Radar Signal Generation with a High–Performance AWG

Tektronix®

Figure 1.

The Tektronix AWG70000 Series Arbitrary Waveform Generators (AWG; Figure 1) deliver sampling rates up to 50GS/s with 10-bit vertical resolution, 20 GHz usable bandwidth, up to 32-GSample waveform memory and excellent SFDR (Spurious Free Dynamic Range) characteristics. The AWG70000 Series also features Streaming Waveform ID which gives users immediate access to 16,383 sequence steps through an Ethernet network connection for radar receiver with interference signal testing. This provides the ability to quickly change waveforms, replicating real world simulations with unprecedented accuracy. This level of performance allows for the direct generation of the fully-modulated RF/µW signals required by modern radar. Most of these requirements are impossible to meet with lower-performance AWGs or traditional vector signal generators (VSG). The purpose of this paper is to show how the characteristics and performance of the AWG70000 Series influence the ability to support different radar technologies, and how the instrument can compensate for internal-/external device imperfections and emulate real-world targets and conditions.

1 Introduction

Generating radar signals is one of the most challenging tasks for a signal generator. The signals' combination of carrier frequency, modulation bandwidth, and, in most cases, their pulsed nature creates a series of requirements difficult to match with existing instrumentation. The increasing complexity of radar systems, the growing use of complex modulation techniques such as OFDM or UWB, and the signal quality requirements for a successful test impose severe constraints on the stimulus equipment used in radar testing. The need

to emulate multi-antenna radar systems based on phased-array antennas or more recently, MIMO architectures, makes it necessary to generate multiple signals with tightly controlled timing and phase alignments. Traditionally, radar signal generation has been implemented with a baseband signal generator and an RF/µW modulator, often integrated as one piece of equipment. The Tektronix AWG70000 Series arbitrary waveform generators can be used effectively to test these architectures, with performance allowing for the direct generation of radar signals with carriers up to 20GHz (beyond the K_u band). This solution offers much higher signal quality, cost-effectiveness, and repeatability than traditional solutions. This paper will 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 Signal Characteristics

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

- Pulsed RF: the signal consists of periodic bursts of an RF carrier, modulated or not (simple pulse radar systems). The rate at which pulses are generated is known as the PRF (Pulse Repetition Frequency), while the period is called the PRI (Pulse Repetition Interval).

- CW (Continuous Wave) Radars: the RF signal is continuous and range is established through time markers carried on the transmitted signal. FM modulation is a popular way to measure distance, as the instantaneous frequency coming from the target is dependent upon distance.
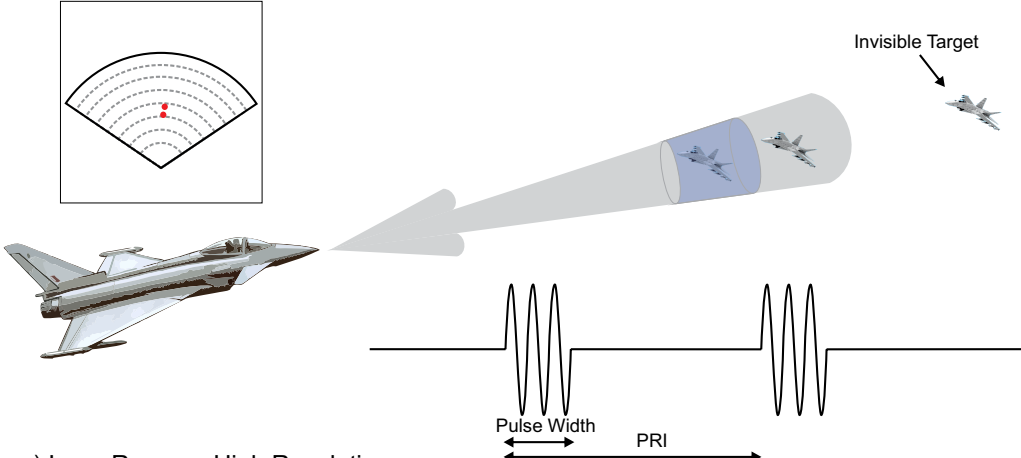
Radar Signal Generation
Fig. 2

$$P_r = \frac{P_t\, G_t\, A_r\, \sigma}{(4\pi)^2\, R^4}$$

a) Long Range
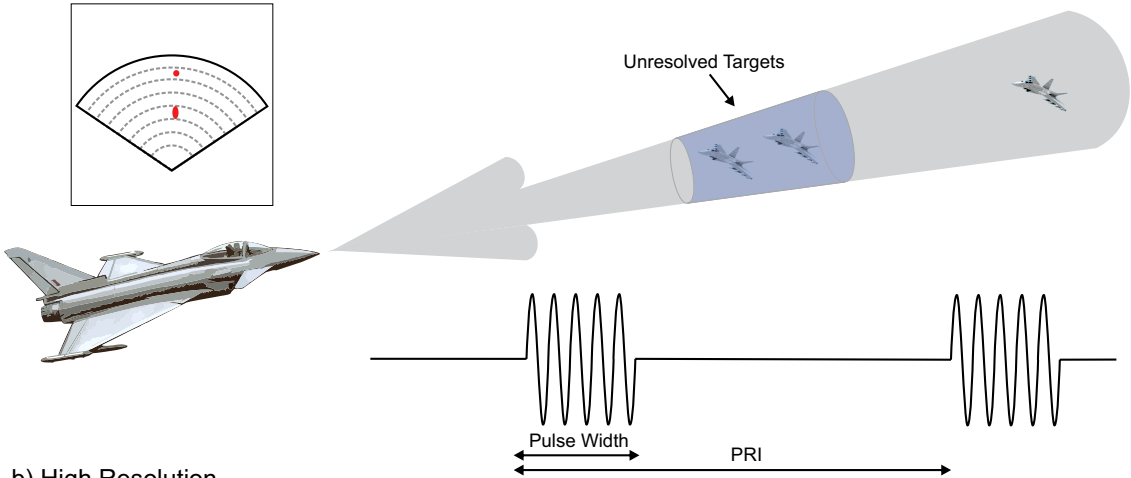
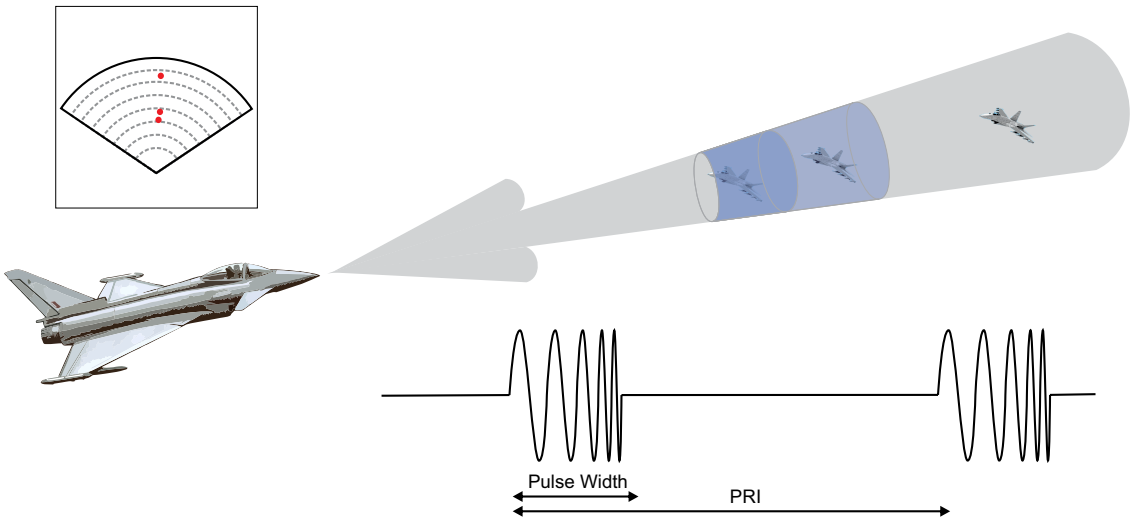b) High Resolution

c) Long Range + High Resolution

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.
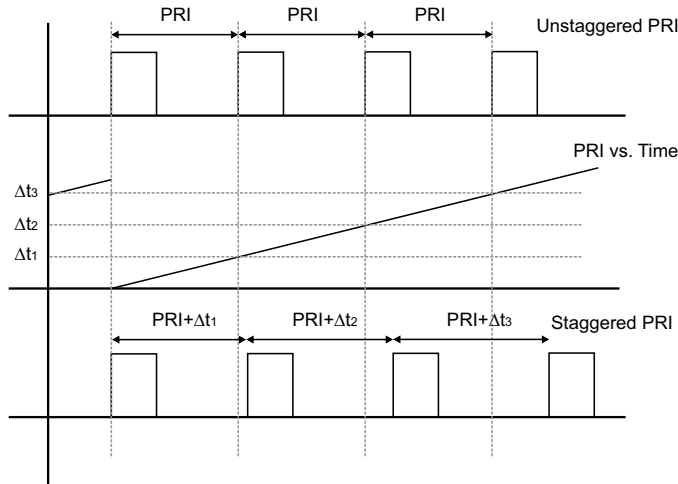
Figure 3. Staggered PRF changes the timing between pulses over time. By doing that, blind speeds can be removed and targets beyond the radar's nominal range can be detected while obtaining a signal more resilient to countermeasures or jamming. Staggering profiles may be rather complex and its correct emulation through an AWG requires long waveform memories to contain the full 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 may vary over time (Figure 3) for a variety of reasons:

- Echo ambiguity: unambiguous ranging of targets is limited by the PRI. Targets located beyond that distance can be mistakenly positioned based on the timing of the nearest transmitted pulse. One way to identify this behavior is to change the timing of consecutive pulses such that their position relative to nearby pulses will change.

- The "Doppler Dilemma:" radar systems rely on the Doppler Effect to measure target velocity and/or reduce the effects of clutter. But 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 speeds greater than the expected target velocities and a slower PRF optimized for range.
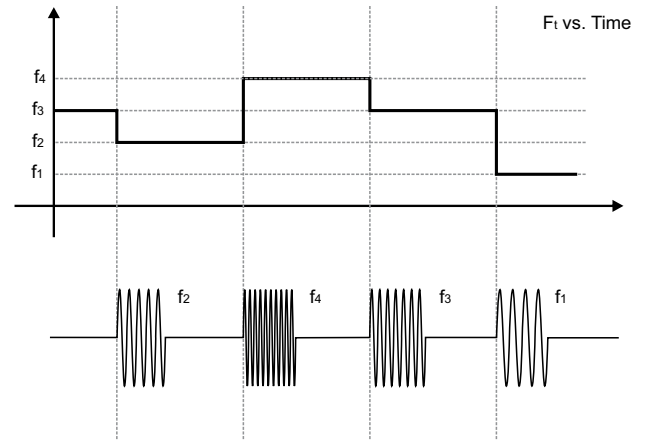
- Protection against jamming: Variable PRI, often combined with complex stagger sequences, allows easier differentiation of echoes from a particular radar system relative to others created by radars operating in the same frequency range, or by intentional jamming. Some stagger sequences are specifically designed to confuse DSP-based jammers.

- 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). The carrier frequency may even change for each transmitted pulse.
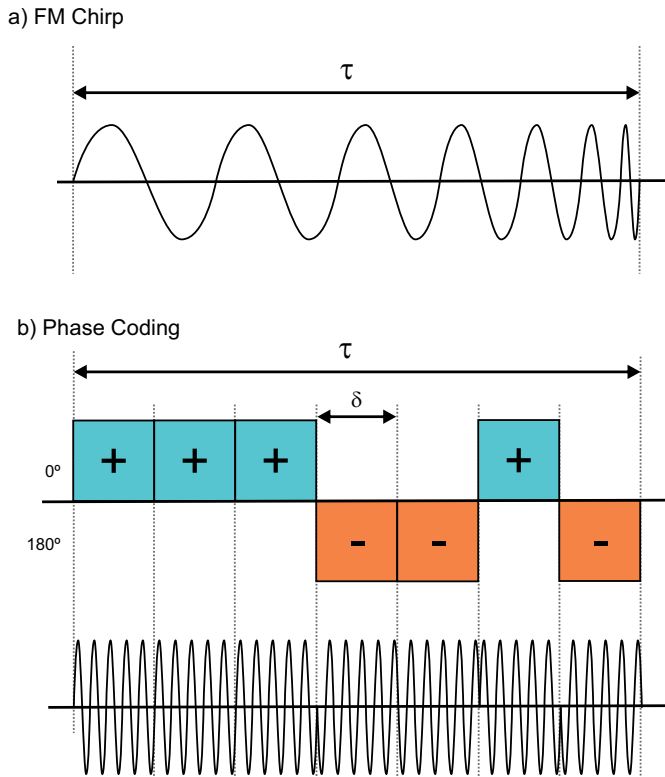
a) FM Chirp

b) Phase Coding

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 that average power is increased for a given peak power) while echo processing at the receiver can deliver much better spatial resolution by "compressing" the pulse through correlation or dispersion processing. There are two main pulse compression methodologies:

- FM Chirps (Figure 5a): these consist of fast frequency sweeps. The sweeps may be linear (LFM) or non-linear (NLFM). Non-linear FM has some advantages regarding bandwidth, yielding better sensitivity and lower noise levels at the receiver.

- Phase modulation (Figure 5b): each pulse is composed of a series of shorter pulses in which the carrier phase is controlled by a 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. In binary-phase-coding the carrier phase changes between 0 and 180 degrees as shown in the Barker code sequence in Figure 5b. Polyphase pulse compression applies the same basic idea but the carrier phase takes more than two values.

Some advanced techniques such as OFDM or MIMO, already in use in broadcast and mobile communications, are being developed for radar applications..

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

Returning echoes, irrespective of the phase characteristics of the transmitted pulse, consist of superposed 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 caused by multi-path, and all kinds of Doppler Effect-related clutter and frequency shifts due to either the transmitter and/or the target's relative speeds. The instantaneous amplitude and phase for a given echo will be also controlled by the target's shape and size. In other words, no matter how complex the transmitted signal may be, the reflected signal will be much more complex.

a) Baseband Generation
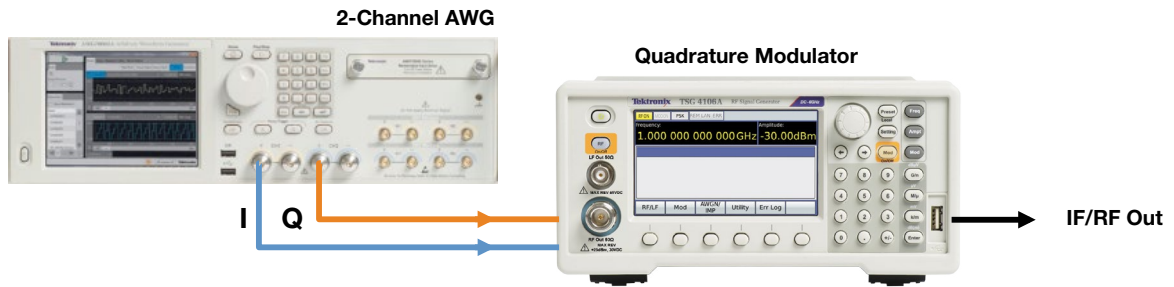
b) Direct RF Generation in the First Nyquist Band
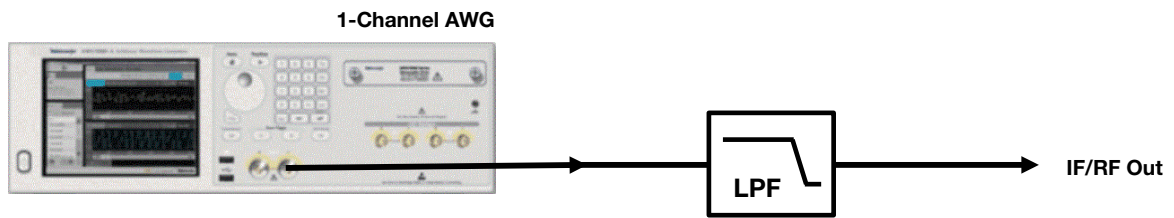
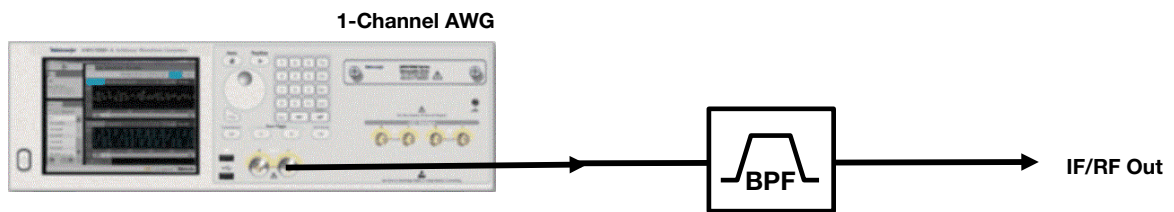**c) Direct RF Generation in the Second Nyquist Band**

Figure 6. AWGs can use diverse methods to generate modulated carriers.. 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) creates 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 three basic methods (Figure 6):

■ Baseband generation: the AWG generates the time-domain signal to be applied to an RF modulator. For simple signals where pulses are generated by controlling the envelope of a carrier, a one-channel AWG output 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 easiest and most flexible solution is a quadrature modulator. This requires two baseband signals: the In-Phase (or I), and the Quadrature (or Q) components. These two baseband signals can be generated by an AWG with two channels or by two synchronized single-channel AWGs.

■ IF (Intermediate Frequency) generation: the AWG generates a modulated signal at a relatively low carrier frequency. Often the signal can be applied directly to a signal-processing block in the receiver or transmitter. In situations involving 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 is able to generate the modulated carrier at the final RF/µW frequency. No additional signal-processing blocks aside from the normal filters or amplifiers are required.

Each of these methods has both advantages and drawbacks. Baseband and IF generation can be implemented with moderate-performance AWGs. For most signals, a sample rate of a few GS/s is sufficient. But in both cases, the modulation bandwidth of the final RF/μW signal will be limited by the characteristics of the modulator or up-converter. For example, commercially available instrument-grade quadrature modulators can generate signals of up to 2GHz bandwidth but this may be not sufficient for some RADAR applications. Worse yet, wideband quadrature modulation is extremely sensitive to I/Q imbalance or quadrature errors. Accurate alignment after careful calibration is required to produce signals of adequate quality. On the other hand, Direct signal generation requires an extremely fast AWG whose sample rate is at least 2.5 times higher than the maximum frequency component of the signal. Traditionally, obtaining good-quality signals with respect to spurious-free dynamic range (SFDR) has been difficult with ultra-high speed AWGs, given their limited DAC resolution (6 bits). However, the latest generation of Tektronix high-speed AWGs, the AWG70000 Series, offers 10-bit 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 glance, the generation of baseband signals appears to be a relatively simple 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. the Barker Codes used in pulse compression) require a suppressed carrier, which is not supported by most AM modulators because the instantaneous phase can take two values--0° and 180° or BPSK. In addition, baseband generation of FM chirps, QPSK/QAM, and, in most cases, UWB OFDM signals, requires a quadrature modulator, as both the instantaneous amplitude and phase of the carrier must be controlled. Emulation of realistic radar echoes that incorporate the effects of the target characteristics, multi-path, Doppler shifts, noise, and jamming always requires quadrature modulation because there are both I and Q components. Consequently 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. The frequency response of both baseband generators and RF modulators is 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 0th (zeroth)-order hold response:

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

This 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. Lastly, 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. Deliberate distortion mathematically applied to waveforms stored in the generator's memory can compensate for external distortions. After careful calibration of the overall frequency response it is possible to design a compensation filter that improves flatness and group delay response. Typically, the compensation filter takes the form of a pre-emphasis filter as it will correct the generation system's overall low-pass frequency response. As high frequency components are boosted, the low-frequency components of the signal must be attenuated in order to maintain a peak-to-peak value that fits within the available DAC dynamic range.
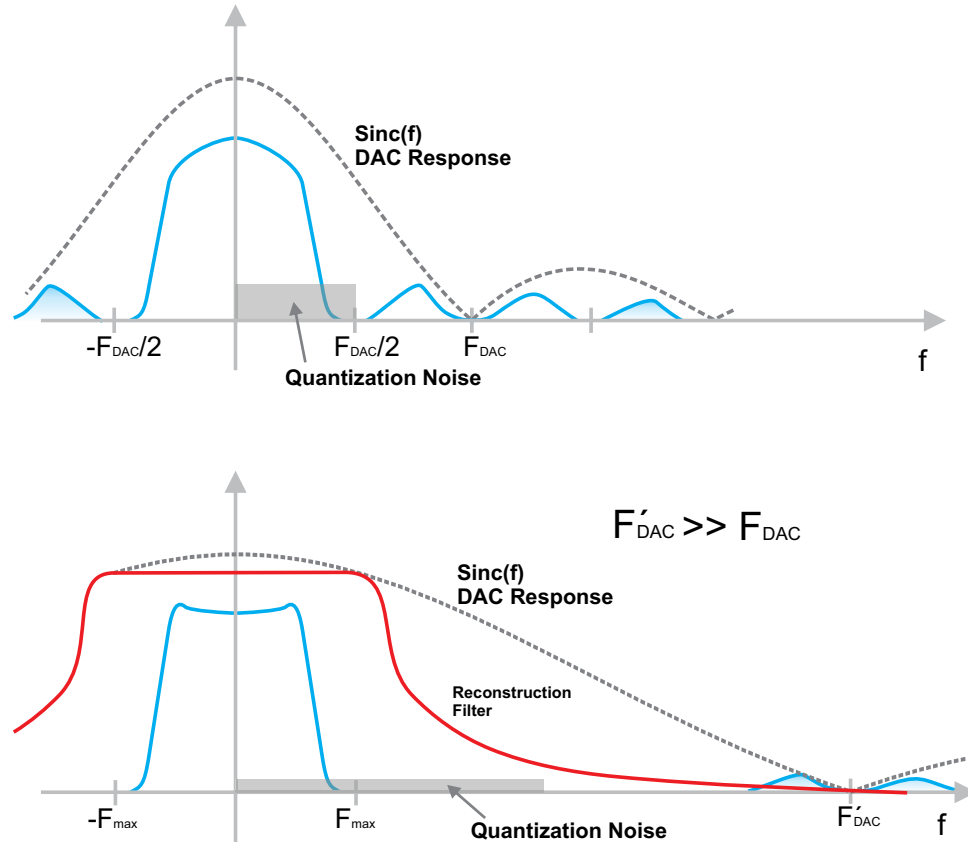
Figure 7. Generating a limited bandwidth signal at a much higher sampling rate than that required by the sampling theorem (Fs=2xBW) is known as oversampling. This technique improves the quality and usability of the signal as it improves SNR (and effective bits) and flatness while relaxing the requirements for reconstruction filters.

The maximum sampling rate greatly influences signal quality. Generally speaking, it is good practice to set the AWG sampling rate well over the minimum Nyquist requirement for a given signal. This is known as oversampling (Figure 7). A 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 onflatness will be 1.65dB, while the same signal generated at 25GS/s will result in flatness of 0.37dB.

■ 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 enables the use of lower-order reconstruction filters with gentler roll-offs and more linear phase response with good image rejection.

■ Lower quantization noise: Although quantization noise is basically a function of the DAC's vertical resolution, the quantization noise power density will decrease as sampling

rate increases, since the same power is spread over a higher bandwidth. Oversampling is, in fact, equivalent to increasing the vertical resolution by a number of bits $\Delta n = 10 \times \log_{10}$(Oversampling Factor)/6.02. As a point of reference, the AWG70001B 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 yields 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). This equates to 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 the memory requirement. 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. Here, the AWG70000 with its 32 GSample waveform memory can generate at 50 GS/s almost four times the time window that competing instruments running at 12 GS/s can create with their 2 GSample 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 independently and synchronously through a 2-channel AWG or by using two synchronized one-channel AWGs . 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 AWG70002B (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 effectiveness for generating IQ baseband signals. Quadrature modulation is 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 used to be rather limited relative to radar signal requirements.

Just as a good oversampling ratio and high analog bandwidth both improve the overall signal quality in any AWG, they also improve uniformity between channels. Operating the AWG to generate a relatively low-frequency signal results in better flatness and phase linearity, so the consistency 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 ensure lower-amplitude images, 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 two-channel AWG70002B instrument, plus its excellent RF frequency response (>10GHz) and spurious performance, the external quadrature modulator may be the weak link. Wideband quadrature modulator response is far from flat and internal I/Q imbalances may be much higher than those from a quality AWGs such as those in the AWG70000 series.

Quadrature imbalance and errors create unwanted images showing up in the RF signal (Figure 8) and located at symmetric frequency locations with 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 will be a function of it. For 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 in 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. Corrections must be based on an extra calibration step of the overall generation system wherein the quadrature error and imbalance as a function of the modulation frequency (positive and negative) is determined and the resulting differential correction filter is selected. After achieving 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 specific 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 corresponding software.
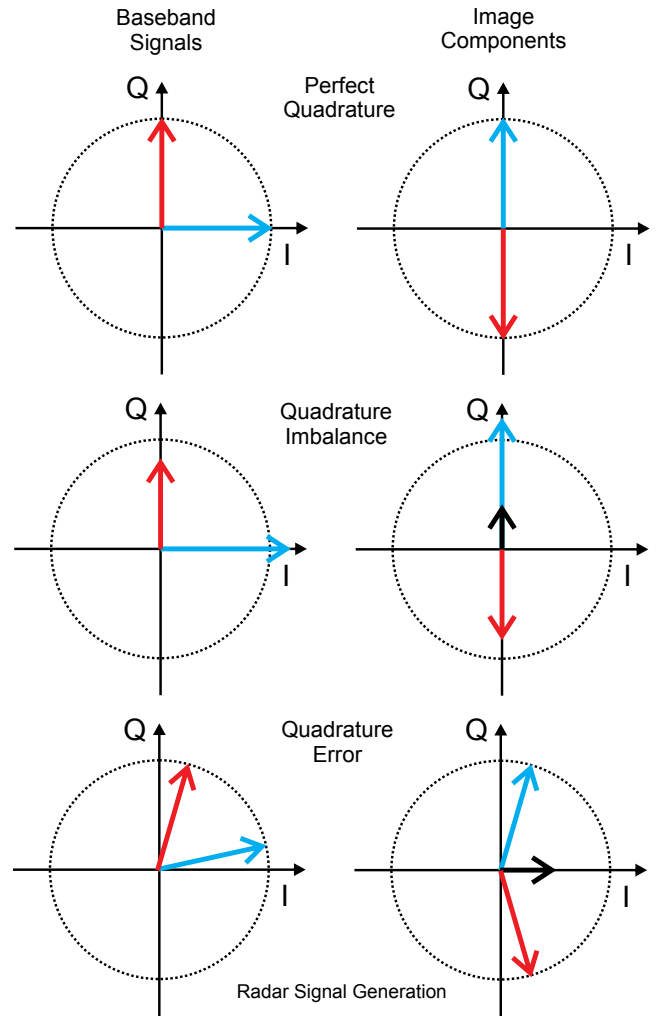

Figure 8. Matching between the I and the Q signals is critical for modulation quality when an external quadrature modulator is involved. Differences may come from the AWG, the interconnections, and the quadrature modulator itself. This is especially true for wideband modulations as mismatches will be 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.
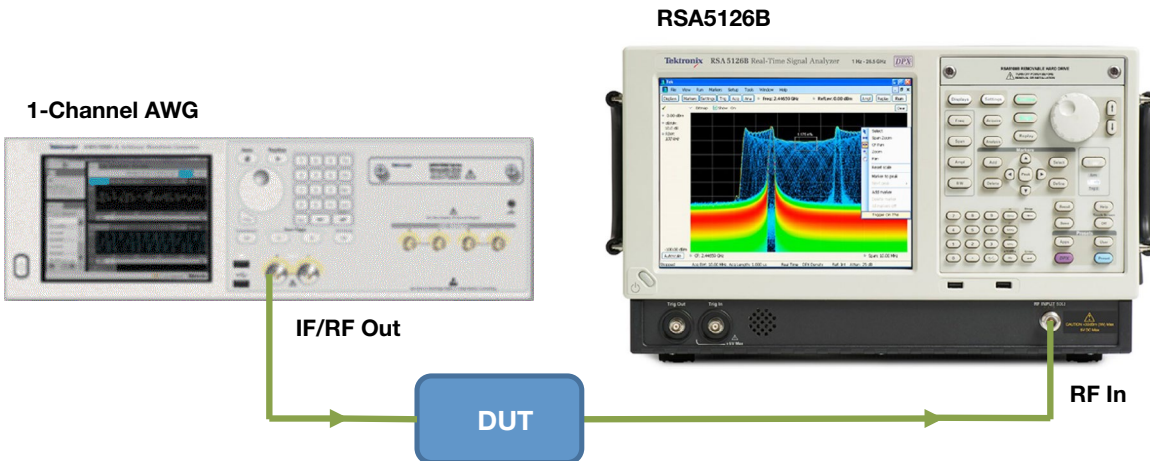
RSA5126B

1-Channel AWG

IF/RF Out

RF In

DUT

Figure 9. Using a generator to simulate the RF environment while analyzing the response of the Device Under Test (DUT) with a Real-Time Signal Analyzer.
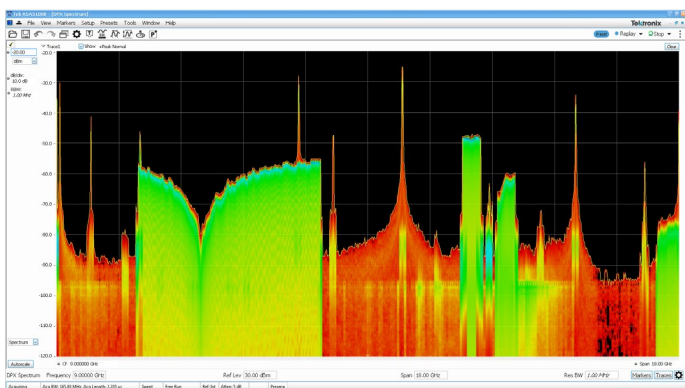

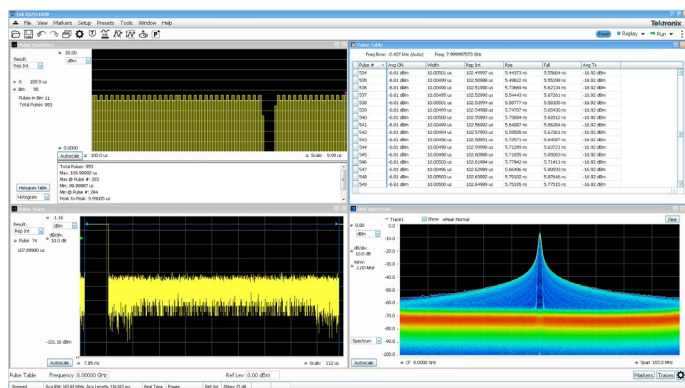**Figure 10.** Wide-band environment generated by a one-channel AWG70001B.

Figure 11. This test result evaluates the pulse repetition interval (PRI) is being measured on a set of 953 pulses constructed as a staggered PRI CW pulse waveform on the AWG70001B.

2.4 De-embedding Radar Subsystems using High-Performance Test Equipment

When a Radar subsystem is being designed the rest of the system is not always available. By using off-the-shelf, general-purpose test equipment to simulate other subsystems the device under test can be tested to exact specifications under controlled signal conditions.

Radars operate in a very cluttered open-air environment. This environment can be simulated using a wide-band AWG to help test a radar receiver's ability to deal with the real-life environment. Figure 10 shows a wide-band environment generated by a one-channel AWG70001B. Various signals such as wide- and narrow-band chirp (LFM), narrowband, CW and frequency-hopped d radar signals are seen here on

the RSA5126B. Several communication signals and other interferers can also be seen in the same frequency bands as the radar signals.

Radar transmitter testing includes extensive evaluation of a wide variety of test signals. In many cases the evaluation includes 100's or 1000's of pulses, which are then evaluated using statistical techniques. The test result shown in Figure 11 evaluates the pulse repetition interval (PRI) is being measured on a set of 953 pulses constructed as a staggered PRI CW pulse waveform on the AWG70001B. The histogram provides a statistical view of the distribution of the PRI measurements, while the pulse table and pulse waveform can be used to view measurements for each individual pulse.
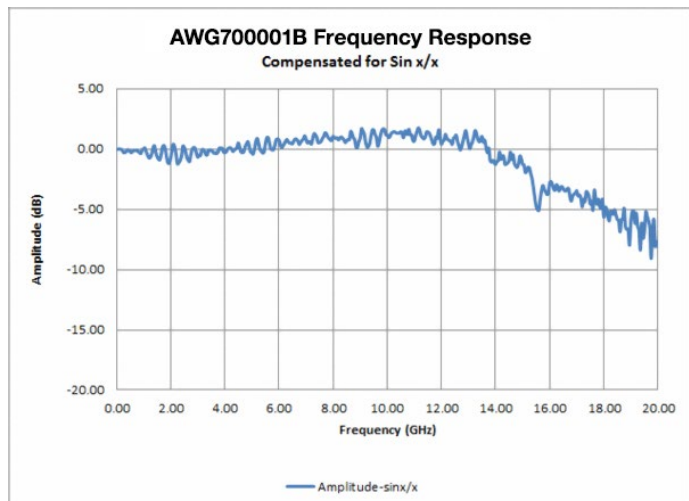
Figure 12. AWG70001B frequency response after removing the influence of the DAC's Sinc(f) response. The low attenuation of frequencies as high as 20 GHz permits the direct generation of modulated carriers at those frequencies.

2.5 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 possible to directly generate a modulated RF signal (Figure 12). Previously, relatively low sampling rate and poor spurious-free dynamic range (SFDR) limited high-speed AWGs to generating carriers of only a few GHz. The Tektronix AWG70000 series, with its 50 GS/s and improved SFDR performance, breaks the limitations, allowing the direct generation of wideband signals with carriers up to 20 GHz and virtually unlimited modulation bandwidth. Direct generation offers important advantages over the traditional baseband/external modulator combination:

- Baseband generation and quadrature modulation are performed mathematically. As a result, there are no unwanted quadrature imbalances or errors. This approach results in higher-quality, 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.

- A 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; only the inherently 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 achievable time-windows. This is why maximum record length is an especially important dimension for high-speed AWGs. The AWG70000 series with its up to 32 GSample 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 AWG70001B 50 GS/s generator can generate a non-repeating signal of up to 640 ms at its maximum sampling rate, so the effects of antenna vibrations of just 3 Hz or aircraft displacements of approximately 200 m can be emulated.
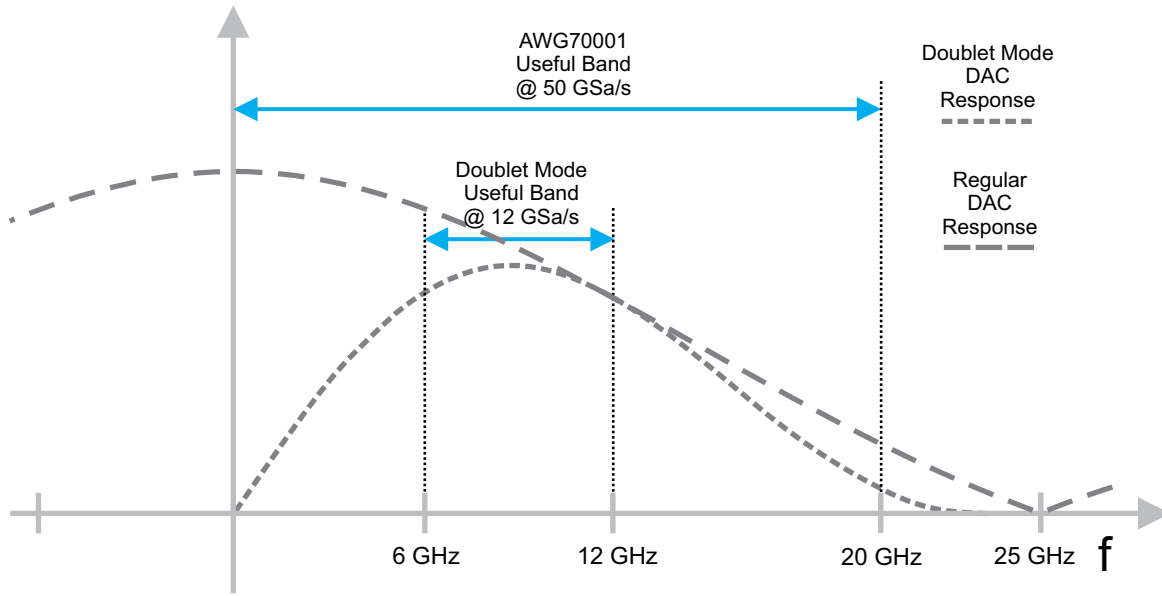
Figure 13. The generation of signals in the second Nyquist zone may be improved with the "Doublet" DAC mode. This mode is specifically designed to boost im¬ages in the second Nyquist zone and attenuate the direct signal located in the first Nyquist zone. Here the response of a 12 GS/s generator using 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 involves using the image in the second Nyquist zone (Figure 6c), the one existing 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 0th-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. Moreover this is possible only when the carrier frequency is located in the middle of the valid Nyquist zone (Figure 13). The Tektronix AWG70000 series is designed to generate signals in the first Nyquist zone so none of these limitations apply.
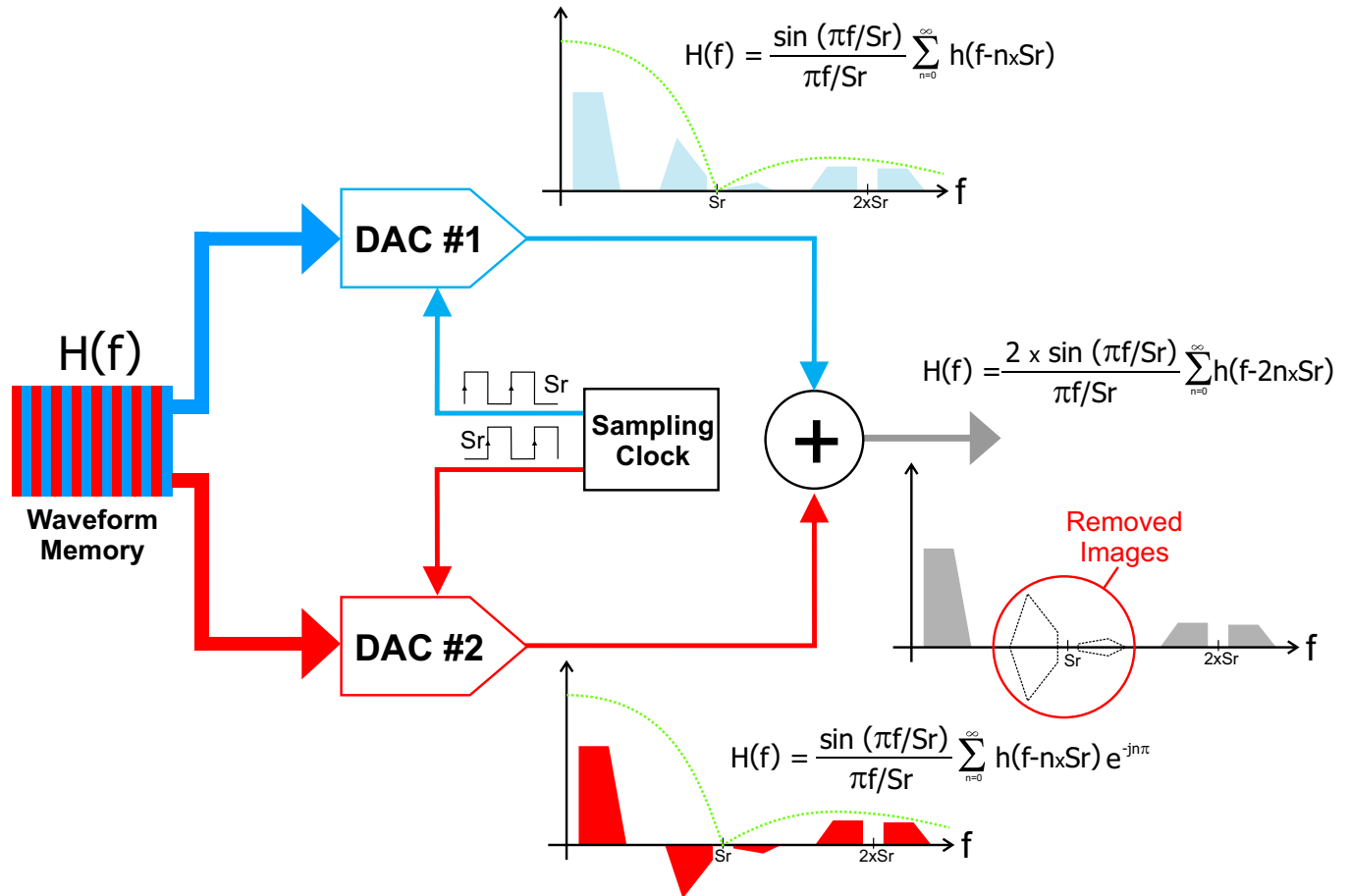
Figure 14. The exclusive interleaving-DAC technology applied in the Tektronix AWG70001 extends the AWG frequency range by using two matched DACs. One the DACs is fed with the even samples of the waveform while the odd samples are applied to the other. The second DAC must be delayed by half the sampling period so images from each DAC in the second Nyquist band cancel each other. This process is equivalent to extending 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 14) 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 the respective channel memories. Ideally signals coming from each channel should be switched on and off alternatively. Tektronix implementation of the interleaving DAC architecture consists of adding the output from both channels with a channel-to-channel delay of half the sampling period (1/2SR). Actually switching the outputs of both DACs at the required speed would be impractical and would generate switching

noise, reducing the SFDR and effective bits. This arrangement effectively doubles the Nyquist frequency to 2 x SR, though the first null of the DAC 0th-order hold response stays at the same frequency. Tektronix is using this approach in the AWG70001B with some important improvements:

- Transparent HW/SW interconnection of both DAC channels.

- Improved frequency response and image rejection through factory alignment and user-adjustable interleaving parameters.

a) Time Window <u>is not</u> a multiple of the carrier period
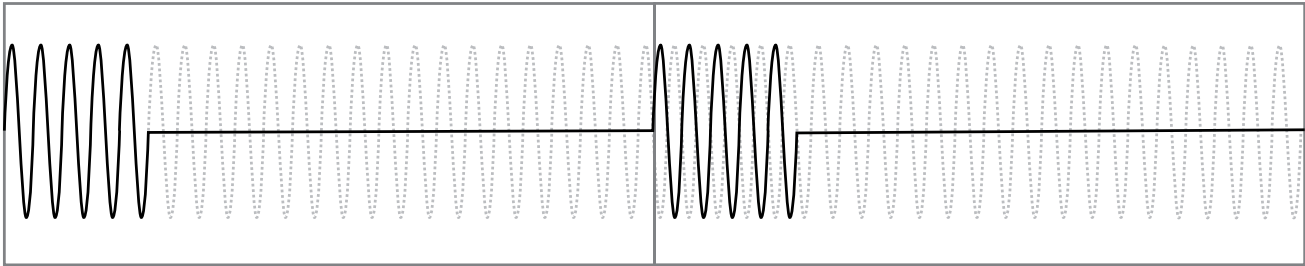
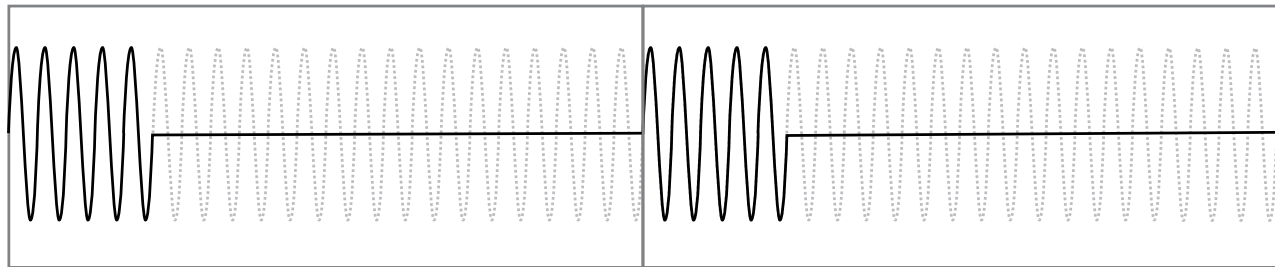b) Time Window <u>is</u> a multiple of the carrier period

Figure 15. 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 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 made 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 15). 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 create an echo emulation signal without any discontinuity or abnormal behavior that could confuse any radar receiver under test.
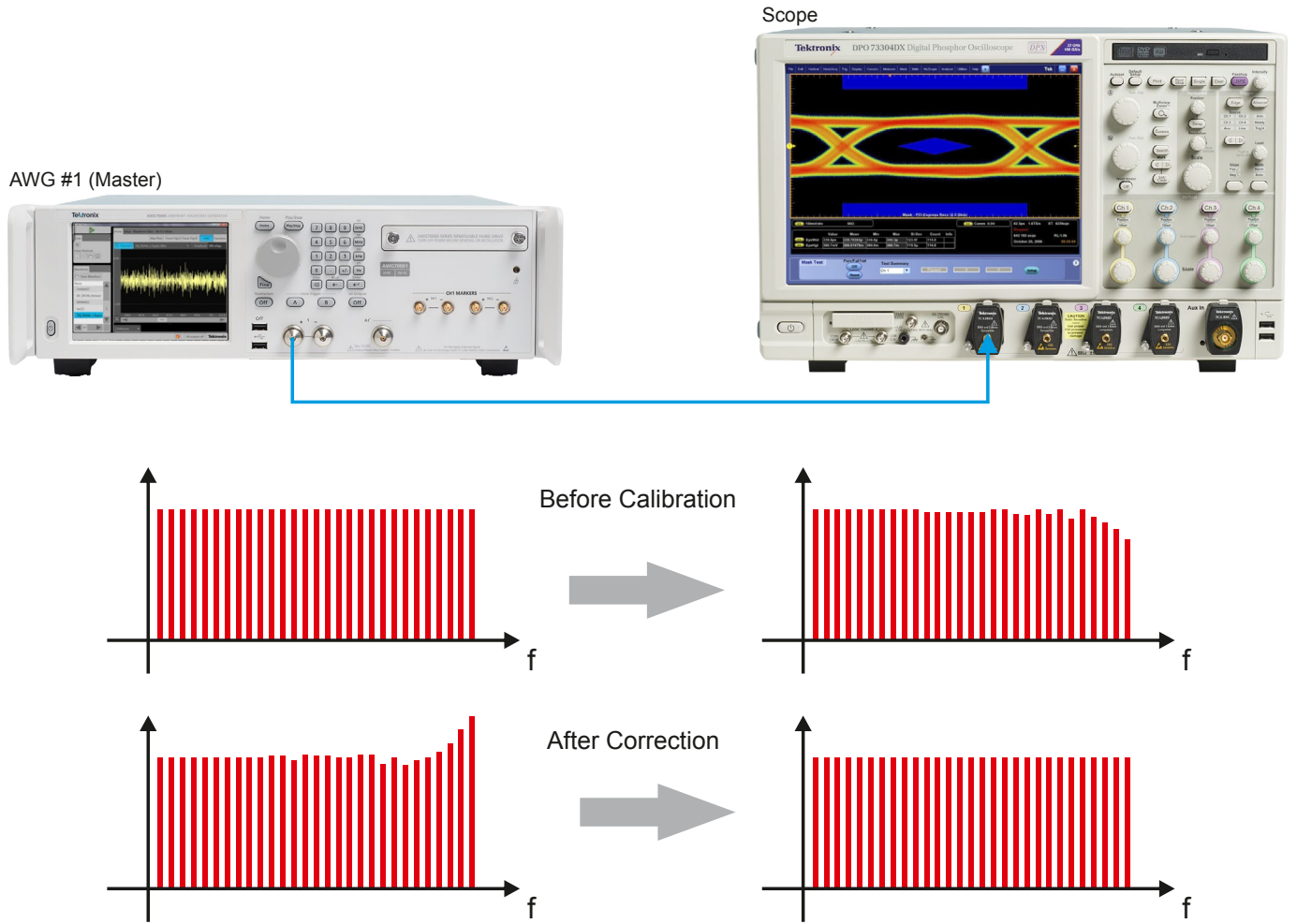
Figure 16. Good-quality wideband signal generation requires proper equalization to make sure flatness and group delay are kept within acceptable limits. Proper correction filters can only be obtained after calibration and they must incorporate the effects of external components such as cabling and amplifiers. The excellent flatness and phase linearity of the Tektronix DPO/DSA70000 Series oscilloscopes makes them an ideal calibration solution. Oscilloscopes, unlike traditional spectrum analyzers, can easily obtain System Under Test frequency response for both amplitude and phase and, equipped with the right software, 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($\pi f/Fs$) 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 12). 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 using 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 16).

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

3.3 AWG Plug-ins for Radar Applications

The Tektronix AWG plug-ins provide a comprehensive set of functions to develop general-purpose and application-oriented modulated signals. The Radar plug-in 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, there is also support for calibration and generation of corrected waveform including the application of user supplied S-parameter models for RF blocks or components.

4 Conclusions

The Tektronix AWG70000 Series generators allow for the direct generation of complex radar signals up to a final carrier frequency of 20GHz. This amazing capacity is made possible by the breakthrough in DAC conversion performance introduced by Tektronix with the AWG70000 series and its exclusive interleaved-DAC architecture. Even the most complex frequency-agile or MIMO radar systems are easy to emulate through direct RF generation thanks to the up to 32-GSample waveform memory and the excellent time alignment between channels within a single generator or across multiple synchronized units.

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