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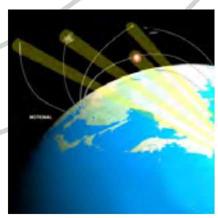
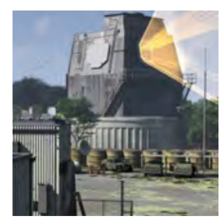
FOCUS ON: RADAR

RADAR, an acronym for radio detection and ranging, dates back to the early part of the 20th century. While radar technology was originally developed to be used for military services, today it is also utilized in many civilian applications. However, the main area of usage for radar technology still involves military services.

This eBook contains a series of articles on the topic of radar technology. Presenting both a historical look at this critical technology, as well as modern generating techniques, this eBook is a must-have for engineers involved with radar signal generation and analysis.

CHRIS DEMARTINO





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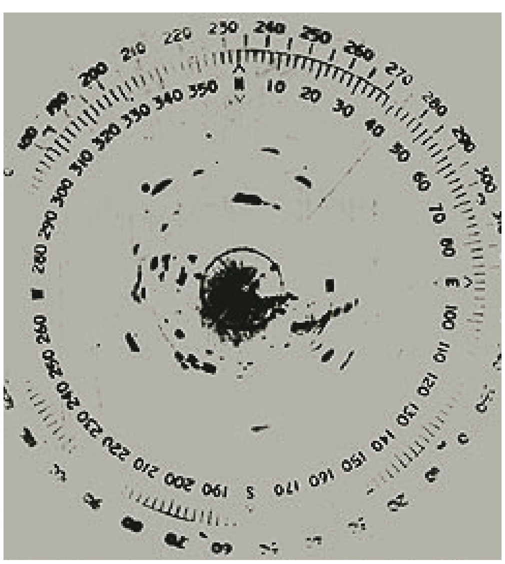
JACK BROWNE, Technical Contributor

CHAPTER 1:

THE RADAR SYSTEMS MAKING HISTORY

Radar technology began prior to World War II and help turned the tide in favor of the Allied Forces. More than 70 years later, radar systems are becoming more invaluable as part of global EW and ECM efforts.

Radar is an essential electronic system for any military force, whether at land, sea, or in the air. In 1922 the U.S. Naval Research Laboratories (NRL) discovered that pulsed radio waves could be used to detect other ships at a distance. Eight years later, the NRL would find that radio waves in radar systems could also be used to detect aircraft from a distance. The NRL's Leo Young and Robert Page are credited with the early pioneering work on radar systems, leading to the first U.S. radar system, the XAF, installed on the battleship USS New York in 1939.



1. The NRL is credited with developing the polar display format used in radar systems. (Courtesy of Naval Research Laboratory)

2. Magnetrons served as the source of transmit RF/microwave power in many early radar systems. (Courtesy of Bing.com)

Naval Research Laboratory

The NRL would develop submarine radar the following year, as well as the ASB radar—the first airborne radar for naval aircraft. The latter was highly effective in the Pacific Theater for searching and destroying Japanese aircraft. The Navy's ASB series radars operated at around 500 MHz with about 5 to 10 kW transmit power generated by four triodes in a push-pull oscillator configuration. Two antennas in the nose of the plane would switch back and forth between receive and transmit functions at a rate of about 30 Hz.

One of the NRL's many contributions to early radar technology included a polar coordinate display to show the target information detected by the radar receiver *(Fig. 1)*. The agency also developed a low-power HF radar called the Multiple Storage, Integration, and Correlation (MUSIC) system. This system measured signals from the ionosphere as well as from the target to warn against

3. The AN/APG-81 radar system uses AESA technology and S-band frequencies for early detection. (Courtesy of Northrop Grumman)

missile launches. It would later be replaced by an enhanced version of the system known as the Magnetic-Drum Radar Equipment (MADRE) system.

Early radar systems were bistatic, with separate antennas for transmit and receive functions. In fact, the first radar system for the U.S. Army Signal Corps (SCR), the SCR-268, operated at 205 MHz with one transmit antenna and two receive antennas. It achieved 75 kW peak power by means of 16 triodes from Eimac. Operators employed three oscilloscopes to translate reflected signals into target range, azimuth, and elevation. The next-generation system, the SCR-270 radar (which detected the planes attacking Pearl Harbor in 1941), used a single antenna for transmit and receive. It generated as much as 200 kW peak power at 110 MHz with a pair of triodes from Westinghouse.

JSTARS

Since those early years, military radar technology has gradually moved to higher frequencies, smaller antennas, and solid-state amplification in place of the triodes and magnetron vacuum tubes *(Fig. 2)* of the early radar systems. Over the past 30 years, radar systems have improved performance due to advances in technology, such as phased-array radars, active electronically scanned array (AESA) technology *(Fig. 3)*, and synthetic aperture radars (SARs).

4. The JSTARS platform is a number of linked, integrated systems that share intelligence, surveillance, and reconnaissance data for threat assessment. (Courtesy of Northrop Grumman)

Radar systems are typically integrated within more comprehensive electronic warfare (EW) suites such as the AN/APY-7 surveillance radar system within the Joint Surveillance Target Attack Radar System (JSTARS) platform. It was first deployed in 1991 during Operation Desert Storm for long-endurance (approximate 9-hr unfueled running time) all-weather surveillance and targeting of moving and stationary targets, both on the ground and at low altitudes.

The JSTARS suite of systems incorporates secure communications technologies to share information with other intelligence, surveillance, and reconnaissance (ISR) platforms *(Fig. 4)*. It employs a variety of communications systems, including satellite communications (satcom), wireless data links, and Single Channel Ground and Airborne Radio System (SINCGARS) radios for communications with other systems and with troops in the air and on the ground. The JSTARS program provides persistent wide-area surveillance for troops in the air and on the ground. Supplied by Northrop Grumman, the extremely reliable

5. The AN/APG-78 Longbow is the well-known fire-control radar system used aboard the U.S. Army's Apache AH-64D attack helicopter. (Courtesy of Northrop Grumman)

radar system is a collaborative U.S. Air Force and Army program managed by the Air Force at Robins AFB, Ga.

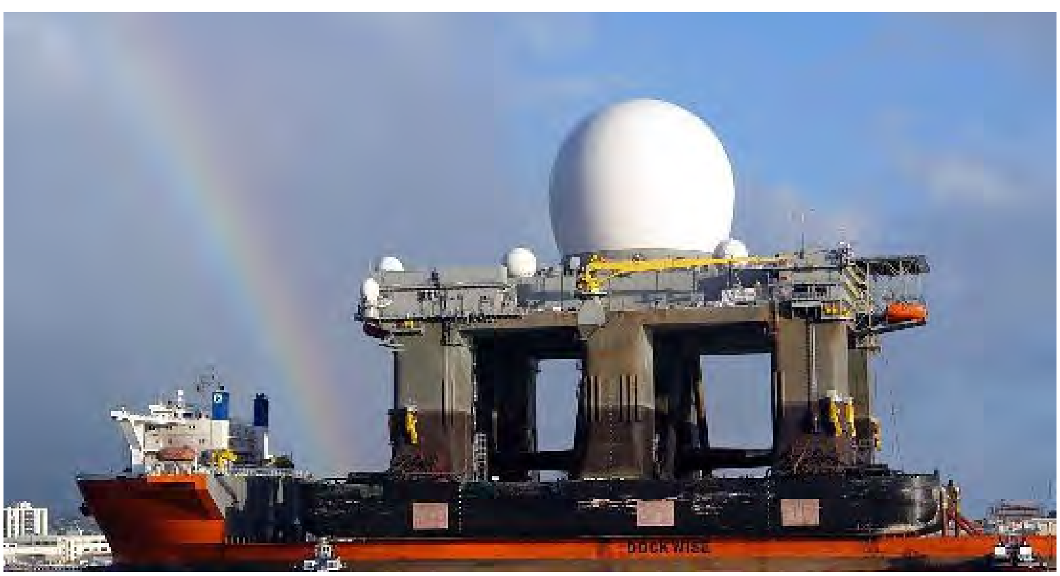
Longbow Radar

Northrop would also team with Lockheed Martin on another well-known radar system, the AN/APG-78 "Longbow" fire-control radar system. Using Ka-band frequencies, the compact radar system has an effective detection range of 8 km. Fielded on the U.S. Army's Apache AH-64D attack helicopter *(Fig. 5)*, the Longbow radar features low probability of intercept and can detect and locate multiple moving and stationary targets. It works in conjunction with the millimeter-wave-guided HELLFIRE Fire and Forget missile to lock onto a target before or after launch.

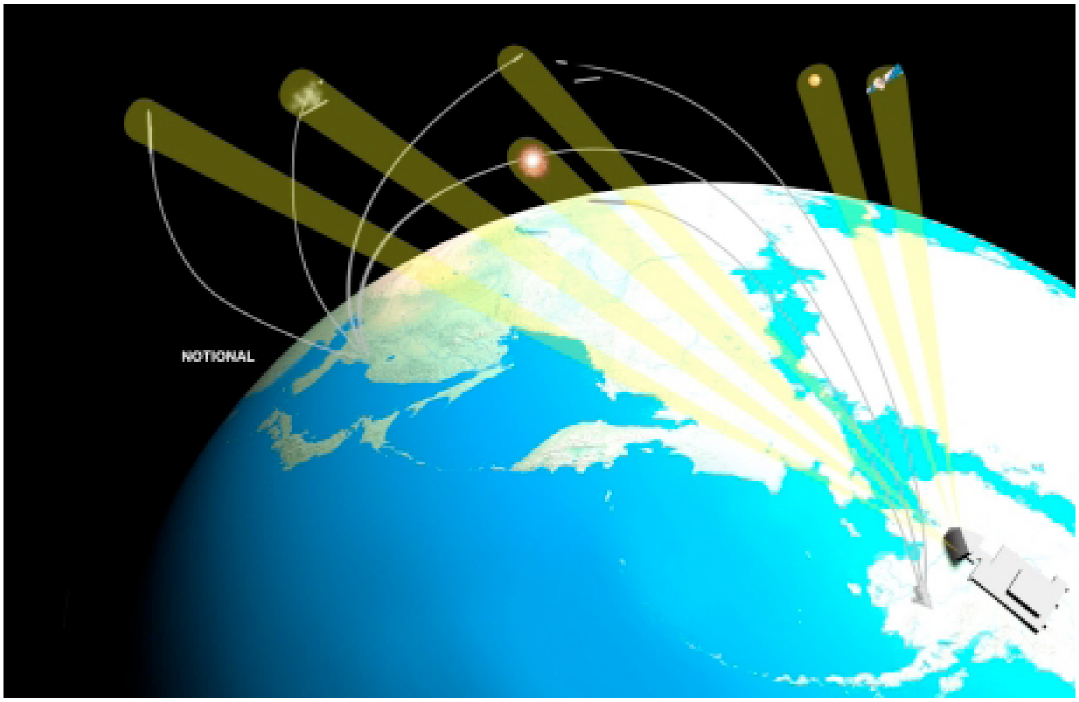
Aegis S-Band Radar

Lockheed might be best known for the Aegis Combat System *(Fig. 6)* which, like the JSTARS platform, is a fully integrated system built around an advanced radar. In this case, the radar is the AN/SPY-1 S-band radar with automatic detect-and-track functionality. The radar system features four complementary three-dimensional passive

6. The Aegis Combat System is built around the AN/SPY-1 S-band radar. (Courtesy of Lockheed Martin)



7. The SBX radar is the world's largest X-band radar system. (Courtesy of Raytheon Co.)



8. The Long Range Discrimination Radar is designed to search for long-range ballistic missile threats. (Courtesy of Lockheed Martin)

electronically scanned array antennas for wide coverage. The naval radar system is aboard vessels for the U.S. Navy, as well as numerous allied naval forces, including the Republic of Korea, Japan, and Norway.

SBX Radar System

Known as the world's largest X-band radar system, the Sea-Based X-Band (SBX) radar system is nine stories high, built on an oil production platform. The radar system stands more than 250 ft. high *(Fig. 7)*, patrolling the world's oceans for ballistic missile launches. The electro-mechanically steered phased-array radar provides full fire-control sensor functions for the Ground-Based Midcourse Defense system, including search, acquisition, tracking, discrimination, and kill assessment. Raytheon Co. builds the SBX radar for Boeing, which is under contract to deliver the system to the U.S. Missile Defense Agency (MDA). The radar system platform is 240 ft. wide and 390 ft. long and includes control rooms, living quarters, storage areas, and infrastructure for the X-band radar.

For the Future

A growing trend in the use of unmanned aerial vehicles (UAVs) for military surveillance has led to the development of the Osprey multi-AESA airborne surveillance radar system by Italy's Leonardo group. The compact X-band radar system was selected by Northrop Grumman for use on the MQ-8C Fire Scout UAV.

Radar technology must continue to evolve to detect and overcome new threats. Present-day fears of long-range ballistic missile attacks on homeland U.S. have driven the construction of the Long-Range Discrimination Radar (LRDR) in Alaska by Lockheed Martin *(Fig. 8)*. In a geographic location to provide early detection of missile launches by North Korea, the system is based on a 2014 request for proposal (RFP) from the MDA. The S-band radar system is leveraging Lockheed's experience in developing the Aegis system while employing the latest solid-state device technologies, such as GaN amplifiers, for high reliability. ■

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CHRIS DEMARTINO, Technology Editor

CHAPTER 2:

RADAR TECHNOLOGY ENCROACHES UPON NEW TERRITORIES

As radar systems utilize more advanced technology, companies must respond with the simulation and test products needed to both design and test modern radar systems.

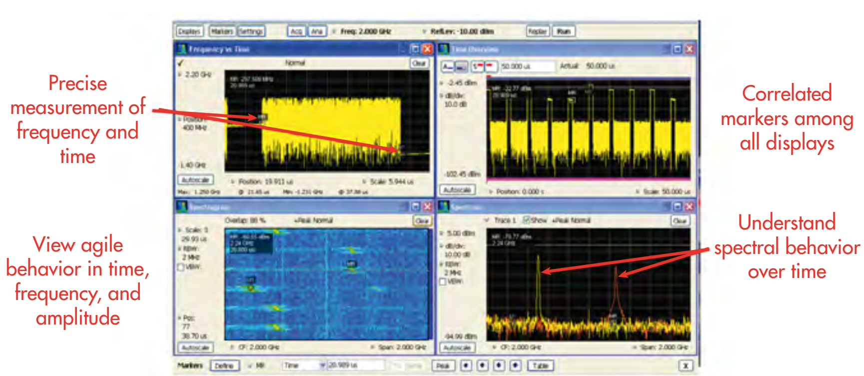
Radar technology has grown in complexity, with a number of advanced techniques now being utilized. For example, complex modulation schemes have found their way into radar applications. These techniques and others have prompted suppliers of test-and-measurement equipment to deliver products to satisfy today's radar test requirements. With recent innovations in test, as well as simulation, radar is quickly advancing to provide heightened capabilities and advanced features.

Radar Test Solutions

Suppliers of test-and-measurement equipment must provide the tools to satisfy today's radar test needs. One company that is providing both hardware and software solutions to meet these challenges is Tektronix (www.tek.com). "Radar systems designers are turning to techniques such as ever-more complex modulation, pulse compression, and frequency hopping schemes—all of which place significant requirements on the test equipment used to design, test, and characterize these complex systems," says David Taylor, a technical marketing manager with the firm.

"To meet modern radar and electronic-warfare (EW) test challenges," Taylor adds, "test solutions must provide simultaneous, multi-domain operation, combining sophisticated signal detection, acquisition, and analysis capabilities in the time, frequency, and modulation domains. Test solutions must also be capable of generating complex high-bandwidth signals so designers can test systems under more realistic conditions."

Meeting current radar test requirements involves more than just hardware. Software is also counted on to analyze and test today's radar systems. "Increasingly, modern wideband and frequency hopping radar systems require the use of automated analysis and visualization software solutions," says Taylor. "With the growing complexity, automated measurement solutions have migrated from being a convenient time-saver to becoming a fundamental requirement for successful radar system design. One example is trend analysis that can involve dozens of pulse parameter measurements on thousands of pulses—it's simply not feasible to setup and perform these measurements manually."



1. The SignalVu software provides a solution for frequency hopping testing. (Courtesy of Tektronix)

Radar designers can take advantage of a variety of tools from Tektronix. "For signal generation needs, our arbitrary waveform generators (AWGs) offer extremely wide modulation bandwidth and deep memory combined with comprehensive waveform generation software," continues Taylor. "Our spectrum analyzers offer simultaneous multi-domain operation combined with high dynamic range. These are combined with oscilloscope-based solutions with up to 70-GHz bandwidth for capturing the widest RF events. And with the addition of SignalVu software *(Fig. 1)*, we provide a common vector signal analysis (VSA) user interface and feature set across all our instruments."

Radar Target Simulation

By utilizing a radar target simulator, radar designers and radar system test engineers can create full simulations of moving targets. Such capability is achieved by the new Series 1100 radar target simulator *(Fig. 2)* from Eastern OptX (www.eastern-optx.com). The Series 1100 receives a transmitted signal from a radar system and adds the round-trip propagation delay associated with the target distance. Next, that signal is output to the radar receiver. The radar input/output (I/O) can be connected directly to the Series 1100 or, alternately, user-specified antennas can be utilized for receiving and transmitting. For a moving target, the system will add the appropriate Doppler shift associated with the target speed and radar frequency.

"The problem that radar system test engineers have is reproducing targets as they would appear in the real world," says Joe Mazzochette, general manager at Eastern OptX. "There are a number of ways to create these targets with electronic simulations. However, our approach is to recreate the propagation path that the radar system would see in the real world.

"The test system must be capable of responding very quickly so it can reproduce fast targets with high refresh rates," Mazzochette adds. "Of course, it has to be accurate. And it has to be capable of accommodating any sort of radar signal format, including pulse, continuous-wave (CW), frequency-agile, and adaptive systems. The Series 1100 test system is a single turnkey box that can be programmed to recreate simulations with very high refresh rates. It can recreate very-high-speed targets (or even very-low-speed targets)—anything from an animal crawling along the ground to the replication of a mortar fire."

The Series 1100 can cover frequencies as high as 40 GHz while achieving greater than 100 dB of dynamic range. It operates with pulsed, frequency hopping, or CW radars, with any encryption or modulation scheme. Target distances can range from 1 to 100,000 meters. Furthermore, the Series 1100 radar target simulator offers expandable range and operation modes to accommodate new system designs. Applications for these test systems include phased array radar systems, tracking and surveillance, and more.

Design Software for Radar Systems

Designing a radar system can be challenging because it involves the analog, digital, and RF domains. A complete system covers everything from the antenna array to radar signal processing algo-

2. This radar target simulator can operate to 40 GHz. (Courtesy of Eastern OptX)

rithms. As a result, there is a need for modeling and simulation software at different phases of the development cycle.

"Radar technology advancement is one of many trends that we expect will encourage component- and system-level designers to rethink their approach to new product development," says Ken Karnofsky, senior strategist, signal processing applications at MathWorks (www.mathworks.com). "From a designer's perspective, radar requires expertise across different engineering areas. These areas include digital signal processing (DSP), RF, and antenna design—a collection of skills that a single engineer rarely possesses. Rather, these complementary talents require underlying modeling, multi-domain simulation, and prototyping tools that provide a commonly understood development platform, in order to enable a clean hand-off at each stage of the design workflow—regardless of the engineer's specific role."

MathWorks is fostering radar system design with a collection of tools that includes MATLAB and Simulink, as well as the Phased Array System and Antenna Toolboxes. "Using certain design tools, such as algorithm development software, will help to bridge the technical divide and accelerate the use of simulation and rapid prototyping environments to enable today's design teams to work more efficiently and effectively," notes Karnofsky. "Companies like MathWorks must match these rising expectations placed on engineering teams with well-integrated design tools. These tools must enable rapid, efficient prototyping, and yield code that can then be implemented at both the conceptual and production phases of product design."

To summarize, it is clear that radar technology has significantly increased in complexity. In response, companies are providing cutting-edge design and test solutions to meet these advanced demands. Expect to see suppliers of design and test products continue to rise to the occasion to meet the needs of current and future radar technology. ■

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JACK BROWNE, Technical Contributor

CHAPTER 3:

RADAR GROWS FROM MILITARY TOOL TO EVERDAY USE

Radar technology has greatly evolved over more than seven decades of development, now serving many different commercial and military applications on the ground, in the air, and at sea.

Radar has been a significant RF/microwave technology since the days of World War II. During that time, radar (a shortening of "radio detection and ranging") proved an invaluable military tool for locating threats and targets and providing advanced warnings of an adversary's position and direction. The basic operation of a radar system involves transmitting a high-frequency signal (usually a pulsed signal) towards the location of an expected target and receiving signals reflected from said target. By performing signal processing on these radar returns, information can be extracted regarding the target, its position, and its speed.

Military uses were once the only applications for radar technology, but times have changed. Radar technology is now finding uses in many commercial, industrial, medical, weather, and especially automotive systems. These new and growing application areas are keeping radar designers—from integrated-circuit (IC) to system-level engineers—busy in search of high-performance, cost-effective solutions from RF through millimeter-wave frequencies.

Military systems still represent the most plentiful source of radar applications, with military radar systems found on land, at sea, and in the air (and in lesser numbers, in space-borne systems). Radar systems have been used in military applications for ground surveillance, missile control, fire control, air traffic control (ATC), moving target indication (MTI), weapons location, and vehicle search.

As land-based radar systems were being developed in support of American troops during World War II, the U.S. Naval Research Labs (NRL) developed radar systems for maritime applications, including onboard submarines. For such uses, a submarine would draw close to the water surface level, enabling a radar antenna to rise above the surface of the sea water to transmit signals in search of enemy aircraft.

Modern ground-based radar systems are transportable by personnel as well as by vehicles, with some systems—such as the AN/PPS-5A/B ground surveillance radar system—in service for a number of decades. Older military radar systems, whether of the ground-, maritime-, or avionic-based variety, are continuously upgraded as newer technologies become available.

With the AN/PPS-5A/B system, for example, systems based on magnetron tube power sources and weighing 125 lb. have largely been replaced by systems using solid-state transmit amplifiers and weighing only 70 lb., with a slight tradeoff in transmit power. This is considered a man-portable radar system that has been packed in waterproof enclosures for dropping into locations with infantry via parachute.

The AN/PPS-5A/B is fairly representative of a ground-based surveillance radar, operating over a fairly narrow bandwidth in the frequency range from 8.8 to 9.0 GHz with a pulse repetition frequency (PRF) of 4 kpulses/s. The system transmits pulses with 1 kW peak power and achieves ranges of about 6 km for detecting personnel and 10 km for detecting vehicles. The system is built for U.S. military customers by a number of different suppliers, including Eaton Corp. (www.eaton.com), Telephonics Corp. (www.telephonics.com), and the Thales Group (www.thalesgroup.com)

In the air, Lockheed Martin has long been an innovative

1. The TRACER radar system operates with lower UHF and VHF frequency bands to effectively detect targets through foliage. [Photo courtesy of Lockheed Martin (www.lockheedmartin.com).]

developer of reliable military radar systems for surveillance. The company's Tactical Reconnaissance and Counter-Concealment (TRACER) radar system *(Fig. 1)* provides effective long-term surveillance of suspect operations by means of synthetic-aperture-radar (SAR) technology. The basic principle of SAR is to use data from multiple radar returns to form the equivalent image that would be produced by a single large aperture antenna. The time delay information from returned radar signals is also converted to spatial dimensional information to produce additional details about a target.

TRACER is a dual-band (UHF and VHF) radar system capable of detecting targets through foiliage, rainfall, and even dust storms, providing real-time tactical ground imagery from the air. The use of the lower-frequency, longer-wavelength UHF and VHF signals compared to higher-frequency signals in many radar systems enables detection through dense foiliage.

The radar signals work with the company's foliage penetration (FOPEN) technology to detect vehicles, buildings, and large metallic objects. TRACER features a portable ground station that works with the airborne electronics to collect and process data and develop precise ground images. The TRACER system is designed for use at low through high altitudes, either from manned or unmanned aircraft.

Military radar systems also are increasingly integrated into other weapons systems for guidance. One of the long-time suppliers of defense-based radar systems, Raytheon Co. (www.raytheon.com), has developed its Small Diameter Bomb II (SDB II) system for the Air Force and Navy to improve missile efficiency under all weather conditions, even when visibility is limited. The firm is currently involved in integrating the radar system onto F-35 Joint Strike Fighter aircraft, F/A-18E/F Super Hornet, and F-15E Strike Eagle aircraft.

The SDB II missile seeker system actually combines several different technologies, with a millimeter-wave radar to detect and track targets through adverse weather, an infrared (IR) imaging system to provide enhanced target discrimination, and a semi-active laser system that allows the SDB II system to track an airborne or ground-based laser designator for identification by allied troops. The radar/IR/laser weapons system can fly more than 45 miles to find a fixed or moving target, providing a great deal of flexibility to an airborne military team.

Raytheon's AN/SPY-6 system is a next-generation air and missile defense radar (AMDR) system that incorporates multiple-frequency radar subsystems at S- and X-band frequencies. To be installed on DDG 51 Navy guided-missile destroyers beginning in 2016 *(Fig. 2)*, the system packs receivers and transmitters together in a compact radar modular assemblies (RMAs) measuring just 2 × 2 × 2 ft. The RMAs are stacked together to form a complete system within the spacing requirements of each naval ship. The AN/SPY-6 AMDR is claimed to provide many times the range and sensitivity of existing naval shipboard radar systems, employing adaptive digital beamforming and advanced digital signal

2. The AN/SPY-6 air and missile defense radar (AMDR) system features S- and X-band radar systems. [Photo courtesy of Raytheon Co. (www.raytheon.com).]

3. The AC100 is an early-model automotive radar system for use at the 24-GHz ISM band, with 100-MHz bandwidth from 24.150 to 24.250 GHz. [Photo courtesy of ZF TRW (www.safety.trw.com).]

processing (DSP) to achieve the improvements in performance.

On the commercial side of marine radar, Raymarine (www.raymarine.com) is a major supplier of ship-board radar systems for a wide range of sea vessels for commercial and consumer applications such as boating and fishing. The company has grown steadily through the years, launching its popular Pathfinder radar system in 1997, and acquiring Raytheon's recreational marine division in 2001. The firm, which also supplies sonar systems and VHF radios, offers a variety of different radar radome and array antennas for different environments, applications, and radar transmit power levels (for increased range).

Into the Ground

In contrast to traditional radar systems in which EM waves propagate through the air to strike a target, ground-penetrating-radar (GPR) systems propagate through different media (usually rock and soil) before striking a target of interest. GPRs usually operate from about 300 to 3000 MHz, at relatively low transmit power levels. Different three-dimensional (3D) scattering patterns will be formed by different target shapes, such as dielectric spheres, in different soils.

The usual wave qualities must be studied in the radar returns—such as signal phase shifts, time delays, and signal attenuation—but the effects of the different propagation media must also be calculated. A forward-looking radar wave will exhibit different vector components when striking the ground, depending upon the composition of the ground (e.g., clay versus sandy soil).

GPRs were initially developed during the Vietnam War for the detection of enemy tunnels. Different types of GPR systems include time-domain-based impulse radar systems, which use short pulses and measure the propagation time to and from the target, and stepped-frequency or frequency-modulated-continuous-wave (FMCW) systems, where the magnitude and phase of each frequency signal is measured and analyzed. Depending upon whether GPR systems are operating with transverse electromagnetic (TE) or transverse magnetic (TM) polarization, radar system performance can be improved by finding the optimum height for the radar antenna above the ground. For even the short distance that the EM waves propagate through the air, the difference in propagation characteristics between the air and the soil must be calculated, and the refraction point at which the radar waves enter the soil must be found.

For example, an innovator in GPR systems, BAE Systems (www.baesystems.com), used a stepped-frequency approach in their GPR systems for tactical ground-based military applications. With 20 transmit/receive antenna pairs in a forward-looking, vehicular-mounted system, the GPR operated from 0.5 to 2.0 GHz in 5-MHz steps and was effective in locating mines through a wide range of soil types. Penetrader Corp. (www.penetrader.com) also is a supplier of GPR systems.

Driving the Future

While radar technology has long been used for tracking and mapping weather patterns, and weather-based applications represent a strong market area for the technology, perhaps the most promising opportunities for radar technology lie in traffic and the consumer automobiles that make up that traffic. Many leading electronics and systems firms, such as Infineon (www.infineon.com) and ZF TRW (www.safety.trw.com), have developed millimeter-wave automotive collision-avoidance radar systems for operation at 77 GHz.

In addition, numerous semiconductor companies, including Freescale (www.freescale.com) and TriQuint Semiconductor (www.triquint.com), are developing radar ICs for the transmit and receive functions at millimeter-wave frequencies. TRW, in fact, now offers automotive radar systems in three different frequency

4. An increasing integration of radar and camera technologies into commercial vehicles is designed to provide safer driving environments. [Photo courtesy of ZF TRW (www.safety.trw.com).]

bands—24, 77, and 79 GHz—with the recent introduction of its AC1000 automotive radar system for use at 79 GHz.

The firm's earliest automotive radar system model, the cost-effective model AC100 *(Fig. 3)*, operates within the 24-GHz ISM band, across the 100-MHz bandwidth from 24.150 to 24.250 GHz. Using a planar patch antenna, it is capable of accurate readings at velocities as high as 250 km/hr. The company's long-range AC3 automotive radar system operates at 77 GHz and is already in the third generation of the product line. The most-recent system, the AC1000 automotive radar, operates at 79 GHz; it supports front-facing collision-warning, side- and rear-facing radar detection, and adaptive cruise control functions for a wide range of driving scenarios *(Fig. 4)*.

ZF TRW earlier this year launched a commercial vehicle system that fuses radar with camera technology. The system uses a common set of sensors to combine data from the radar system and multiple cameras for increased vehicular safety. According to Ken Kaiser, vice president of engineering for the ZF TRW Global Electronics Business, "Fusing the data from camera and radar every 30 to 40 milliseconds helps to confirm when a situation warrants action from on-board systems such as rapid braking via the electronic stability control system for Automatic Emergency Braking." The trend of integrating radar technology with other electronic systems is quite strong for commercial automotive applications, as in military radar systems, and will continue as radar technology is applied to achieve complete 360-deg. safety around a commercial vehicle.

Radar technology comes in many forms and packages, and this article has only scratched the surface of the different types available, including in continuous-wave (CW) form in frequency-modulated CW (FMCW) radar systems. With the help of high-frequency IC manufacturers, radar technology is reaching well into the millimeter-wave frequency range at prices affordable and competitive for automobile manufacturers, who will be able to include radar-based safety features on commercial automobiles for customers in virtually every price range. ■

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KIP PETTIGREW, Sources and Analyzers Product and Marketing Manager
Tektronix, Inc.

CHAPTER 4: GENERATE COMPLEX RADAR SIGNALS WITH AWGs

Arbitrary waveform generators leverage the capabilities of high-performance digital-to-analog converters to directly produce radar waveforms to 20 GHz for measurement and simulation.

Generating radar signals can be challenging for any test signal generator. Radar technology, which was once primarily used for military applications, is becoming a standard feature in the collision-avoidance systems of an increasing number of commercial vehicles. Testing these systems requires a signal source capable of combinations of carrier frequency, modulation bandwidth, and tightly controlled pulses that can be difficult to produce.

The need to emulate multiple-antenna radar systems based on phased-array antennas—or, more recently, multiple-input, multiple-output (MIMO) antenna architectures—makes it necessary for a radar test signal source to generate multiple signals with tightly controlled timing and phase alignments.

Radar signals have traditionally been produced by means of a baseband signal generator and an RF/microwave modulator. However, with the emergence of high-speed, high-frequency arbitrary waveform generators (AWGs) based on high-speed digital-to-analog converters (DACs), it is now possible to directly generate radar signals with carrier frequencies to 20 GHz (beyond Ku-band frequencies). In contrast to the baseband/modulator approach, the use of an AWG delivers higher signal quality, greater repeatability, and much better cost-effectiveness than traditional radar signal generation options.

Before looking at how AWGs can be applied to radar signal generation requirements, however, it's helpful to review typical radar and electronic warfare (EW) signal characteristics.

Radar systems are simple in concept, although often complex in function and implementation. They operate by transmitting short pulsed signals to "illuminate" or bounce off a target and then receive the signals that have been reflected by the target. Information from the radar returns can tell a great deal about a target, such as its distance from the radar's transmit antenna, its relative size or radar cross section (RCS), and even its Doppler motion relative to the transmitted radar system.

Understanding Radar Signals

Carrier frequencies used in radar systems cover most of the usable radio-frequency (RF) spectrum, from the low frequencies used in long range and over-the-horizon (OTH) surveillance radar systems to the shorter millimeter-wave signals used in high-resolution military and civilian radars. Most radar systems operate below Ku-band frequencies (below 18 GHz).

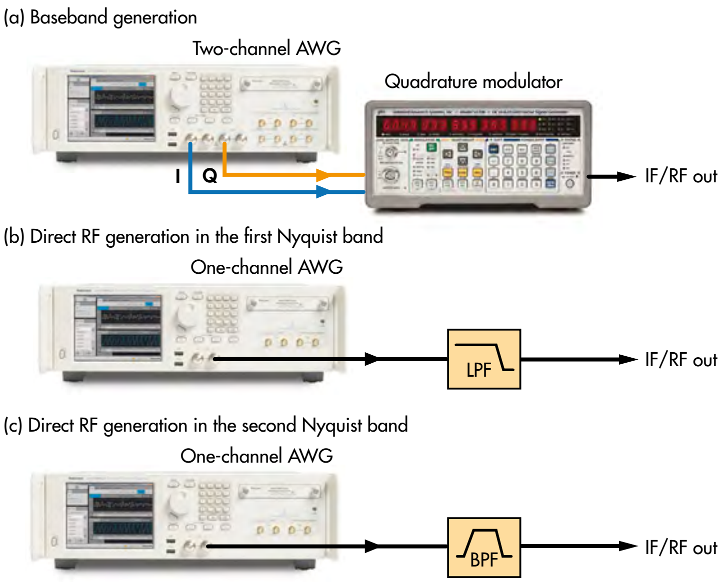
Radar systems operate according to the radar range equation, which can be written in various forms. In one of the most common formats, the maximum detection range of a radar, R_{max}, is defined according to

$$R_{max} = \{(P_t G^2 \lambda^2 \sigma)/[(4\pi)^3 P_{min}]\}^{0.25}$$

where

P_t = the transmit power;
P_{min} = the minimum detectable signal;
G = the gain of the antenna;
λ = the transmit wavelength; and
σ = the radar cross section (RCS) of the target;

While this depiction of the radar range equation provides only a rough idea (no units of measure) of how the concept of reflected signal frequencies can provide information about an illuminated target, it offers an idea of how the different variables—such as transmit frequency and power and target RCS—contribute to the operation and performance of a radar. The radar range equation implies that the detection range is maximized as power increases,



1. AWGs generate signals using three basic methods: (a) baseband generation, (b) direct RF generation in the first Nyquist band, and (c) direct RF generation in the second Nyquist band.

while spatial resolution improves as radar pulses become narrower. Since these two requirements are contradictory, pulse-compression techniques are often used to achieve optimized performance.

Radar signal characteristics can be described by two broad categories: pulsed RF and continuous-wave (CW) signals. In pulsed RF operation, the signal consists of periodic bursts of an RF carrier, which may or may not be modulated in terms of one or more signal characteristics, such as amplitude modulation (AM), frequency modulation (FM), or phase modulation (PM). The rate at which the pulses is generated is referred to as the pulse repetition frequency (PRF), while the period at which the pulses is generated is called the pulse repetition interval (PRI).

In CW radars, the RF signal is continuous and the range of the radar system is established through time markers carried on by a transmitted signal. The use of FM is the typical way to measure distance to target, since the instantaneous frequency detected from an illuminated target is dependent upon distance.

For pulsed RF radars, transmissions may be fixed or variable in frequency, using various frequency-hopping patterns. These patterns are complex by design, meant to be repeating by nature and difficult to predict. The carrier frequency may also change for each transmitted pulse. Some of the reasons that designers vary PRF over time are as follows:

• Echo ambiguity: Unambiguous ranging of targets is limited by the PRI, and targets located beyond that distance can be mistakenly positioned. One way to identify this behavior is to change the timing of consecutive pulses such that their position relative to nearby pulses will change.

• Doppler dilemma: 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 unseen 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 increased range.

•Protection against jamming: Variable PRI, often combined with complex stagger sequences, allows easier differentiation of signal echoes across radar systems. Some stagger sequences are also designed to confuse jammers based on digital-signal-processing (DSP) techniques.

Pulse compression techniques can increase the range of a radar system by transmitting longer pulses for increased average power. Echo processing at the receiver can deliver much better spatial resolution by "compressing" the pulse through correlation or dispersion processing. The two main pulse compression methodologies are as follows:

• FM chirp, which consists of fast frequency sweeps that can be linear frequency modulation (LFM) or nonlinear frequency modulation (NLFM). NLFM has some advantages compared to LFM in terms of efficient use of bandwidth, signal sensitivity, and receiver noise levels.

• Phase modulation, in which each pulse is composed of a series of shorter pulses where the carrier phase is controlled by a low-autocorrelation binary sequence of symbols. In binary-phase-coding modulation, the carrier phase changes between 0 and 180 deg. Polyphase pulse compression applies the same basic idea of changing phase, but the carrier phase is switched among more than simply two phase states.

Carrier phase coherence is an important issue for certain radar systems. In certain radar systems, such as high-performance coherent moving-target-indication (MTI) radar systems—where the phase of each pulse provides details about the precise position of a moving target—the phase coherence between consecutive pulses must be preserved to ensure precise positioning of the target.

Radar receivers detect target echo signals consisting of multiple superimposed signals returning from the same target. Some of the relative phase differences may be due to different signal reflections, different multipath signal delays, and different Doppler-related signal clutter and frequency shifts. While the transmitted signal may exhibit complex timing and modulation, the reflected signal will be much more complex due to environmental effects.

Generating Radar Signals

As *Fig. 1* shows, AWGs can generate radar signals using three different basic methods: baseband generation, intermediate-frequency (IF) signal generation, and direct RF signal generation. When creating radar signals through baseband generation, an AWG generates a time-domain signal to be applied to an RF modulator. For simple signals, a single-channel AWG output is applied to an amplitude modulator (AM).

For more complex signals with complex forms of digital modulation or fast frequency sweeps (FM chirp), both the amplitude and the phase of the carrier must be instantaneously controlled. In such a case, the easiest and most flexible solution is a quadrature modulator with two baseband signals.

When creating radar signals by means of IF generation, an AWG generates a modulated signal at a relatively low carrier frequency. Often the signal can be applied directly to a signal-processing function block in the receiver or transmitter. In situations involving the final RF/microwave frequency, a frequency upconverter block may be needed to achieve the final required carrier frequency.

When creating radar signals by means of the final method, through direct RF/microwave generation, an AWG generates the modulated carrier at the final RF/microwave frequency. No additional signal-processing blocks aside from the expected filters and amplifiers are required to achieve the required radar signals.

Each radar signal generation approach has benefits and shortcomings. For most baseband and IF signals, an AWG with a sample rate of a few gigasamples per second (GSamples/s) is sufficient to achieve the required output frequencies. However, the modulation bandwidth of the final RF/microwave signal will be limited by the modulator or frequency upconverter.

In addition, wideband quadrature modulation is sensitive in in-phase/quadrature (I/Q) amplitude and phase imbalance or quadrature errors. Accurate alignment after a careful calibration is required to produce signals of sufficient quality using the baseband or IF radar signal generation approach.

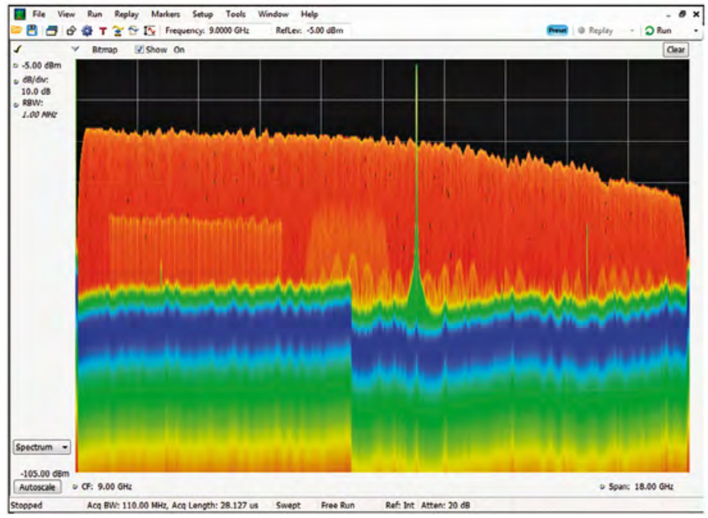
Direct signal generation requires an extremely fast AWG with a sample rate at least 2.5 times higher than the maximum frequency component of the signal to be generated. These speeds are now possible with the latest generation of AWGs that can deliver quality signal generation beyond Ku-band frequencies (12 to 18 GHz).

An AWG can generate both undistorted or intentionally distorted signals according to their programming. The use of intentional distortion can compensate for distortion caused by external effects or components (such as connectors, cables, and other components) and can be used, for example, to improve amplitude flatness or group delay of a test setup.

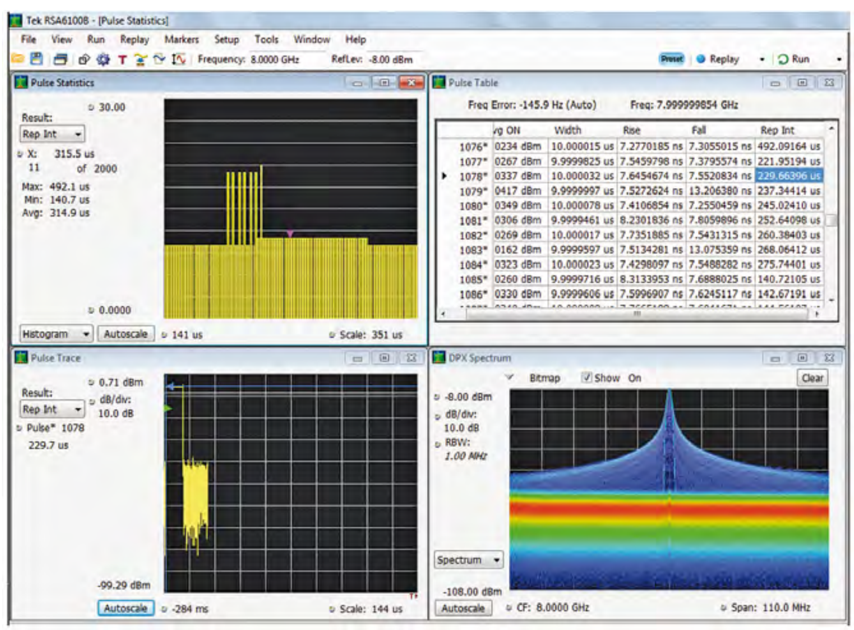
Such compensation takes the form of a pre-emphasis filter to correct the signal-generation system's overall lowpass frequency response. As high-frequency components are boosted, the low-frequency components of the signal must be attenuated to maintain a peak-to-peak value that fits within the available DAC dynamic range.

An AWG's maximum sampling rate greatly influences signal quality. It is good practice to set the AWG sampling rate well above the minimum Nyquist requirement for generating a given signal frequency. Such oversampling increases signal quality in various ways, including providing flatter frequency response, greater image rejection, lower quantization noise, and lower pulse-to-pulse jitter. In fact, the main drawback to oversampling is the need for more memory – a reason why long record lengths are important to high-speed AWGs.

Generating test signals that closely resemble radar system signals can provide a tremendous boost when designing a radar system. For example, when one of the subsystems of a radar system is being designed, the remaining parts of the system are often unavailable



2. With its high-speed digital-to-analog signal conversion architecture, a modern AWG is capable of producing a wideband signal environment suitable for radar system testing.



3. This test result evaluates PRI on a set of 2,000 pulses constructed as a staggered PRI CW pulse waveform on a commercial AWG (a model AWG70001A from Tektronix).

for testing. By using off-the-shelf, general-purpose test equipment to simulate other subsystems within the full system, the device under test (DUT) can be tested under controlled signal conditions.

A test signal source capable of generating signals that closely match the signals that will be used by an actual radar system provides the means of characterizing that system under actual operating conditions. A wideband AWG, for example, can be used to simulate a cluttered open-air signal environment, as represented by *Fig. 2*.

The signal environment includes wide- and narrowband chip signals, narrowband signals, CW signals, and frequency-hopped radar signals, all captured by a real-time spectrum analyzer. 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 involves hundreds or thousands of pulses that are then analyzed using statistical techniques. As an example, *Fig. 3* evaluates the PRI on a set of 2,000 pulses constructed as a staggered PRI CW pulse waveform using a high-speed AWG. 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 pulse.

Direct Carrier Generation

An ideal AWG can generate output signals from DC to within one-half the sampling rate. Given a sufficiently high sampling rate, an AWG can directly generate a modulated RF/microwave test signal. Prior to current-generation AWGs, available AWGs suffered from relatively low sampling rates and poor spurious-free dynamic range (SFDR), which limited the generation of output signals for radar tested to a few GHz.

Direct signal generation with an AWG offers several advantages over traditional baseband/external modulator signal generation approaches. Among them:

- Baseband generation and quadrature modulation are performed mathematically;
- No additional equipment is required;
- A single AWG can generate multiple dissimilar carriers or wideband noise so that more realistic test scenarios can be provided by a single instrument; and
- Direct signal generation can be achieved using a simplified calibration procedure.

Although these advantages are significant, actual implementations of this architecture can reveal some drawbacks as well. One important issue is record length requirements. For a given record length, RL, the maximum time window, TW, that can be implemented is inversely proportional to the sampling frequency, f_s, or $TW = RL/f_s$.

Since sampling rates for direct RF generation must be higher than those for baseband signal generation, a given record length translates into a shorter TW for direct RF generation than for baseband signal generation. The RL is crucial for 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.

Generation of wideband signals may require the controlled addition of linear distortion to correct for amplitude flatness problems and phase linearity issues, such as those stemming from coaxial cables and connectors. 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 because this translates directly to phase noise in the generated carriers.

Some applications, such as MIMO radar generation, require multiple test signal channels. The channels must also be synchronized, so they must share the same sampling clock and be time-aligned. Any timing difference among channels or channel-to-channel jitter will result in a reduced-quality radar test signal. When more than one instrument must be synchronized, standardized synchronization methodologies can simplify the alignment tasks while dramatically improving repeatability and reliability.

Continuous signal generation with an AWG is made possible by seamlessly cycling the contents of the waveform memory through the DAC. To obtain useful signals, consistency of the signal around the wrap-around event must be preserved. Timing characteristics of radar signals are especially important for the following reasons:

- PRI: An integer number of PRIs 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, carrier phase must be preserved. This condition can be met if record length and sampling rate are selected so that the resulting time window is an exact multiple of the carrier frequency period.
- Echo consistency: Multipath, filtering effects, and echoes beyond the unambiguous range must propagate from the end of one cycle to the next. The previous effects are seen as the convolution between the transmitted signal and the target system impulse response. Applying circular convolution to a consistent transmitted data set will create an echo emulation signal without any discontinuity or abnormal behavior.

In short, the latest AWGs allow for the direct generation of complex radar signals to carrier signals as high as 20 GHz in frequency. Such performance capabilities are made possible by recent breakthroughs in DAC technology and DAC components. Even the most complex frequency-agile or MIMO radar systems can now be emulated through direct RF/microwave generation—either coupled with deep waveform memory and time alignment between channels within a single signal generator, or else by means of multiple synchronized sources. ■

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ROBIN JACKMAN, Field Applications Engineer
Tektronix, Inc.

CHAPTER 5: MEASURING MODERN PULSED RADAR SIGNALS

Measurements in the frequency domain and time domain with spectrum analyzers and oscilloscopes can help evaluate the pulsed signals found in modern radar systems.

Radar technology was once mainly the domain of military users, but it continues to expand into instruments for weather, automotive safety, and even astronomy. Measurements of radar systems are as important as ever, especially as these systems impact so many different applications.

Fortunately, improvements in test instruments and measurement techniques have made it possible to accurately measure, analyze, and troubleshoot radar systems with many different signal types—both in the frequency and time domains—to help achieve and maintain optimum performance levels in these radar systems.

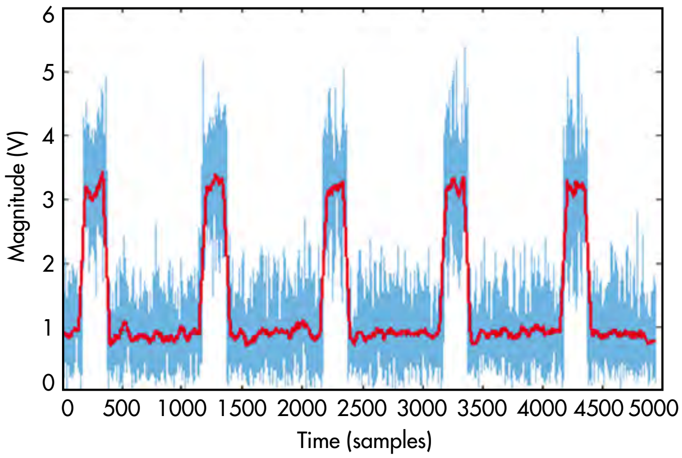
Traditionally, radar measurements have required the use of oscilloscope and crystal detector for time domain parameters and a spectrum analyzer for frequency-domain parameters. Measurements were made on pulsed signals and depended on the type of radar system. They involved measurements of pulse width—plus pulse repetition interval (PRI) or pulse repetition frequency (PRF)—along with such parameters as signal amplitude, noise, and interference (depending upon the functions of the particular radar under test).

Modern radar systems continue to evolve, with improvements in range, resolution, and immunity to interference. This has made it possible for radar engineers to employ a wide variety of modulation techniques that were previously unavailable. Along with the growing complexity and sophistication of modern radar systems, the measurement systems for evaluating those systems also become more complex. Accordingly, it is important to keep track of which test systems and capabilities are needed for evaluating different radar systems, since many lives depend upon these systems.

Traditionally, the signals being evaluated during testing of a pulsed radar transmitter consisted of a steady stream of pulses. This may not be the case in modern radar systems, as pulses are generated in a number of different ways in newer systems. Modern radar designs typically strive to transmit pulses at minimum power levels while receiving return signals at greatly reduced levels.

A number of different techniques may be used in the process, including the use of modulating pulses to achieve pulse compression, varying the PRI to eliminate range-gate blind spots, and using narrow or frequency-chirped pulses. New test equipment is needed to evaluate a growing number of radar system parameters, with such capabilities as segmented acquisition memory, streamed recording, and advanced triggering techniques. Fortunately, the latest generations of spectrum analyzers and oscilloscopes have been designed to meet the measurement needs of both new and emerging radar systems.

Some modern radar measurements are more appropriate in the frequency domain, while others are better made in the time domain; some may require the use of testing in both domains. Frequency-domain testing with a spectrum analyzer may include testing for out-of-band spurious emissions, which can be caused by many parts of a radar system [including digital-signal-processing (DSP) and control software]. Spurious signals can also be caused by hardware. Spectrum measurements of transmitted signals help detect transients and memory effects. Spectrum analyzer measurements also measure signal power levels which a channel of interest and adjacent channels as well as the behavior of frequency-hopped signals.

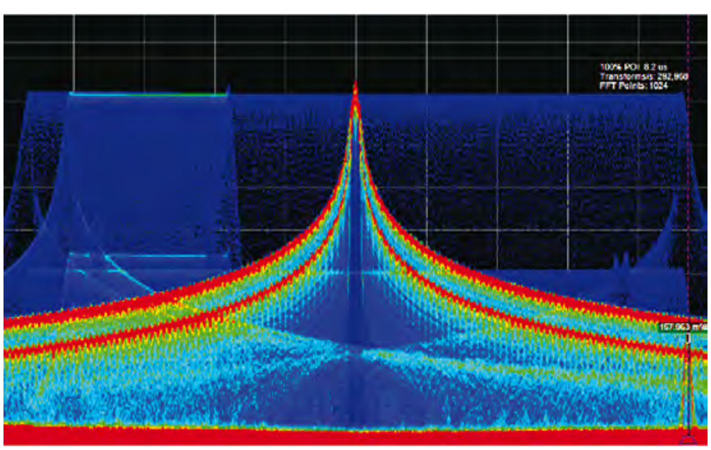


1. Modern pulse analysis methods speed up the process of pulse measurement by using powerful statistical algorithms such as Moving Average.

Single-pulse measurements are commonly performed in the time domain, with an oscilloscope, to evaluate the quality of individual pulses. Time-domain testing is also performed for pulse-width and PRI measurements, rise/fall-time measurements, and analysis of analog modulation.

Many modern radar transmitters may require multiple-pulse testing to reveal differences between the individual pulses that can cause false or "blurred" radar readings. This can be achieved via parametric trend analysis, whereby measurements are parameterized so that all linear measurements can be made on a common pulse model. Once the model has been determined, parameters for each pulse can be measured.

Linear radar pulse measurements that can be made with this model include rise and fall times, PRI, and pulse width. Statistical analysis is then applied to calculate variations in the ensemble of detected pulses. Pulse-to-pulse trends, histograms, and even frequency-domain analysis can be applied to highlight potential problems in a radar system.



2. Some modern test instruments can process and analyze up to 390,625 spectrums/s.

Since finding a radar pulse can be an algorithm-intensive process, increased computing power is needed for modern pulse measurement solutions. This is especially true when measuring pulses over a wide range of amplitudes, since noise can make it difficult to detect and analyze pulses at lower amplitude levels.

For standard pulse-detection algorithms, a basic tradeoff exists between reliability and speed. Greater reliability means that the algorithm takes a longer time to complete—even though the pulse measurements may operate only on data already stored in memory. Modern pulse analysis methods speed up the process of characterizing transmitter designs by taking advantage of the increased computing power of modern test and instruments, with their capabilities to quickly crunch through multiple algorithms.

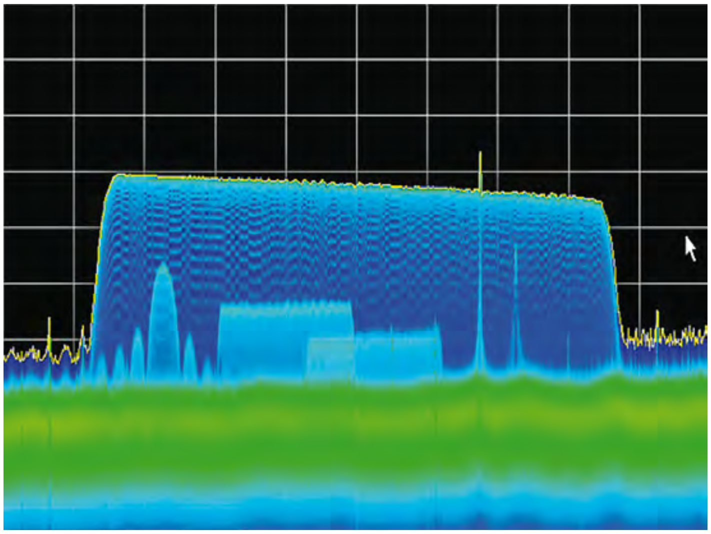
For example, one method applies four separate algorithms to perform pulse detection: Magnitude Histogram, Local Statistics, Moving Average (*as shown in Fig. 1*), and Least Squares Carrier Fit. Each of these algorithms is within the DSP circuitry of the test instrument one at a time, with the simplest and fastest to perform first. If a pulse is found at any time, the process ends. This method ensures that a pulse is detected and its amplitude measured as accurately (and quickly) as possible.

Powerful test instruments are required to efficiently and quickly run such algorithms. Many of today's high-performance spectrum analyzers include advanced algorithms like these on board. Often they have built-in tools for making dozens of measurements automatically on each pulse. These include new measurements, such as impulse-response (also known as time sidelobe) and delta frequency measurements. Many modern high-performance spectrum analyzers also include new statistics capabilities, such as pulse trending and histogram analysis, to better understand variations in pulse parameters.

Some modern spectrum analyzers provide the rapid processing power to analyze as many as 390,625 spectrums/s (*Fig. 2*). In addition, some time-domain visualization tools contained within modern spectrum analyzers can analyze as many as 50,000 time records/s to provide another high-speed method for analyzing radar pulses.

Real-time spectrum analyzers provide the means of measuring rapidly changing signals, such as signals that mat change in real time. This latest-generation of spectrum analyzers samples incoming RF/microwave spectrum for analysis in the time domain and converts the input signal information to the frequency domain by means of Fast Fourier Transform (FFT). Real-time spectrum analyzers can make it possible to observe signals that are difficult to detect with a standard spectrum analyzer, such as infrequently occurring signals or low-power signals that are nearby other signals within a spectrum of interest.

As an example, *Fig. 3* shows a swept DPX display spanning several gigahertz. The display reveals a large low-frequency-modulated (LFM) chirp pulse, as well as (left to right) a lower-



3. Real-time visualization tools make it possible to observe infrequently occurring defects or low power signals "hiding" within other signals.

power continuous-wave (CW) pulse, two even lower-power LFM chirps, and three other pulsed signals.

For time-domain analysis of pulsed signals, displays are available in modern instruments for showing amplitude, frequency, and phase versus time in real time *(Fig. 4)*. Such display capabilities make it possible to visualize many signal artifacts not readily apparent in a frequency-domain view.

In addition, some present-day test equipment provides the capability to correction frequency- and time-domain displays in one package, essentially combining a spectrum analyzer and an oscilloscope within a single instrument enclosure. To correlate the measurements of time and frequency in real time, a measurement system is needed with appropriate sample rates, bandwidth, and memory depth that can be applied to fully characterize pulsed radar systems.

Once a signal artifact has been detected visually, triggering can be used to isolate it so that further analysis can be made. For long signal acquisitions, triggering makes use of the acquisition memory more efficiently. This is especially true for pulsed RF/microwave signals, since the "off" time is rarely used, although it almost always makes up a majority of the signal playback time. Advanced triggering capabilities in modern instruments make it possible to trigger on signals within signals, as well as to use numerous trigger qualifiers across different time, frequency, and amplitude parameters.

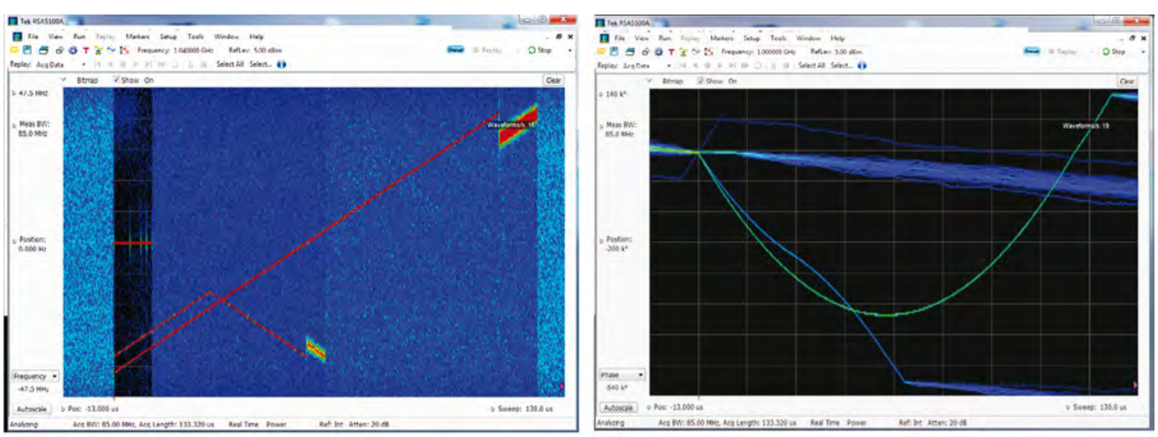
Having access to more trigger types can simplify the evaluation of complex signal effects. As shown in *Fig. 5,* a frequency-mask trigger (FMT) can act as user-defined monitor for multiple frequencies. Time-qualified triggering provides a way to trigger on events of specific user-defined duration. Along with hold-off features, this can help eliminate false triggering.

Frequency-edge triggers are very useful because they not only serve real-time testing by triggering real-time measurements, but enable all of the other measurements in an oscilloscope. Using different types of triggers with trigger input and output signals can make it possible to synchronize multiple signal instances in a radar system.

Modern real-time spectrum analyzers and software provide the means for capturing "runt" pulses, which are transient signals buried among larger signals within a bandwidth or short pulses found within a string of longer pulses. Runt pulses often overlap in time and frequency with the desired signal, making them especially hard to trap and separate.

An amplitude-qualified trigger provides the capability to capture runt signals, since an analyzer with this type of trigger can isolate pulses of specific amplitude and/or width within a pulse train. Advanced triggering capabilities make it possible to detect transient signals in many radar systems, whether for analysis of radar system instability, glitches, or interference.

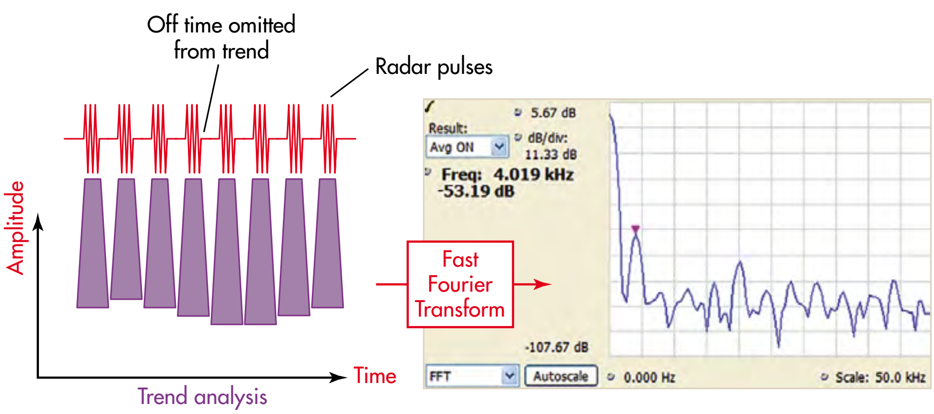
Modern statistical methods can be applied to explore the nature of a pulse's modulation and reveal information about its source. This is often done by converting amplitude trend data from the time domain to the frequency domain via FFT. The spectral view



(a) (b)

4. Modern instruments can display amplitude, frequency and phase versus time in real time, revealing otherwise hard-to-see system artifacts. On the left, the frequency-versus-time display of an up-chirp, up-down chirp, and modulated chirp can be seen. On the right, a phase-versus-time display for the same pulses shows a different phase view.

5. Advanced triggering capabilities make it possible to use numerous trigger qualifiers across time, frequency, and amplitude parameters. The frequency-mask trigger shown here can act as user-defined monitor for multiple frequencies.



6. Amplitude trend data was converted from the time domain into the frequency domain via FFT. The spectral view shows 4-kHz modulation, so it is probably not from the incoming power.

can show whether modulation occurs at a single frequency or is at multiple frequencies. An FFT performed on pulse signals and the instrument's spectral view of the amplitude trend data reveal 4-kHz modulation on a pulse *(Fig. 6)*. The low modulation frequency means that it is not coming from incoming power, but more likely from a switching power supply.

Modern radar systems—whether for commercial, industrial, or military applications—continue to grow in complexity, and so, too, must the measurement solutions for these systems. But modern spectrum analyzers and oscilloscopes use a variety of new methods that let them accurately measure, test, analyze, and troubleshoot systems with varying signals. Such techniques employing real-time analyzers and the use of test software can greatly help to simplify these challenging measurements of pulsed signals, both in the frequency and time domains. ■

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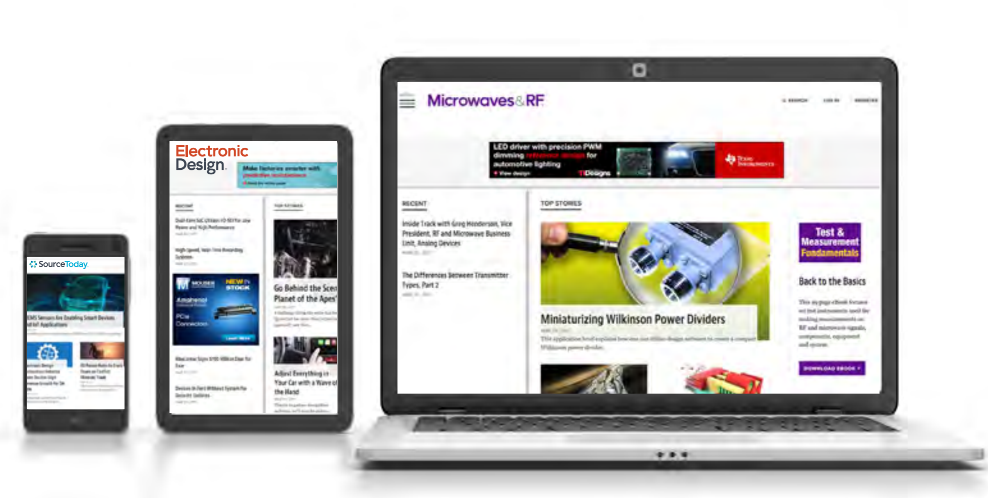

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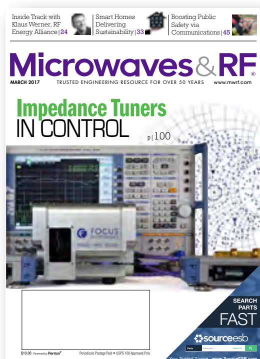

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