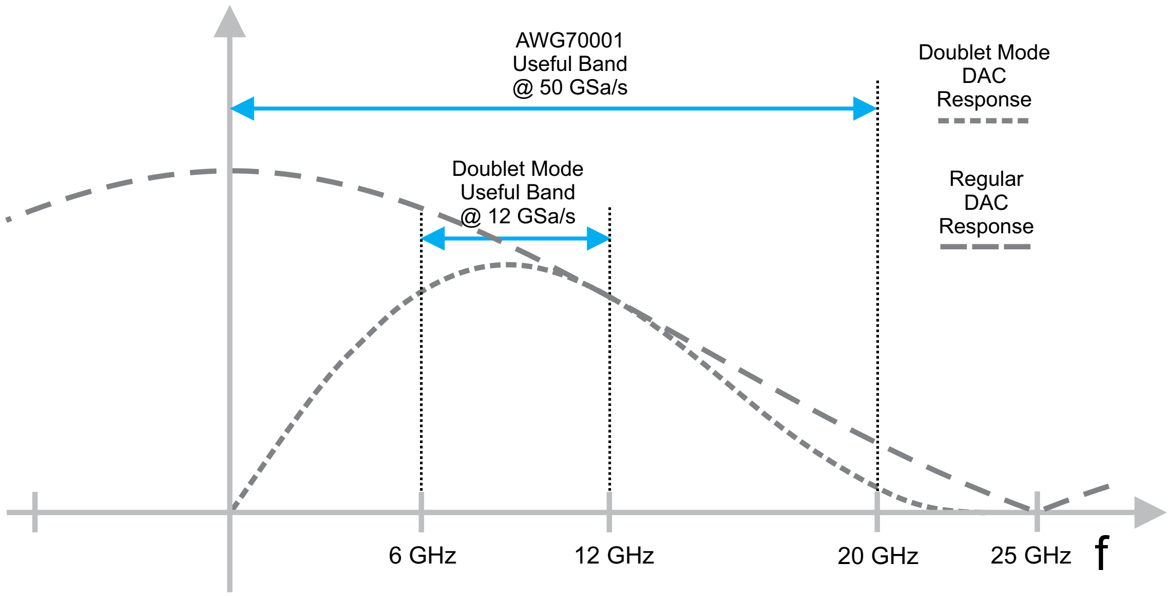


Figure 10. The generation of signals in the second Nyquist zone may be improved through the usage of the "Doublet" DAC mode. This mode is specifically designed to boost images in the second Nyquist zone and attenuate the direct signal located in the first Nyquist zone. Here the response of a 12 GS/s generator using a "doublet" mode DAC and that of the Tektronix AWG70001 running at 50 GS/s are compared. Although the frequency coverage of the 12 GS/s generator has been extended, the AWG70001 clearly outperforms it in terms of both carrier frequency range (0-20GHz vs. 6-12GHz) and modulation bandwidth (20 GHz vs. 6GHz).

An alternative method to extend the carrier frequency range for a particular AWG consists in the usage of the image in the second Nyquist zone (Figure 6c), the one comprised between Fs/2 and Fs. The usability of the image can be improved by filtering out the fundamental signal located in the first Nyquist zone. The quality of this signal is rather limited given the much lower amplitude and the steeper roll-off in the AWG frequency response. Some generators even incorporate DAC working modes specifically designed to improve the performance for signals generated in the second Nyquist zone. Doublet-mode DACs (also known as Mix-Mode™ DACs) generate a higher amplitude image and a reduced amplitude fundamental signal while removing the first null of the zeroth-order hold response of a regular DAC. However, maximum modulation bandwidth and the capability to generate multiple carriers are still limited to less than half the sampling rate and, even worse, this is only possible when the carrier frequency is located in the middle of the valid Nyquist zone (Figure 10). The Tektronix AWG70000 series is designed to generate signals in the first Nyquist zone so none of the above limitations apply.

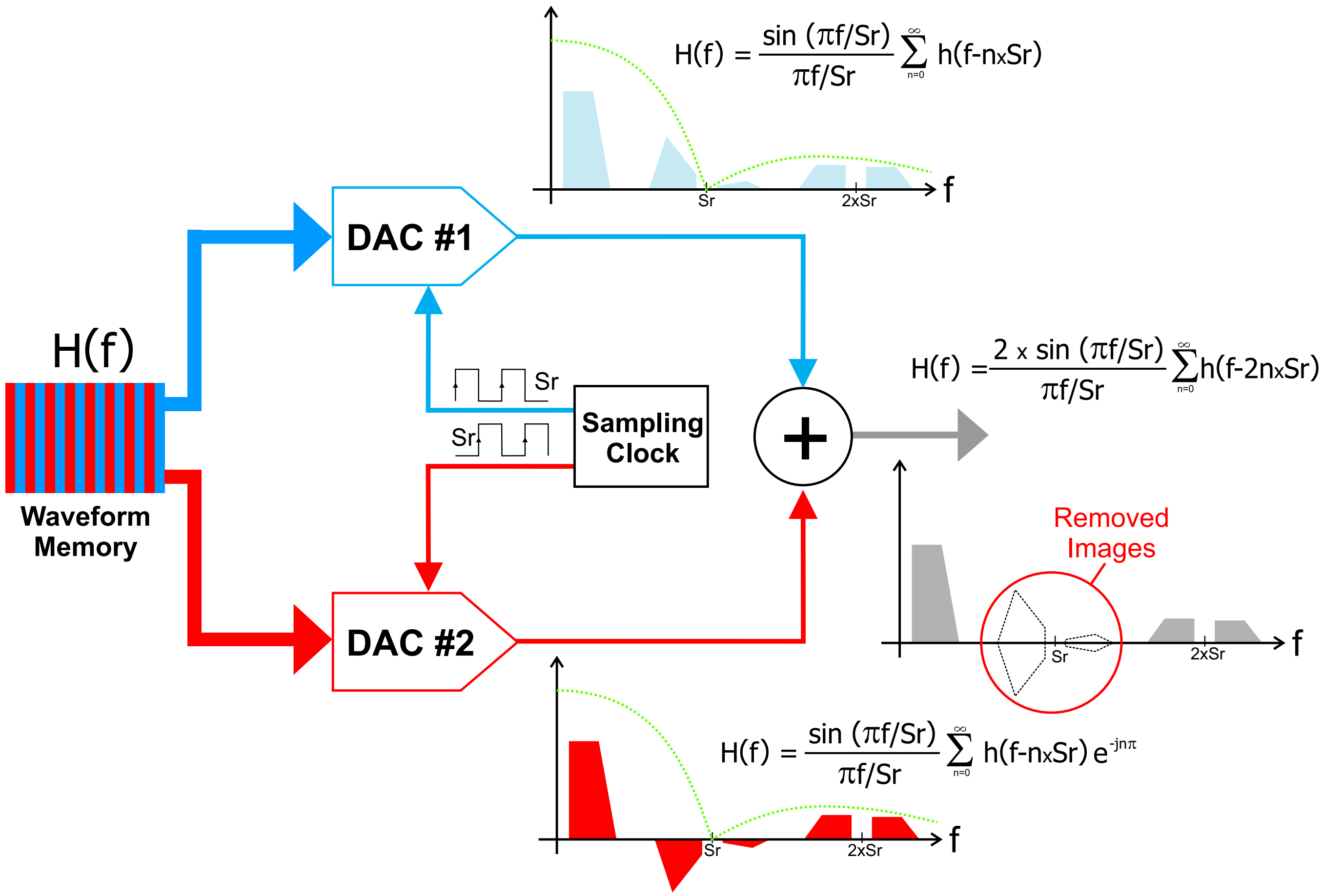


Figure 11. The exclusive interleaving-DAC technology applied in the Tektronix AWG70001 extends the AWG frequency range by using two matched DACs. One the DACs is fed with the even samples of the waveform while the odd samples are applied to the other. The second DAC must be delayed by half the sampling period so images from each DAC in the second Nyquist band cancel each other. This process is equivalent to extend the first Nyquist band to Fs instead of Fs/2 so the overall effect is that of a regular DAC running at 2xFs sample rate.

Tektronix, with its exclusive interleaved-DAC architecture (Figure 11) goes in the opposite direction as it is designed to obtain higher effective sampling rates by interleaving two DACs. It can be seen as two "true-arb" channels properly timed where odd and even samples are stored in each channel's memory. Ideally signals coming out from each channel should be switched on and off alternatively. Tektronix implementation of the interleaving DAC architecture consists in adding the output from both channels with a channel-to-channel delay of half the sampling period (1/2SR), as actually switching the outputs of both DACs at the required speed would be unpractical as it would generate a high switching noise reducing the SFDR and effective bits performance. This arrangement effectively doubles the Nyquist frequency to 2xSR although the first null of the DAC zeroth order hold response stays at the same frequency. Tektronix is using this approach in the AWG70001Awith some important improvements:

- Transparent HW/SW interconnection of both AWG channels.
- Improved frequency response and image rejection through factory alignment and user-adjustable interleaving parameters.

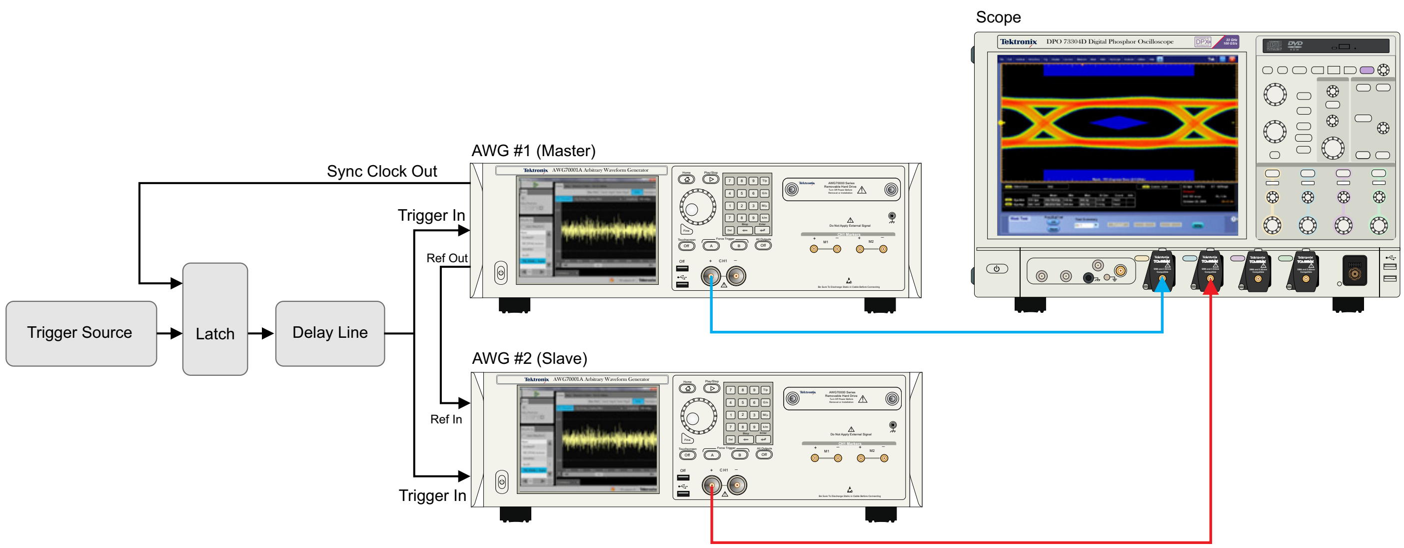


Figure 12. Uninterrupted signal generation is only possible through seamless repetition of the waveform stored in the AWG memory. Some applications require preserving the carrier phase between consecutive pulses (i.e. MTI radars). In this situation, both record lengths and sample rate must be selected so an integer number of carrier cycles fit in the resulting time window (b). If this condition is not met then the carrier phase will not be preserved between consecutive waveform iterations (a).

Although direct carrier generation does not suffer of any quadrature impairment due to I/Q mismatch, wideband signals may need some linear distortion to compensate for flatness and phase linearity issues, including those created by cabling and interconnections, over such high bandwidth. Applying corrections based only on the amplitude response improves modulation quality performance although phase response compensation is also required for optimal performance. Direct carrier generation also requires excellent sampling clock jitter performance as this translates directly to phase noise in the generated carriers.

Some applications, such as MIMO radar generation, require multiple channels. All the channels involved must be synchronized, so they must share the same sampling clock, and be time-aligned. Any timing difference or channel-to-channel jitter will result in a reduced quality signal. When more than one instrument must be synchronized, standardized synchronization methodologies and appropriate firmware as those available for the AWG70000 series generators can greatly simplify the alignment tasks and dramatically improve repeatability and reliability.

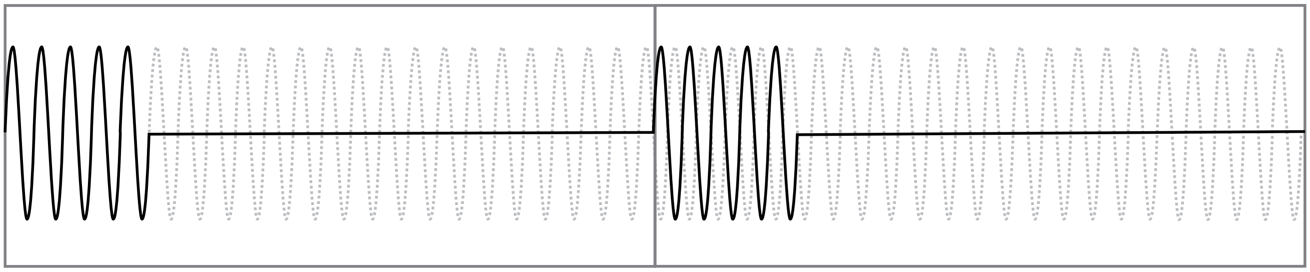
3 Creating Radar Waveforms for AWGs

3.1 Signal Consistency

Continuous signal generation with an AWG is only possible by seamlessly cycling the contents of the waveform memory through the DAC. In order to obtain useful signals, consistency of the signal around the wrap-around event must be preserved (Figure 12). Timing characteristics of radar signals are especially important:

- PRI: An integer number of pulse repetition intervals must be stored in the waveform memory. Otherwise abnormal pulse timing (longer or shorter than required) will occur every time the waveform is cycled.
- Carrier phase: For coherent radar emulation, the phase of the carrier must be preserved. This condition can be met if record length and sampling rate are selected in such a way that the resulting time window is an exact multiple of the carrier frequency period.
- Echo consistency: Multi-path, filtering effects, and echoes beyond the unambiguous range must propagate from the end of one cycle to the next. The previous effects may be seen as the convolution between the transmitted signal and the target system impulse response. Applying circular convolution to a consistent transmitted data will result in an echo emulation signal without any discontinuity or abnormal behavior that could confuse any radar receiver under test.

a) Time Window is not a multiple of the carrier period



b) Time Window is a multiple of the carrier period

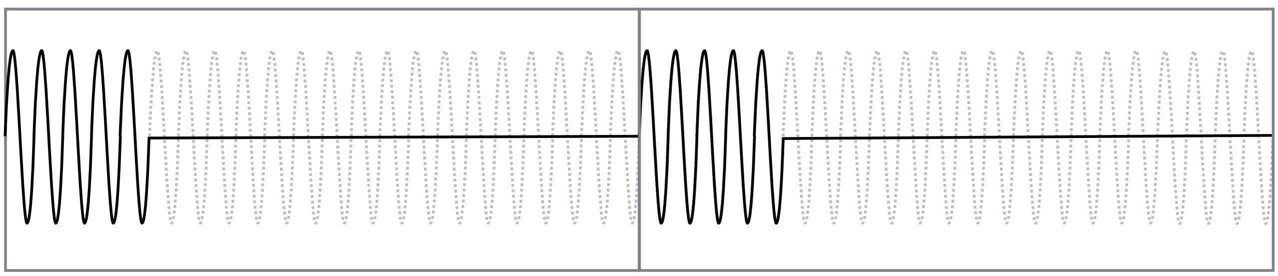


Figure 13. Good quality wideband signal generation require proper equalization to make sure flatness and group delay is kept within acceptable limits. Proper correction filters can only be obtained after calibration and they must incorporate the effects of external components such as cabling and amplifiers. The excellent flatness and phase linearity of the Tektronix DPO/DSA70000 series oscilloscopes makes them the ideal calibration device. Oscilloscopes, unlike traditional spectrum analyzers, can easily obtain system under test frequency response for both amplitude and phase and, equipped with the right software, they can also be used to analyze RF wideband signals.

3.2 Instrument Calibration and Signal Correction

The AWG70000 output stages are flatness corrected up to 10GHz. Correction includes compensation for the ideal sinc(ϖf/Fs) DAC response. For baseband generation this translates into excellent modulation quality with modulation bandwidths up to 20GHz. Beyond 10GHz, the AWG70000 series response shows a relatively gentle roll-off response (Figure 8). Moderate attenuation allows for the direct generation of usable radar signals up to 20GHz. In order to improve modulation quality at those frequencies, it is advisable to correct the frequency response through correction factors obtained from the proper calibration procedures. The Tektronix DPO/DSA70000 series real-time oscilloscopes are the ideal calibration tool as they show excellent flatness and phase linearity over their full bandwidth and almost perfect channel-to-channel alignment (Figure 13).

Once the correction filter response is obtained in the frequency domain, it must be applied to the original, uncorrected waveform through convolution. Convolution must be circular when signal looping is required.

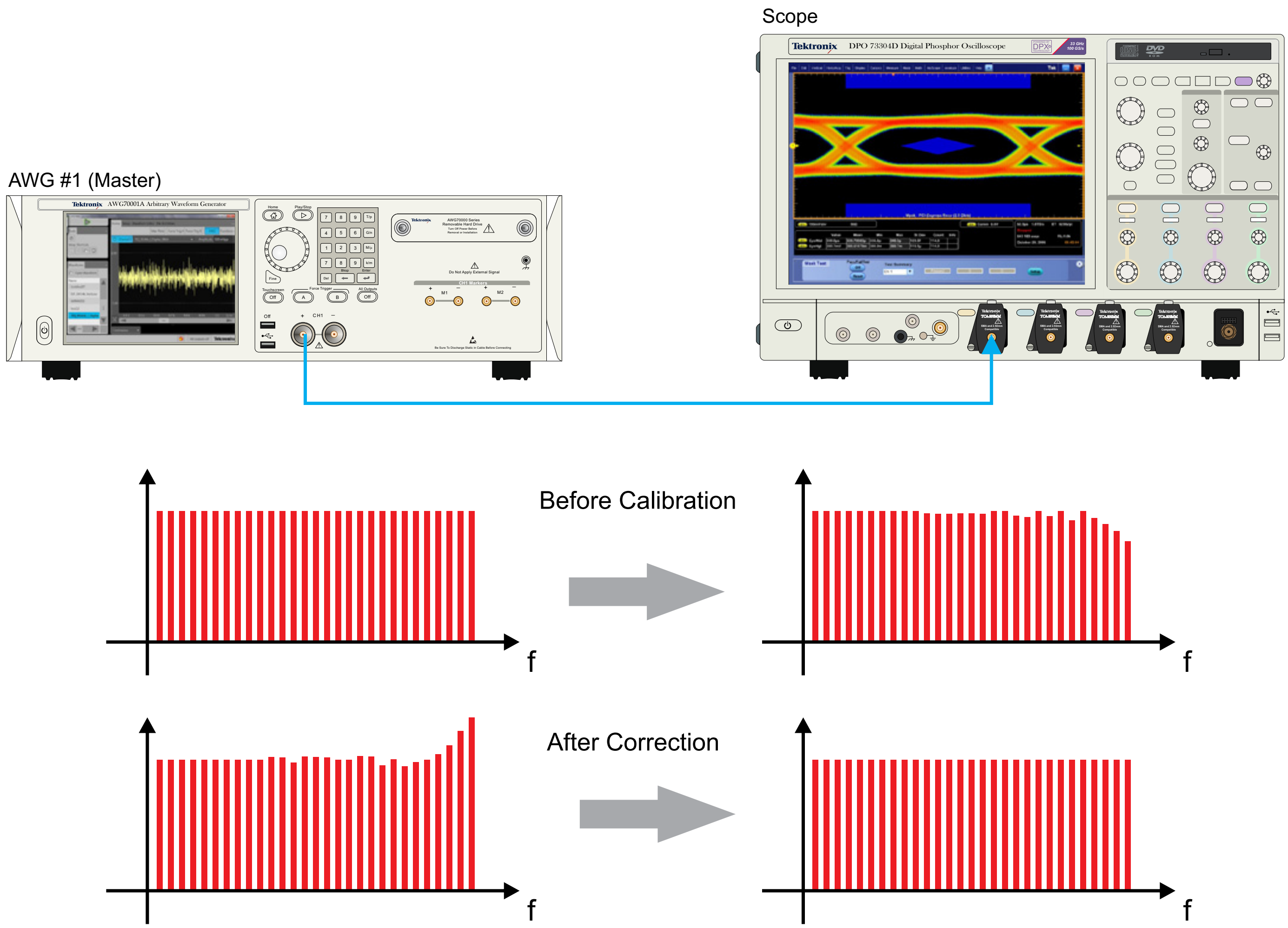


Figure 14.

3.3 RFXpress for Radar Applications

The Tektronix RFXpress (Figure 14) software tool provides a comprehensive set of functions to develop general purpose and application oriented modulated signals, both for baseband and direct RF signal generation. Option RDR has been specifically designed for radar signal generation. These are the most important radar-oriented functions supported by the tool:

- Create Single or Multiple Pulse Groups to form a Coherent or Non-coherent Pulse Train
- Define Each Pulse Group Independently or Add Different Pulse Groups to Simulate Simultaneous Multiple Target Returns
- Define Inter and Intra Pulse-hopping Patterns in both Frequency and Amplitude
- Define all Pulse Parameters including Start Time, Rise Time, Off Time, Fall Time, Pulse Width, Droop, Overshoot, and Ripple
- Define a Staggered PRI with Ramp, User-defined Profiles and Add up to 10 Different Multipaths
- Support for a Variety of Intra-modulation Types including FM Chirp, QPSK, BPSK, FM Step, Barker/Frank/Polyphase Codes including P1/P2/P3/P4, User-defined Step FM/AM and Step PM/AM, and Custom Modulation
- Define Antenna Beam Profile and Simulate Target Returns

There are options available for UWB-MBOA and user-defined OFDM signal generation as well as interference addition that can be also useful to radar users. Optionally, it also supports calibration and generation of corrected waveform including the application of user supplied S-parameter models for RF blocks or components.

4 Conclusions

The AWG70000 series generators allow for the direct generation of complex radar signal right at the final carrier frequency up to 20GHz. This amazing capacity is made possible by the breakthrough in DAC conversion performance introduced by Tektronix with the AWG70000 series and its exclusive interleave-DAC architecture. Even the most complex frequency-agile or MIMO radar systems are easy to emulate through direct RF generation thanks to the superb 16 GSamples memory waveform and the excellent time alignment between channels within the same generator or across multiple synchronized devices.

References

Charles E. Cook & Marvin Bernfeld, “Radar Signals – An Introduction to Theory and Application”, 1993, Artech House.

T. C. Hill & Shigetsune Torin, “Amplitude Correction for Impulse Response Measurement of Radar Pulses”, Tektronix White Paper 37W-25527-0.

T. C. Hill & Shigetsune Torin, “Impulse Response as a Measurement of the Quality of Chirp Radar Pulses”, Tektronix White Paper 37W-25531-0.

“Fundamentals of Radar Measurements”, Tektronix Primer 37W-22065-2.

“Advanced Radar Analysis”, Tektronix Primer 37W-23378-1.

“Calibrate, Characterize and Emulate Systems Using RFXpress® in AWG Series”, Tektronix White Paper 76W-24426-0.

“Generating Advanced Radar Signals Using Arbitrary Waveform Generators”, Tektronix Application Note 76W-20730-3.

“AWG70000 Series Multiple Unit Synchronization”, Tektronix Application Note 76W-29177-0.

“XYZ of Signal Generators”, Tektronix Primer 76W-16672-5.

Joan Mercade, “DAC Interleaving in Ultra-High-Speed Arbs”, Evaluation Engineering, December 2009.

Contact Tektronix:

ASEAN / Australia (65) 6356 3900
Austria* 00800 2255 4835
Balkans, Israel, South Africa and other ISE Countries +41 52 675 3777
Belgium* 00800 2255 4835
Brazil +55 (11) 3759 7627
Canada 1 (800) 833-9200
Central East Europe and the Baltics +41 52 675 3777
Central Europe & Greece +41 52 675 3777
Denmark +45 80 88 1401
Finland +41 52 675 3777
France* 00800 2255 4835
Germany* 00800 2255 4835
Hong Kong 400-820-5835
Ireland* 00800 2255 4835
India +91-80-30792600
Italy* 00800 2255 4835
Japan 0120-441-046
Luxembourg +41 52 675 3777
Macau 400-820-5835
Mongolia 400-820-5835
Mexico, Central/South America & Caribbean 52 (55) 56 04 50 90
Middle East, Asia and North Africa +41 52 675 3777
The Netherlands* 00800 2255 4835
Norway 800 16098
People's Republic of China 400-820-5835
Poland +41 52 675 3777
Portugal 80 08 12370
Puerto Rico 1 (800) 833-9200
Republic of Korea +822-6917-5000
Russia +7 (495) 7484900
Singapore +65 6356-3900
South Africa +27 11 206 8360
Spain* 00800 2255 4835
Sweden* 00800 2255 4835
Switzerland* 00800 2255 4835
Taiwan 886-2-2656-6688
United Kingdom* 00800 2255 4835
USA 1 (800) 833-9200

* **If the European phone number above is not accessible, please call +41 52 675 3777**

Contact List Updated March 2013

For Further Information
Tektronix maintains a comprehensive, constantly expanding collection of application notes, technical briefs and other resources to help engineers working on the cutting edge of technology. Please visit **www.tektronix.com**

06/13 EA/WWW 37W-29247-0