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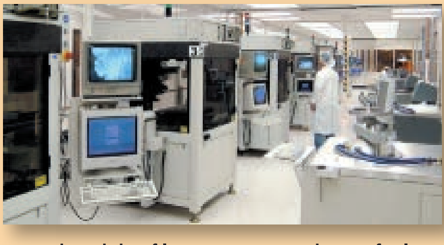

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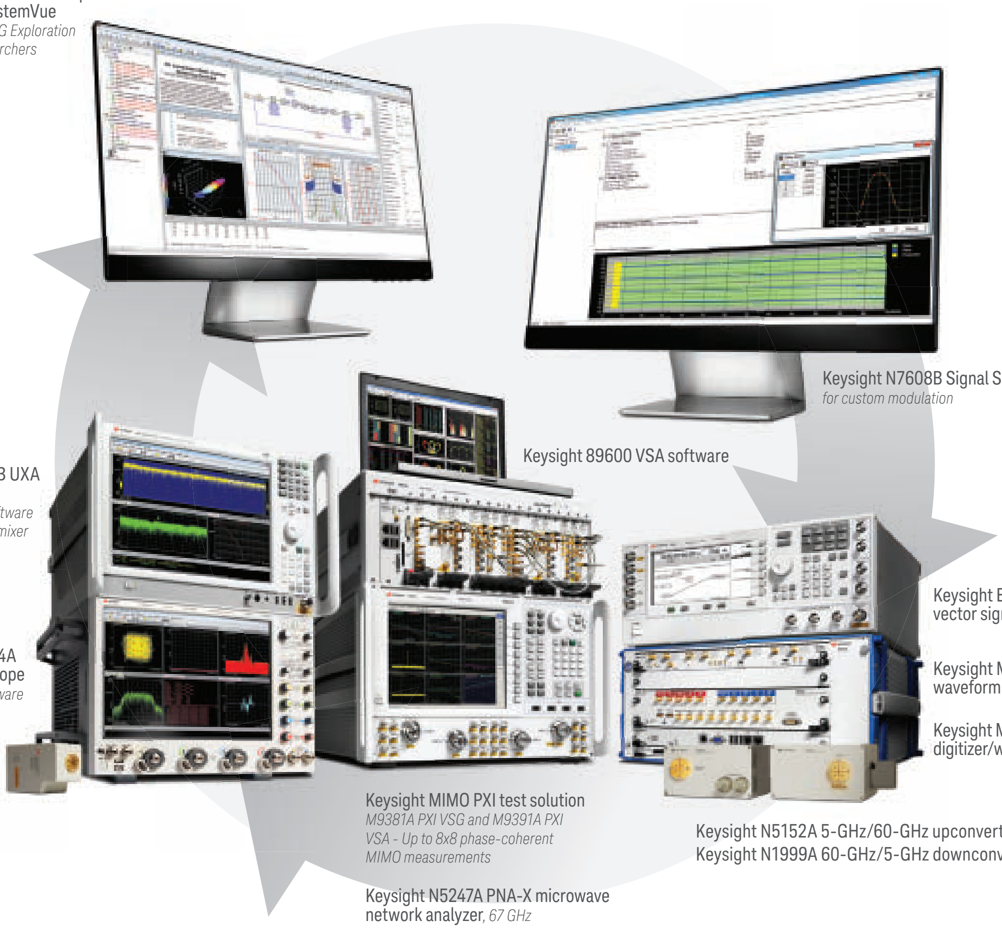


KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights

Early Returns: U.S. Export Control Reform Positive

Gary Lerude
Microwave Journal ***Technical Editor***

For decades, U.S. export control regulations have been a target of frustration for industry and government, both within and outside the country. The frustration led to episodic discussions by presidential administrations of reforming the system, followed by little action. Those whose careers have taken them to foreign shores to sell U.S. electronics have encountered exasperated if not furious customers promising never to buy another component requiring a U.S. export license. Others who have engaged the Departments of State or Commerce seeking a license — often beginning with the question of which agency had jurisdiction for a product — can likely tell stories of Kafkaesque experiences with ITAR, commodity jurisdictions, EAR99, end use and dual use.

Those who have experienced this history might find the "export control reform" that ushered in 2015 hard to believe, even miraculous. Yet, teams from the Departments of Defense, State and Commerce have patiently and steadfastly fashioned a major and encouraging reform.

GENESIS

April 20, 2010. U.S. Secretary of Defense Robert Gates stood before the 400-member Business Executives for National Security (BENS) and outlined his vision for export control reform,[1] one piece of his broader mission to "adapt and reform America's national security apparatus." Gates wasn't acting alone. The prior August, President Barack Obama made export control reform one of the initiatives of his administration.

Saying that the U.S. had one of the most stringent export control regimes in the world, Gates added "stringent is not the same as effective." He said that what was being controlled with the existing policy was too broad, quoting Frederick the Great that "he who defends everything defends nothing." The multi-agency bureaucracy for export control that was created to provide checks and balances was inefficient. Which agency had the authority and jurisdiction for a particular license was often confusing, both to exporters and government officials. Perhaps the worst issue was the friction the system caused with U.S. allies. "Finally, the current export control regime impedes the effectiveness of our closest military allies, tests their patience and goodwill, and hinders their ability to cooperate with U.S. Forces," Gates said.

He was preaching to the choir. The audience knew the issues. They wanted to hear what he would do to fix the problems. The solution the Secretary of Defense outlined had been agreed upon by his counterparts at State, Commerce and Homeland Security as well as the Director of National Intelligence and the National Security Advisor. Although it would also require congressional action, presumably the heads of these agencies could make it happen — unlike

the initiatives under previous administrations.

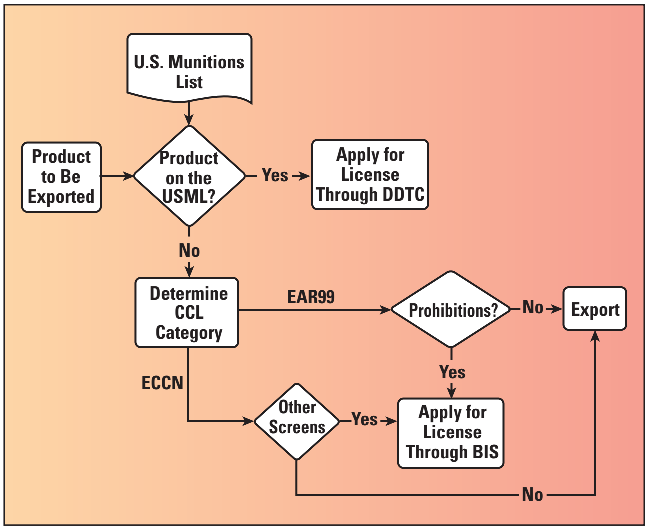
The ultimate export control reform objective articulated by Secretary Gates that day had four elements: creating a single export control list, using a single information technology (IT) system, issuing licenses through a single agency and coordinating enforcement through a single agency. In Gates' view, "A single export control list will make it clear to U.S. companies which items require licenses for export and which do not." He added that the single licensing agency "which will have jurisdiction over both munitions and dual-use items and technologies, will streamline the review process and ensure that export decisions are consistent and made on the real capabilities of the technology. This single entity would also reduce exporters' current confusion over where and how to submit export license applications, as well as which technologies and items are likely to be approved."

Gates said the process of export control reform would occur in three phases. Acting within its existing authority, the Executive branch would begin the transition to a single control list and licensing agency. Completing the effort would require legislation by Congress, which would be the third phase. The middle step would implement the single IT system to support the unified export control list and licensing system. While the vision of a single list and agency is not yet reality, significant change is occurring within the existing structure.

EXPORT 101

Prior to reform, a company wishing to export a product (or service or technical data) first classified it as either 1) defense or 2) commercial or "dual-use." The defense category captured products designed or modified for a military system or application, like the F-35 fighter. These "defense articles" were identified on the United States Munitions List (USML). The second category encompassed products developed for purely commercial markets, such as mobile phones, or products that could be used in either military or commercial applications (dual-use). A transistor is one example of a dual-use product.

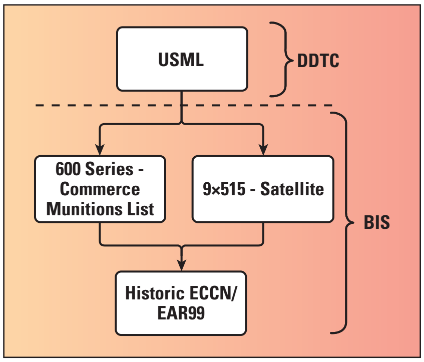
The export of defense articles required a license issued by the Directorate of Defense Trade Controls (DDTC) of the Department of State and governed by the International Traffic in Arms Regulations (ITAR). The export of commercial and dual-use products was governed by the Bureau of Industry and Security (BIS), part of the Department of Commerce, per the Export Administration Regulations (EAR). BIS maintained a Commerce Control List (CCL) of products that, along with the purchaser and destination country, determined if the product could be exported and, if so, whether an export license was required.



▲ *Fig. 1 Export license decision tree, prior to export reform.*

Figure 1 shows the process a company would follow to determine whether a license was required to export a product. Confused? If so, companies could request a Commodity Jurisdiction (CJ) from the DDTC, which would determine if the product fell on the USML and was subject to ITAR. After ruling out the USML, a company could request a commodity classification from BIS, which would determine whether the product was governed by the EAR and then its Export Control Classification Number (ECCN). However, BIS could not say whether an item was on the USML.

More frustrating than the uncertainty of which agency had jurisdiction for a product was the inflexibility of the ITAR. The regulations treated the components of a system the same as the system. Exporting a bolt designed for a fighter was controlled essentially the same as the fighter. While the likelihood of getting an export license for a bolt would presumably be greater, the process was the same. This flood of licenses clogged the system, consuming resources that should have been focused on licenses truly important to national defense.



▲ *Fig. 2 Export license decision hierarchy following export reform.*

The first step to reform the export licensing system has been to pare the USML to only the defense articles that are deemed most important to U.S. national security. DDTC retains responsibility for issuing the export licenses for these items. Not-as-critical defense items have been transferred to BIS and categorized on a newly created group of export control numbers called the "600 series" on the CCL (and 9×515 for satellite items). BIS is responsible for issuing licenses for these transferred items. ***Figure 2*** illustrates the control hierarchy post reform.

The USML comprises 21 categories, spanning ammunition to ships, directed energy weapons to toxicological agents.[2] By the end of last year, 15 of the 21 had been revised to move the not-as-critical items to the CCL. Two of the categories on the USML are relevant to the RF/microwave industry, and both have been updated: military electronics (category XI) and spacecraft and related articles (cat-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egory XV). In paring the USML to just the defense articles that provide the United States with a critical military or intelligence advantage, the lists contain specific products and avoid, with some exceptions, "catch all" phrases.

The revised military electronics category identifies systems such as radar; electronic combat; command, control and communications; direction finding equipment; and equipment specially designed to test these systems. Below the system level, the USML logically captures application specific integrated circuits (ASIC) and programmable logic devices (PLD) that are programmed for these systems as well as printed circuit boards and multi-chip modules where the layout is "specially designed" for the system.

The list also identifies a few RF components as defense articles:

- Circulators where the isolation is greater than 30 dB and any dimension is a quarter-wavelength or smaller at the highest operating frequency
- Transmit or transmit/receive (T/R) modules that incorporate monolithic microwave integrated circuits (MMIC) or discrete RF power transistors, have electronically variable phase and a size small enough to enable a phased array
- Digital radio frequency memory (DRFM) with better than 400 MHz instantaneous bandwidth and four bits or greater resolution
- Certain vacuum electronics devices with multiple or sheet electron beams or cross-field amplifiers.

The revision includes a provision that "developmental electronic equipment or systems funded by the Department of Defense" will be on the USML beginning July 1, 2015. There are a couple of exceptions to this: if the contract identifies the product as "being developed for both civil and military applications" or a CJ determines that the EAR governs the product.

In category XV, pertaining to satellites and spacecraft, only two space-qualified components remain on the USML:

- Certain MMICs that integrate a T/R module on a single die and
- Low phase noise oscillators for space-based radar.

MMICs AND DISCRETE MICROWAVE TRANSISTORS

Exporting MMIC power amplifiers and microwave power transistors has long been a concern to the Department of Defense (DoD). In the 1980s and '90s, the DoD funded the early development of GaAs MMICs as an enabling technology for active phased array radar. DoD also invested in gallium nitride (GaN) to achieve even higher power than available with GaAs. Active phased arrays have revolutionized radar; they provide a strategic military advantage, and, understandably, the DoD wants to retain U.S. technology leadership. Restricting exports has been a bulwark of their strategy. U.S. industry and the DoD have long debated the best way to protect national security interests while not hindering the industry's competitiveness in global commercial markets. Commercial markets for MMICs dwarf military applications, and GaAs and GaN process technology are found worldwide, in Europe, Japan, Taiwan and mainland China. Where to draw that line has been an interesting eddy in the wider current of export control reform.

To govern commercial and dual-use products, the EAR has categories for "microwave monolithic integrated circuits" (3A001.b.2) and "discrete microwave transistors" (3A001.b.3). Historically, the requirement for an export license from BIS was determined by the operating frequency and average output power. Average power proved to be confusing, as the application (e.g., pulsed or continuous wave) really determined the average power, not the device.

During 2012 and 2013, BIS solicited industry feedback on a proposal to change from average to "peak saturated power." They also subdivided the prior frequency range into more bands covering 2.7 to above 90 GHz. These revisions were proposed to the Wassenaar Arrangement, a consortium of 41 nations that harmonize export controls.[3] In December 2013, the Wassenaar Arrangement formally adopted and incorporated these changes to their list of dual-use goods and technologies.

As the same changes were working their way through the U.S. bureaucracy to be incorporated in the EAR, a multi-agency team was developing the criteria for the new 600 series control for military electronics – ECCN 3A611 – that would result from revisions to the USML. The team added efficiency to the usual parameters of power, frequency and bandwidth to define which devices would fall on the Commerce munitions list. Assuming military applications demand higher efficiency, efficiency would be a clear differentiator to protect critical technology. The proposed thresholds for MMICs (ECCN 3A611.c) and microwave power transistors (3A611.d) were issued on July 1, 2014 and scheduled for implementation on December 30, 2014.

The 3A611 proposal was viewed with alarm by several MMIC suppliers and at least one commercial telecommunications system manufacturer. In response, representatives from several U.S. companies gathered in Washington to meet with government officials from BIS, DDTC, the Defense Technology Security Administration (DTSA), and other DoD organizations on August 15, 2014. The forum hosted by BIS allowed industry to provide feedback on the proposed 3A611 criteria. The industry group said that the efficiency requirements of commercial applications are often as great — even greater — than those of military systems. Further, they explained that efficiency is a nebulous specification, with multiple definitions and values that vary with how the device is biased and driven. If the new 3A611 guidelines were implemented, industry argued that exports for bona fide civil applications would be required to follow the more stringent licensing requirements. Cellular and WiMAX base stations, point-to-point radio for backhaul, satellite ground terminals, test equipment for communications and civilian radar were cited as markets that would be adversely impacted. One semiconductor company said that 39 products that previously did not require a license (i.e., classified as EAR99) would require licenses. All 39 of the products were sold internationally to commercial customers, some for more than a de-

cade. The system manufacturer said the lack of a de minimis provision in 3A611 would force a redesign to use non U.S. MMIC suppliers. The government team asked each company to provide data on the specific products and associated revenue that would be affected, allowing them to understand the economic impact.

On December 23, just a week before the 3A611 categories for MMICs and microwave power transistors were to become effective, BIS published a final rule in the Federal Register that eliminated 3A611.c and .d. The ruling stated "BIS did not adopt changes to the control based on fractional bandwidth, peak saturated power output, and/or power added efficiency because the agency found that attempting to designate some MMIC power amplifiers and discrete microwave transistors as civil and others as military based on those characteristics is impractical, and any resulting classification would not accurately reflect real world applications for those devices."

However, the final rule added "national security" and "regional stability" controls to the existing 3A001.b.2 and b.3 ECCNs, except for civil telecommunications applications. This restricts the license exceptions for MMICs and discrete microwave transistors that are being exported for applications other than civil telecommunications. As explained in the ruling "These actions will allow the U.S. Government to examine in advance the exports and reexports of MMIC power amplifiers and discrete microwave transistors that pose the greatest risk of diversion or enhancement of potential adversaries' military capabilities without imposing unnecessary licensing requirements on low risk transactions."

Table 1 summarizes the performance thresholds for MMICs that require an export license (ECCN 3A001.b.2). ***Table 2*** contains the same information for discrete microwave transistors (ECCN 3A001.b.3). Both tables are taken from the CCL as of December 30, 2014.

TABLE 1

3A001.b.2 MMIC OUTPUT POWER AND BANDWIDTH THRESHOLDS

Frequency Band (GHz)	Peak Saturated Output Power Greater Than	Fractional Bandwidth Greater Than (%)
2.7 to 2.9	75 W	15
2.9 to 3.2	55 W	15
3.2 to 3.7	40 W	15
3.7 to 6.8	20 W	15
6.8 to 8.5	10 W	10
8.5 to 16	5 W	10
16 to 31.8	3 W	10
31.8 to 37	0.1 nW	
37 to 43.5	1 W	10
43.5 to 75	31.62 mW	10
75 to 90	10 mW	5
Above 90	0.1 nW	

FRIENDLY LICENSING OFFICERS

Kevin Wolf is the Assistant Secretary of Commerce for Export Administration (see ***Figure 3***). He joined the Obama administration after spending 17 years with a Washington law firm that focused on export cases. Sworn in two months before Robert Gates spoke at the BENS conference, Wolf became the regulator and the export control reform champion at BIS.

As he has done dozens of times since 2010, Wolf rattles off the list of benefits spawned by export reform. "Commerce allows license exceptions," he begins, the biggest being provisions associated with the 36 strategic trade authorization (STA) countries. These include replacement parts, limited value shipments and temporary exports. Unlike ITAR, the EAR has a de minimis provision that allows exports where the value of the product is less than 25 percent of the total value of the end equipment, so long as the ultimate end use is not in an embargoed country. BIS doesn't require separate licenses for manufacturing, technical assistance agreements or proposals. Congressional reporting, registration and import are all simpler, and BIS doesn't charge for licenses. He concludes that Commerce is very flexible, meaning they can tailor licenses, and adds "we have very friendly licensing officers."

Although it's early in the process, Wolf is pleased with the initial results. DDTC is seeing a significant reduction in license applications and CJs, "especially for lower-level items." That's the

TABLE 2	
3A001.b.3 DISCRETE MICROWAVE TRANSISTOR OUTPUT POWER THRESHOLDS	
Frequency Band (GHz)	***Peak Saturated Output Power Greater Than***
2.7 to 2.9	400 W
2.9 to 3.2	205 W
3.2 to 3.7	115 W
3.7 to 6.8	60 W
6.8 to 8.5	50 W
8.5 to 12	15 W
12 to 16	40 W
16 to 31.8	7 W
31.8 to 37	0.5 W
37 to 43.5	1 W
Above 43.5	0.1 nW

▲ *Fig. 3 Kevin Wolf, Assistant Secretary of Commerce for Export Administration.*

intent. Although they hoped to have purely objective criteria for each of the products, it wasn't possible with MMICs. They recognized that efficiency was not an effective discriminator between commercial and military so adopted an end-use definition, carving out civil telecommunications to minimize the adverse impact on industry. Even so, Wolf is "very grateful for the clarity," which is better than before.

The view from industry is similar to Kevin Wolf's. James Klein (see ***Figure 4***) is president of the Infrastructure and Defense Products (IDP) business of Qorvo, the combination of TriQuint's IDP business unit and RFMD's Multi-Market Products Group (MPG). Qorvo is likely the largest RF/microwave semiconductor supplier with a portfolio in both defense and commercial markets.

▲ *Fig. 4 James Klein, president of the Infrastructure and Defense Products business at Qorvo.*

TriQuint's Richardson, Texas facility is a "trusted source," first accredited by DoD in 2008, and the company's GaN technology has been developed with significant R&D funding from DoD. Qorvo is also a major supplier of MMICs for base station, point-to-point radio and optical markets.

Export control reform has been positive, according to Klein, although the change just occurred at the beginning of 2015. They saw 37 products move from the 3A001 classification to EAR99, due to the change from average to peak power; a few moved the other way. They are still learning about the Commerce licensing process for products that are not classified as civil telecommunications, such as automotive radar. He feels it's premature to judge whether the changes will increase their international defense business. "It's too early to tell." If he has a concern, it's that the initial rollout has been a little conservative, meaning the export thresholds don't recognize the fast-moving trends in the commercial markets that push frequencies and power levels higher. As examples he notes LTE-Advanced and 5G, the latter moving to adopt millimeter wave spectrum for very high data rate links.

Klein sees Qorvo's responsibility as helping government officials keep up to date with the market and international suppliers. "Qorvo has a broad portfolio of products, serving a wide range of commercial and defense-related markets. The new export regulations have been positive for products that are applicable to the civil tele-

communications industry, which is a very important market for us. We will continue to work with the Department of Commerce to understand how the new rules are applied for defense and aerospace, and we are hopeful that we will see improvements in licensing speed and availability for that market segment going forward."

Speaking unofficially, because he was not authorized to speak for his company, an executive with a manufacturer of vacuum electronics products sees the changes in export control as "overall positive." Their non-classified defense products have moved from the USML to the 600 series category governed by BIS. "ITAR was a hazy, gray area subject to interpretation. It's more predictable now, and I'm feeling much more comfortable." The change has opened up their sales process, since they can submit most proposals under a license exception. "I'm loving that aspect of it," he says. However he is concerned with the stipulation in the USML that products developed with government funding could be ITAR controlled. That may cause them to avoid some government development programs.

Everyone agrees that it's too early to judge the success of the changes, despite the initial positive signs. In another year companies and government regulators will have considerable experience to judge what is working well, where the bottlenecks lie and further changes that are warranted. Kevin Wolf says the government's mantra with export control reform has been "flexibility, adaptability and transparency," and he encourages industry to communicate with the agencies.

Speaking at the annual BIS export conference held in July 2014, Wolf reflected on the progress since the administration committed to export reform. "This is all moving us closer to one of my personal goals for the limited time I have in government, which is that the export control agencies think of themselves as part of one system, one administration, bound by the rules, but willing and able to change those rules in a transparent, regularized process as foreign policy and national security considerations change, and as technology evolves."[5] ■

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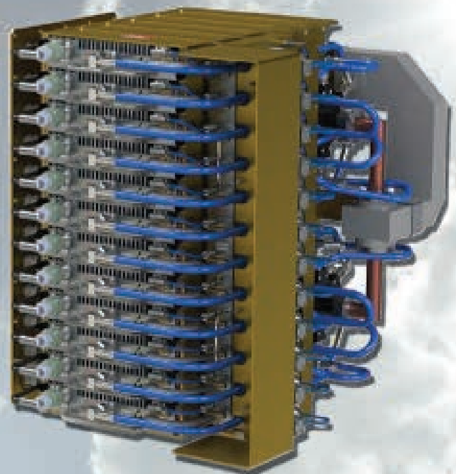
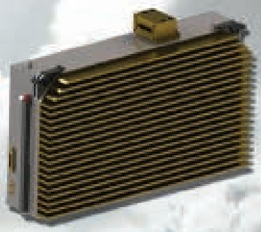
Editor's Note: Share your experiences with export control reform. You may leave comments at the online version of the article, www.microwavejournal.com/exportcontrolreform.

Solid State Power Amplifiers

S-Band





X-Band

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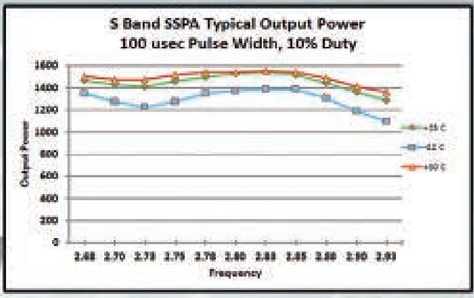
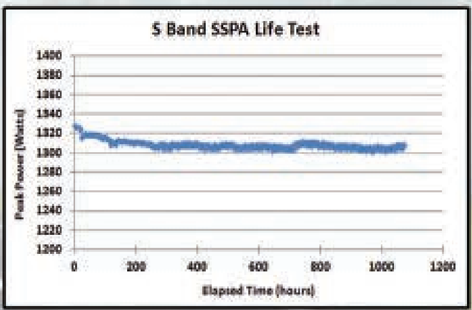
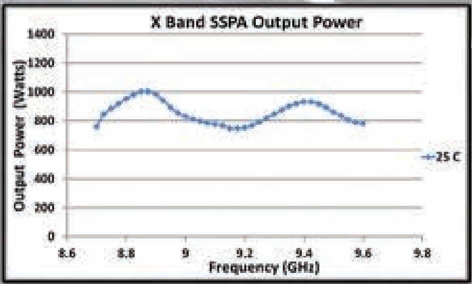
2.7 - 2.9 GHz S-Band: 1.3 kW Modules
1.2 - 1.4 GHz L-Band: 700 W Modules
Power Combine Modules up to 25KW







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INVITED PAPER

A&D Test & Measurement Trends

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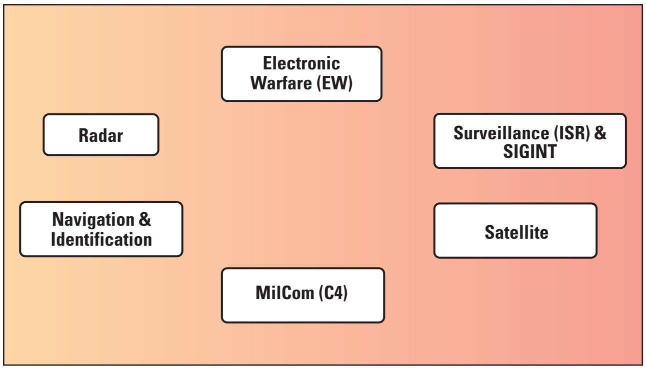
With shrinking defense budgets and smaller military forces relying on greater technological capabilities, the push is stronger than ever to do more with less while at the same time meeting unprecedented performance and reliability requirements. In response to these pressures, test tools must provide greater ease of use, lower test costs and perhaps most importantly, cutting edge performance.

The aerospace and defense (A&D) environment can be broken up in several ways. When discussing test and measurement equipment it is best to divide it into separate functional areas as shown in ***Figure 1***. Common technologies include, but aren't limited to, array antennas, multi-function systems, mixed-signal processing and mmWave.

ADVANCED CAPABILITIES NEEDED FROM TEST EQUIPMENT

The development of new and advanced EW, radar and communications systems drives requirements for performance and usability of signal simulation and analysis equipment. Test systems must employ wider bandwidth signals and move acquired or stored RF signal data from one instrument or storage element to another in a real time environment. Data transfer rates on the order of 10 GB/s (equivalent to about 2 GHz RF bandwidth) are required. High speed (to real time) reduction and analysis of massive data streams within the instrument is a common need. This must be accomplished in the FPGA, DSP or GPU; the instrument controller can no longer be relied upon. Operations include digital up- and down-conversion, simultaneous high resolution time and frequency display and real time signal generation from acquired raw data or data generated algorithmically for playback.

Many technologies including radar, EW and SIGINT are moving to multiple distributed apertures for higher performance and more capability. Multi-aperture, multi-function systems require multiple, coherent RF channels for signal generation and analysis.

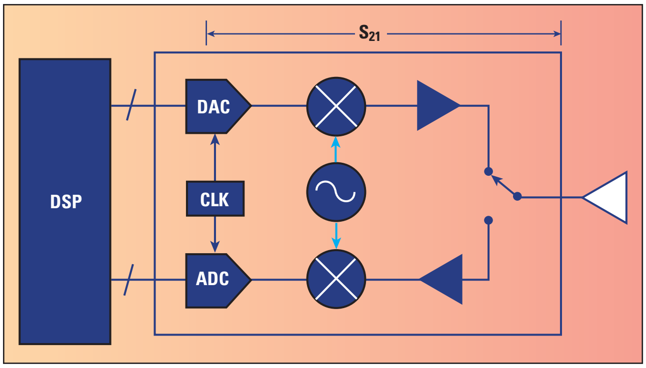


▲ *Fig. 1 A&D applications for test and measurement.*

TESTING ARRAY ANTENNAS AND TRANSMIT/RECEIVE MODULES (TRM)

In radar and EW systems the use of active electronically scanned array (AESA) antennas has become nearly ubiquitous for their many advantages. They enable operation in multiple modes to engage several targets simultaneously and take advantage of powerful signal

processing capabilities for threat discrimination. Because the beam can be formed and steered electronically, no gimbal is required, permitting agile beam repositioning at extremely high rates.

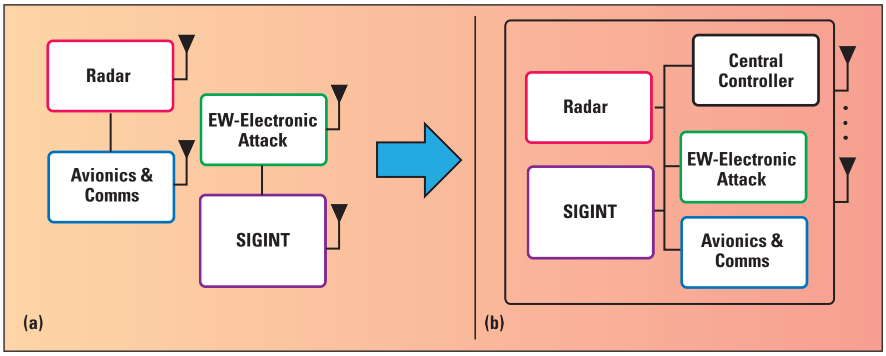


▲ *Fig. 2 T/R module concept for digital array radar.*

For satellite applications, rapid electronic repositioning of the antenna beam or the use of multiple beams permits a single AESA to communicate with multiple spatially distributed ground stations. Distributed TRMs provide an architecture tolerant to failure, providing high reliability in a harsh environment. Also, the antenna can be located on the surface of a spacecraft to avoid physical deployment.

A concept gaining favor for reducing AESA characterization time is using a wider bandwidth signal than is typically available with a traditional network analyzer. With a wideband signal, a group of frequency states is tested at one time, and the wide bandwidth stimulus more closely matches device or system operating conditions.

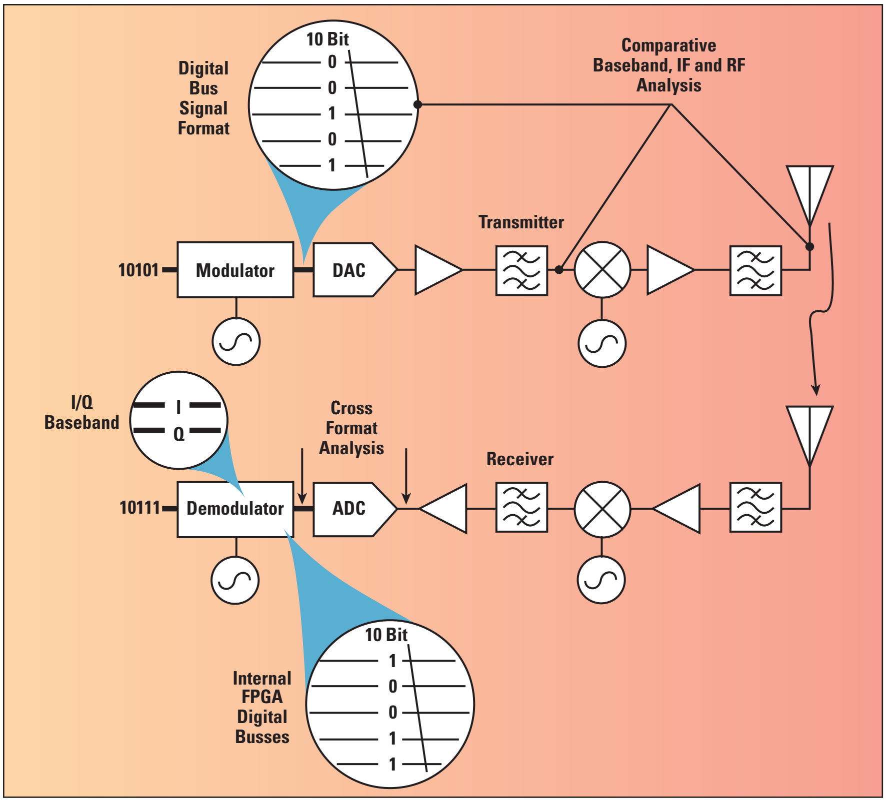
Digital broadband signal processing is moving closer to the antenna, creating a digital array radar (DAR), where the only connection to the TRM is a digital bus (see ***Figure 2***). It poses a new and unique problem when one side of a network is comprised of several lanes of digital data representing what began as an analog signal on the other side. A new methodology is needed to measure network response parameters. Parameters like true time delay might be extracted from the DSP rather than from analog measurements of phase and amplitude. Digital interconnects and serializer/deserializer links add their own distortion and latency that must be characterized.



▲ *Fig. 3 Systems that have historically operated independently (a) are more integrated (b).*

NEED FOR SOFTWARE DEFINED TEST SYSTEMS

A&D system architectures are becoming more integrated (see ***Figure 3***), sharing physical resources such as antennas and processors to reduce size, weight and power (SWaP) as well as sharing information to make better and more timely decisions, such as how to configure in a given environment or react to a specific threat. This, in turn, drives changes in the way these systems are evaluated. Like the systems they assess, test solutions must use common hardware elements, be software and firmware definable and rapidly reconfigured when required.



▲ *Fig. 4 Test challenges with mixed signal implementation.*

MIXED SIGNAL TESTING REQUIRES COMPARATIVE MEASUREMENT

In modern satellite, radar and EW architectures, formats change as the signal passes through the transmitter and receiver. The signal is often represented on time sampled dual I/Q signal busses, which further complicates testing. Diagnosing digital issues requires different test interfaces to different hardware and the probing of I/Q busses with many test connections. Probing is often complicat-

ed when using FPGAs, as many of the desired test points may not be accessible outside of the chip.

As illustrated in ***Figure 4***, cross format analysis is often needed for troubleshooting. For A&D systems, it is frequently necessary to compare an analog signal with the originating digital signal, requiring a cross-domain analysis capability. Comparative analysis can extend well beyond baseband I/Q measurements, continuing through IF and RF frequencies to Ka-Band and higher into the mmWave region.

Vector signal analysis (VSA) software using the same measurement algorithms that can be used with logic analyzers, digital oscilloscopes, and RF signal analyzers is needed to ensure proper comparison of results. This enables the performance of a mixed-signal digital/RF transmitter chain to be probed at various stages, providing the system engineer with insight into which sections of the design are causing issues or contributing the most to transmitter output error vector magnitude (EVM). This can be valuable both to debug and budget system-level transmitter performance.

If FPGAs are used, an FPGA dynamic probe can probe at various stages of the FPGA design using the VSA software with a logic analyzer. The same VSA software can then be used with a digital oscilloscope or RF signal analyzer at points further along the transmit and receive chain.

NEW APPLICATIONS IN mmWAVE

The smaller wavelengths at mmWave frequencies (30 to 300 GHz) enable antenna dimensions to be small compared with microwave antennas, so transmitter and receiver systems can be very compact. Smaller wavelengths also enable higher resolution, particularly for synthetic aperture radar (SAR). With a smaller user base, mmWave bands tend to be much less cluttered than the VHF, UHF and microwave frequency bands. Additionally, large modulation bandwidths can be realized with the current abundance of available spectrum.

In contrast to the advantages offered by mmWave systems, there are also a number of challenges and difficulties. Millimeter wave signals have a poor ability to penetrate materials and are easily blocked. Losses through most propagation mediums, such as the atmosphere, or through transmission lines like coaxial cable or waveguide are very high. Because the physical dimensions decrease, the associated hardware becomes smaller and more fragile. That also means that it is harder to manufacture and machine to the tolerances needed for adequate performance. The combination of these factors, along with the lower volume of mmWave products manufactured, keeps costs high. These challenges are faced by the test equipment industry, as well.

CONCLUSION

Test equipment must adapt and improve to support the applications enabled by advancing A&D system technologies. Flexible, reconfigurable software-defined mixed-signal instrumentation provides a method for controlling test costs through hardware reuse and reduced time to first measurement. ■

Efficient Design and Analysis of Airborne Radomes

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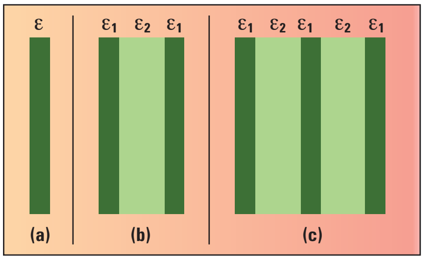
Altair Engineering Inc., Hampton Va.

Keeping present-day challenges in mind, a complete solution is given for the design and analysis of radomes, from materials characterization through transmission loss analysis, to full 3D radome analysis for calculating radome induced effects. Also discussed is the design and analysis of frequency selective surface (FSS) radomes.

A radome (radar dome) is a structural, weatherproof enclosure that protects a radar system or antenna from its physical environment with minimal impact on the electrical performance of the antenna. Radomes must be radio frequency transparent and therefore constructed of materials that minimally attenuate the electromagnetic signal transmitted or received by the antenna. Selecting a proper radome for a given antenna can improve overall system performance by, for example, maintaining alignment, eliminating wind loading, allowing for all-weather operation and providing shelter for installation and maintenance.[1] Radomes find use in a wide variety of applications like satellite, broadcast, weather, communications, telemetry, tracking, surveillance and radio astronomy. Simulation results are obtained using the commercial 3D electromagnetic simulation software, FEKO.[2]

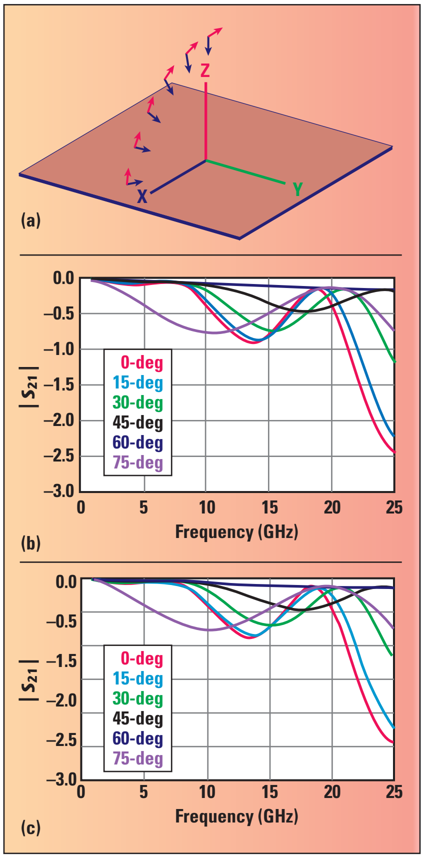


▲ *Fig. 1 Monolithic radome wall (a), A-sandwich ($\varepsilon_1 > \varepsilon_2$) or B-sandwich ($\varepsilon_1 < \varepsilon_2$) design (b), multi-layered dielectric wall design (c).*

CHARACTERIZING THE RADOME WALL CONFIGURATION

Radomes, on a broad scale, are classified as monolithic and sandwich designs, based on wall construction as shown in ***Figure 1***.[3] There are two types of monolithic designs, half-wave radomes (style-a) and electrically thin-walled radomes (style-b). The sandwich designs can be categorized into A-sandwich (style-c), B-sandwich (style-e) and multi-layered dielectric wall (style-d) radomes. One can also introduce an FSS layer into any of the styles to reduce its out-of-band radar cross section (RCS). The choice of a particular configuration or style depends on the application.

Transmission loss serves as a key design criterion in selecting wall construction materials irrespective of the radome style. The wall construction material can be used to design a radome of any shape, depending on the application, after characterizing transmission loss. There are several different computational electromagnetic (CEM) methods to determine transmission loss of single- and multi-layered dielectric wall configurations, but the most accurate and efficient is the use of planar Green's functions with the Method of Moments (MoM).[4] The perfect alignment of transmission loss data computed using planar Green's functions with published results, as shown in ***Figure 2***, validates the accuracy of this method. Transmission loss data is computed for various incident angles over a broad frequency range for an A-sandwich radome, constructed using 0.0762 cm quartz polycyanate skins (ε_r = 3.23, tan d = 0.016) and a

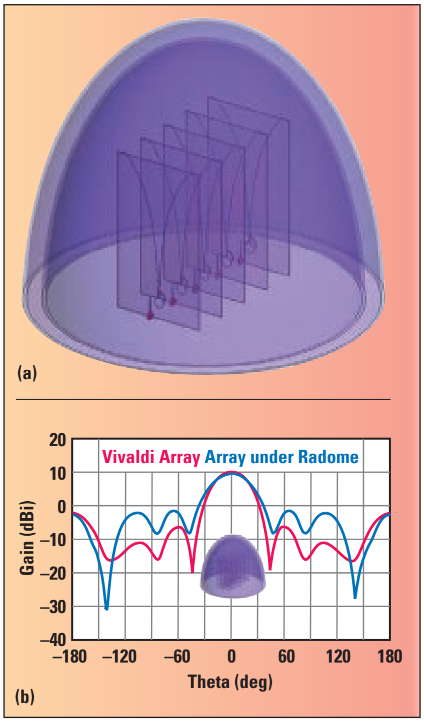


▲ *Fig. 2 Plane wave incident on the planar Green's function layers at various incident angles (a), transmission loss data computed using Planar Green's Functions (b), published transmission loss results[3] (c) for A-sandwich radome.*

1.016 cm phenolic honeycomb core (ε_r = 1.10, tan d = 0.001). The computation time required for these simulations is a nominal 3 seconds, consuming a total of 171 kBytes of memory.

FULL RADOME ANALYSIS

Although transmission loss can be calculated for any incident angle of a planar wall configuration, the shape of the radome introduces other dynamic constraints that change electrical performance. Dissipative losses within the dielectric material, electrical phase shifts introduced by the radome's presence and internal reflections cause insertion loss, increased antenna sidelobe levels and boresight error.[3] It is important, therefore, to analyze radome performance with respect to these additional parameters. The following are various examples of radomes ranging from electrically small to large along with a discussion of CEM methods used for analysis.



▲ *Fig. 3 Vivaldi antenna array under a nose cone shaped A-sandwich radome (a), array patterns with and without the radome at 9.4 GHz (b).*

Modest-Size Radomes

One can use the full-wave CEM solvers like MoM,[5] Finite Element Method (FEM)[6] and Finite Difference Time Domain (FDTD)[7] for the complete analysis of an arbitrary shaped radome. These full-wave solvers are equally accurate but differ in the computational resources consumed. MoM outshines FEM and FDTD for monolithic and A-sandwich radomes because of the small number of dielectric interfaces in these designs and the fact that an air or free-space volume doesn't need to be included. As the number of dielectric interfaces increase with multilayered radomes, FEM being the sparse matrix approximation method, consumes less resources compared to MoM. FDTD has the potential to be the optimal solver for broadband applications, which require solutions over a wide frequency range.

Figure 3 shows a nose cone shaped A-sandwich radome for X-Band applications treated with MoM. The radome profile is built with 0.79732 cm thick skins (ε_r = 4.8, tan d = 0.0002) and a 3.18972 cm thick core (ε_r = 1.3, tan d = 0.001). The radome is modest in size with a base inner radius of 1 wavelength and inner height of 1.75 wavelengths, at 9.4 GHz.

Radome induced effects can be calculated by comparing array patterns with and without the radome. One can readily deduce from Figure 3 that the radome introduces an insertion loss of 0.6 dB. There is no shift in the main beam direction which indicates zero boresight error. The sidelobe levels are increased by 5.4 dB, because the signal blockage from the radome reflects RF energy back and reduces the gain. This reflection and retraction of the RF wave front increases sidelobe levels.

Thin-Walled Radomes

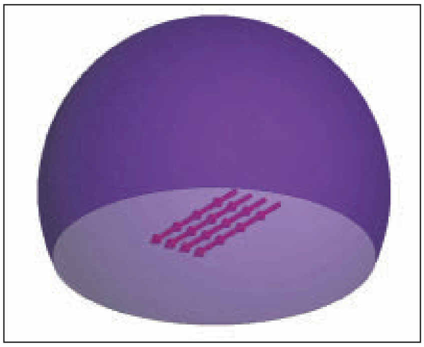
A comprehensive radome analysis that explicitly models the dielectric layers is expected to yield the most accurate results. Unfortunately, modeling the physical layers is nearly impossible in scenarios where the overall thickness is much smaller than a wavelength, because the discretization required for the CEM solvers should be comparable to the thickness. However, one can utilize the special formulations that facilitate the analysis of multiple layers of thin dielectric and anisotropic sheets/layers, referred to as the thin dielectric sheet (TDS) approximation.[4] TDS replaces all the dielectric layers with one equivalent layer treated with a special impedance boundary condition. The TDS formulation can be used in combination with MoM, where the integral equation (MoM solves the electric/magnetic field integral equations to determine the unknown surface currents) is modified to include the surface impedance of the equivalent dielectric layers.

The transmission loss data illustrated in Figure 2 indicates that the A-sandwich configuration should be completely transparent to the RF signal at the lower end of the frequency band. A spherical shell radome is built with the same A-sandwich configuration and analyzed for radome induced effects. ***Figure 4*** shows the radome protecting a dipole array. This radome is treated with the TDS approximation as the overall thickness of the 3-layer radome wall is much smaller than a wavelength at the lower end of the frequency band (more specifically at 2.35 GHz).

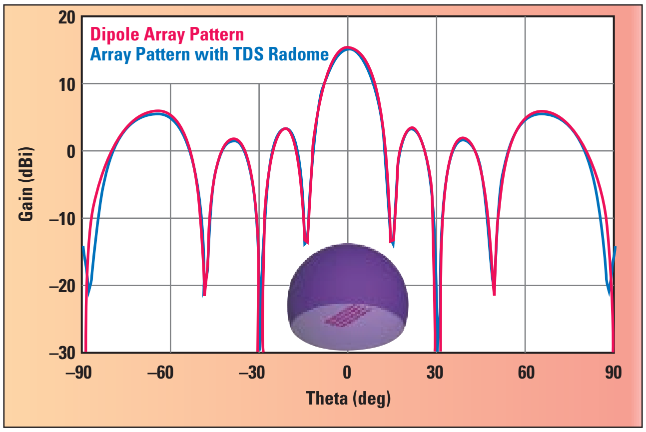
The gain patterns with and without the radome (see ***Figure 5***) demonstrate that the A-sandwich configuration introduces minimal insertion loss, analogous to the data in Figure 2. The gain pattern also indicates negligible boresight error as there is no shift in the main beam direction.

Moderate Size Radomes

As the electrical size of radomes increase, standard full-wave solvers (e.g., MoM and FEM) require significant computational resources. The multi-level fast multipole method (MLFMM)[8] overcomes this challenge by the accelerating MoM solver with fewer computational resources. MLFMM tremendously reduces the computational resource requirements when applied to geometries measuring multiple wavelengths in size. The most appealing aspect of MLFMM is the preserved accuracy, which is governed by a user-controlled residual. In addition, MLFMM can be hybridized with FEM.

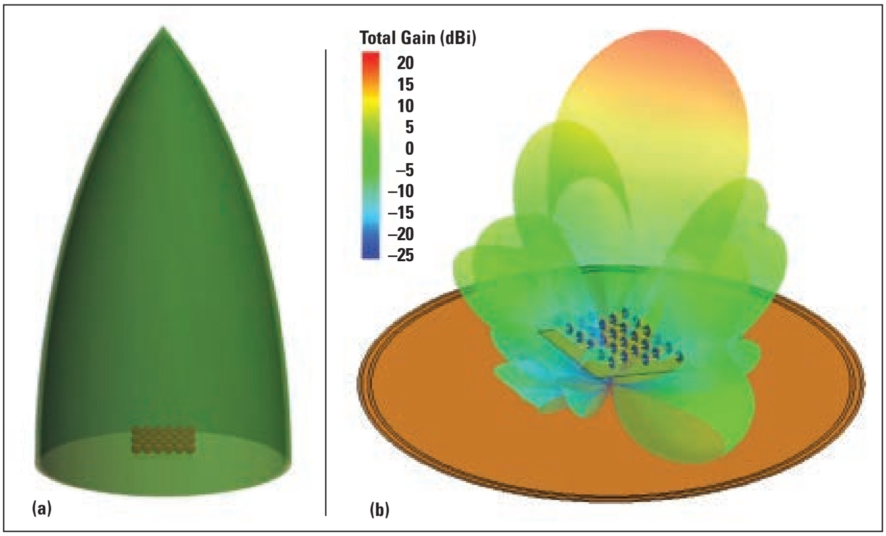


▲ *Fig. 4 Dipole array under the spherical shell A-sandwich radome, treated with TDS approximation.*

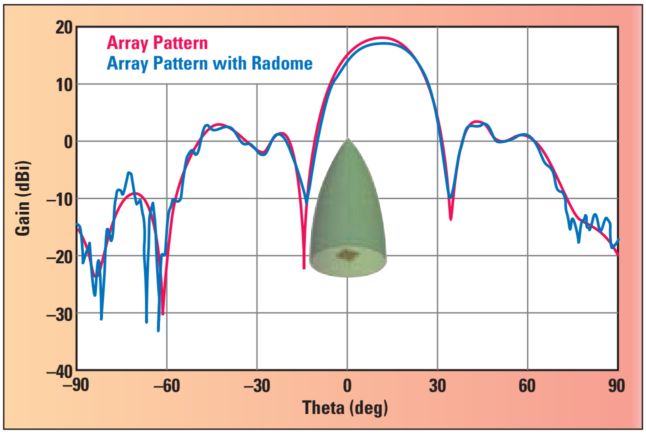


▲ *Fig. 5 Dipole array patterns, with and without the radome, at 2.35 GHz.*

Figure 6 shows an ogive shaped A-sandwich radome protecting a dipole array. The electrical size of the radome at its operating frequency of 8.5 GHz is 4.5 and 16.5 wavelengths for base inner radius and inner height, respectively. MLFMM is the optimal solver for the analysis of this electrically large radome. The A-sandwich configuration is constructed with 0.24 cm thick skins (ε_r = 4.8, tan d = 0.0002) and a 0.4 cm thick core (ε_r = 1.3, tan d = 0.001). The layers are explicitly present in the simulation (the TDS approximation was not used). The antenna array under the radome is mechanically tilted to point at a 10° elevation angle.



▲ *Fig. 6 Dipole array under an ogive shaped A-sandwich radome (a), radiation pattern of the dipole array (b).*



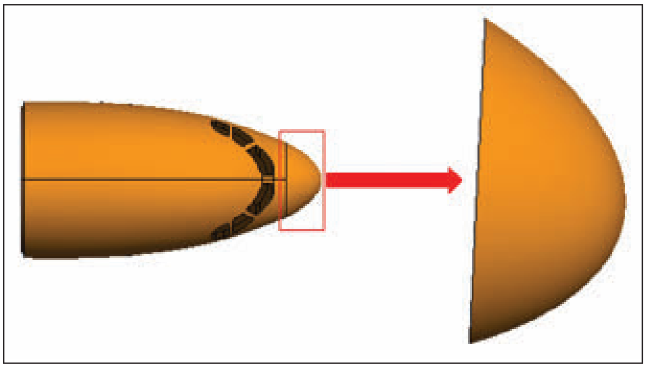
▲ *Fig. 7 Array pattern with and without the radome.*

The radome induced effects are illustrated in ***Figure 7***. The A-sandwich ogive introduces a 2.3 degree boresight error and a 1.1 dB insertion loss. Note that the radome design leaves the antenna sidelobe levels intact.

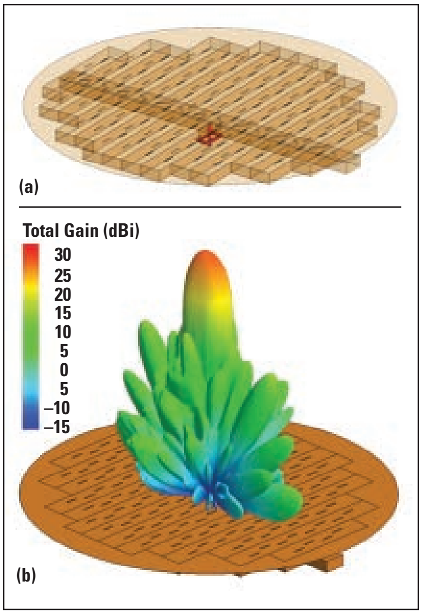
Electrically Large Radomes

Applications such as satellite communications and airborne weather radar require huge radomes to protect the electrically large antennas. The computational resources required to analyze these large structures could become prohibitively large with the aforementioned solvers. One must therefore use asymptotic solvers, particularly Ray Launching Geometrical Optics (RL-GO),[9,10] which are efficient when modeling the transmission of rays through objects, like radomes or lenses.

Figure 8 shows the nose cone of an Airbus A380-800 passenger aircraft, which usually covers the weather radar that operates in X-Band, typically at 9.4 GHz. A slotted waveguide (SWG) array, illustrated in ***Figure 9***, is the most popular antenna for the weather radar. The SWG array is designed in such a way that it is fed from the bottom with a single waveguide that is orthogonal to the array waveguides. The length, width and spacing of the slots is optimized for the de-



▲ *Fig. 8 Nose cone of Airbus A380-800 passenger aircraft.*



▲ *Fig. 9 Slotted waveguide array design (a) and array pattern (b).*

sired pointed beam pattern.

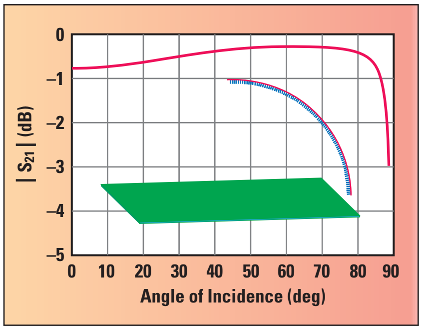
Aircraft require nose cone radomes that can withstand extreme aerodynamic stresses. For such applications, monolithic half-wave wall configurations are preferred over other styles. ***Figure 10*** shows the transmission loss data of a monolithic wall configuration made of a glass composite (ε_r = 4.0, tan d = 0.015) with a thickness of 9 mm. The outer surface of the radome wall is coated with a 0.2 mm typical paint layer (ε_r = 3.46, tan d = 0.068). The material properties chosen for the nose cone radar are obtained from Nair and Jha.[11] According to its transmission loss data, the radome performs well over a wide range of incident angles.

The weather radar typically scans 60° to 90° on either side of the aircraft heading, while the tilt feature permits the crew to adjust the vertical projection of the beam, typically 10° up or down from the aircraft longitudinal axis. ***Figure 11*** shows the SWG array scanning on both sides of the aircraft. Comparison of its array pattern with and without the radome indicates that a transmission loss of 0.7 dB is introduced because of the glass composite. It can also be observed that the monolithic radome does not introduce any boresight error. The complete analysis of this huge radome is performed using the asymptotic RL-GO method in combination with TDS.

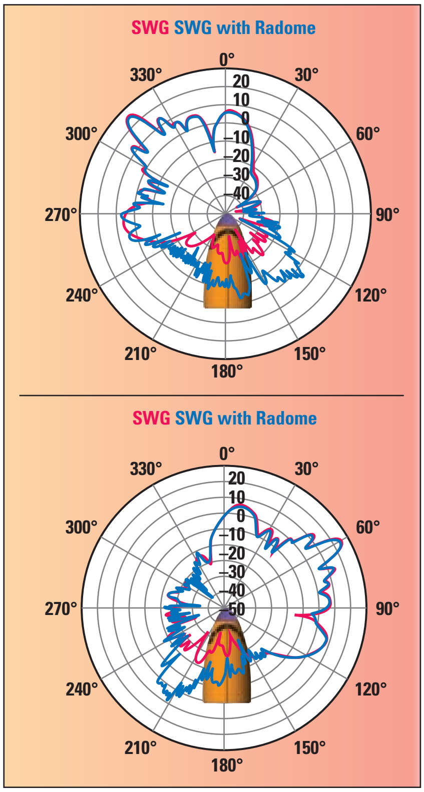
FSS Radomes

FSS structures are two-dimensional arrays of periodic resonant elements (printed or slot) designed to either transmit or reflect certain frequency bands. Radomes constructed with slot-FSS layers sandwiched between the dielectric walls act as bandpass filters and reduce out-of-band RCS.[12] Transmission loss analysis is also used to characterize the electrical performance of layered FSS wall configurations; however, the planar Green's function approach becomes computationally expensive as it requires modeling a large finite FSS layer sandwiched between infinite dielectric layers. One can overcome this problem by using periodic boundary conditions (PBC)[13] for transmission loss analysis.

PBC analysis requires only a single unit cell large enough to include the FSS element sandwiched between the dielectric layers. The boundary conditions effectively duplicate the unit cell indefinitely, representing the layered configuration as an infinite structure in both dimensions of a 2D plane. This allows for transmission loss analysis of the layered FSS configurations over a range of incident angles. The accuracy of this approach is substantiated by comparison with the planar Green's function method, which was previously validated with published data. ***Figure 12*** shows a comparison



▲ *Fig. 10 Transmission loss data of a monolithic radome made of glass composite.*



▲ *Fig. 11 SWG array scanning at different angles on both sides of the aircraft, with and without the radome.*

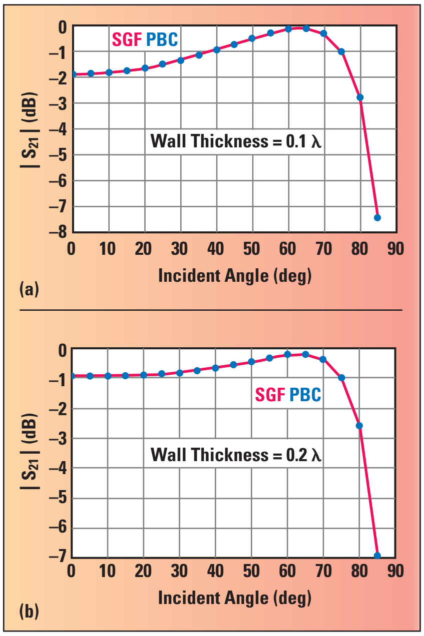
between the planar Green's functions and PBC approach at various incidence angles for two different wall thicknesses of a monolithic radome (ε_r = 4.0, tan d = 0.015). The perfect alignment between PBC and planar Green's function results validates the accuracy of the approach.

The first step in designing an FSS radome is the selection of a periodic element to meet electromagnetic specifications. A Jerusalem cross-slot FSS geometry is chosen to design an X-Band radome. The FSS layer is placed in the middle of the core layer in an A-Sandwich configuration,[1] with

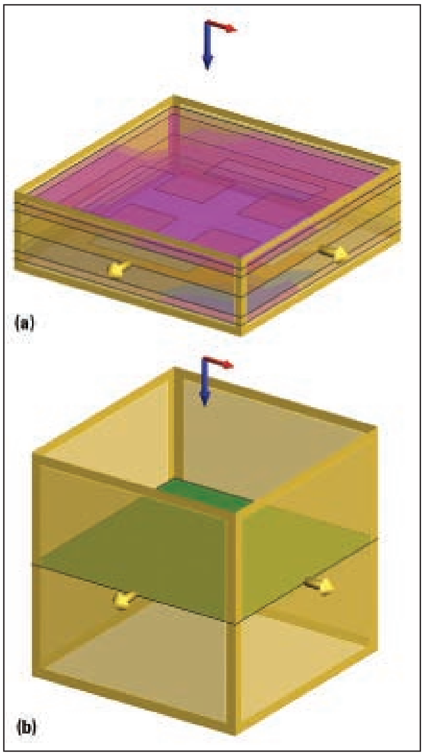
0.319 mm thick skins (ε_r = 4.8, tan d = 0.0002) and a 1.595 mm thick core (ε_r = 1.3, tan d = 0.001).

Analysis of 3D arbitrary shape radomes with all the explicit layers including the FSS layers is a near impossible task because of the difficulty involved in wrapping the FSS layer onto the curved radome surface. This analysis is simplified by converting the transmission/reflection coefficients of the layered FSS configuration into frequency dependent impedance parameters. One can then replace the explicit layers with a single impedance sheet. This approach dramatically reduces the computational resources when compared with a full analysis of the complete explicit geometry. ***Figure 13*** shows both the layered FSS configuration and its equivalent impedance sheet. The transmission/reflection coefficients of the impedance sheet are compared with the complete A-sandwich layered FSS configuration in ***Figure 14***, validating the accuracy of the impedance sheet approximation. The results also illustrate that the radome is designed to be completely transparent at 9.4 GHz, while exhibiting high insertion loss at both upper and lower frequencies.

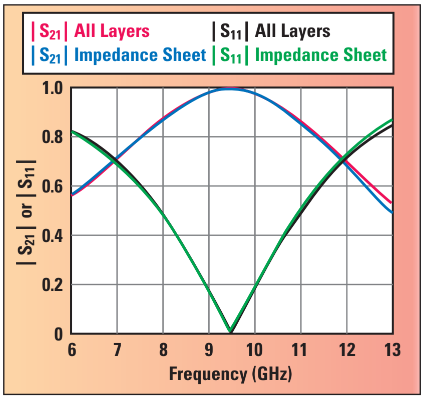
The radome induced effects are computed through the analysis of a nose cone radome of the above A-sandwich FSS configuration covering a Vivaldi antenna. The Vivaldi antenna patterns with and without the radome (see ***Figure 15***) demonstrate that the radome introduces negligible insertion loss and boresight error at the center of the passband (9.4 GHz).



▲ *Fig. 12 Transmission performance of a thin-walled radome for various incidence angles, comparing planar Green's functions and PBC with wall thickness of 0.1 λ (a) and 0.2 λ (b).*



▲ *Fig. 13 Jerusalem cross-slot FSS layers inside an A-sandwich layered configuration (a), impedance sheet replacing the layered FSS configuration (b).*



▲ *Fig. 14 Comparison of transmission and reflection coefficients between the layered configuration with FSS and its equivalent impedance sheet.*

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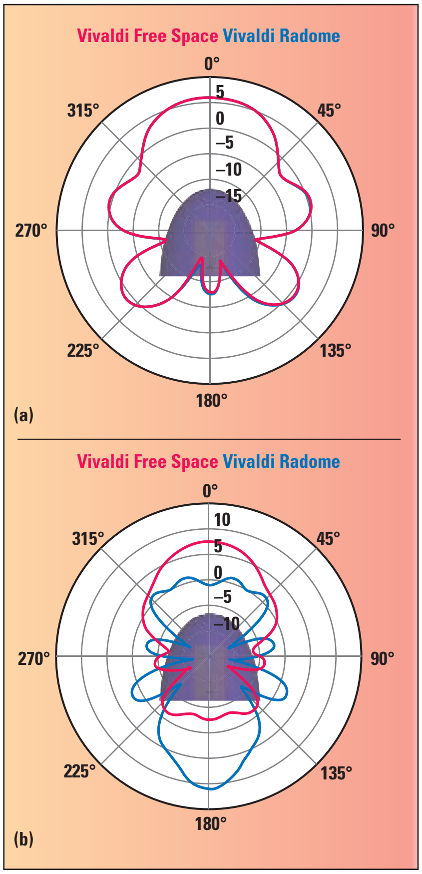

▲ *Fig. 15 Vivaldi antenna pattern with and without the radome at 9.4 GHz (a) and 12.5 GHz (b).*

The sidelobe level is also unaffected when operating within the intended frequency band. In contrast, the FSS radome has the greatest rejection at 12.5 GHz, which is consistent with the data in Figure 14.

CONCLUSION

The computational electromagnetic methods for the complete analysis of radomes ranging from electrically modest to electrically large are discussed with examples. Radome wall construction materials can be quickly characterized for different configurations through a transmission loss analysis using planar Green's functions and/or periodic boundary conditions. A complete radome analysis to investigate the radome induced effects can be performed using different solvers (e.g., MoM, FEM, FDTD, MLFMM or RL-GO). In addition, a hybridized combination of solvers can be used depending on the electrical size of the radome. The thin dielectric sheet approximation is available for the efficient analysis of thin-walled radomes. A radome with an embedded FSS can be approximated by an impedance sheet with frequency-dependent characteristics. In summary, efficient simulation methods are available for many practical antenna-with-radome applications. ■

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INVITED PAPER

Wideband Frequency Modulation Applications and Techniques

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Frequency modulation (FM) is used extensively in audio communication and data transfer. When spectrum efficiency is important narrowband FM (NBFM) is used but when better signal quality is required wideband FM (WBFM) is used at the expense of greater spectrum usage. The term WBFM is used in applications where the modulation index is equal to or larger than 1. However, in this article, we are going to address applications and techniques for WBFM with modulation indexes much larger than that, going up to 100 and beyond. In such applications spectral efficiency is less important and sometimes large spectral spread is actually desired. The purpose of this article is to present some major applications in the commercial and defense markets as well as the common techniques of generating WBFM.

FM-CW radars generate a continuous-wave (CW) signal that is typically modulated by a saw-tooth waveform; such a signal is called a chirp. This signal is then amplified and transmitted. The received signal is amplified, filtered and converted to zero-IF by mixing with the transmitted signal. The basic block diagram of the FM-CW transmitter is shown in ***Figure 1***. The received signal is delayed by the time it takes the signal to reach the target and return. Also, the frequency of the received signal is shifted by the doppler effect due to the target's relative velocity. Overall, by the comparison (or mixing) of the transmitted and received signals both the range and the velocity of the target can be extracted. This principle is shown in ***Figure 2***.

The advantage of FM-CW radar is excellent signal to noise ratio (SNR) and, since it transmits all the time, the simplicity of the information extraction and the ability to detect very close-range targets. Pulsed radars, for instance, cannot receive the signal while transmitting. The result is a "shadow time" that prohibits the pulsed radar from detecting very close-range targets.

The FM-CW radar overcomes this problem and can support very close-range targets. In order to get an accurate reading of a target, the frequency change rate must be very high, so there will be a detectible frequency difference between

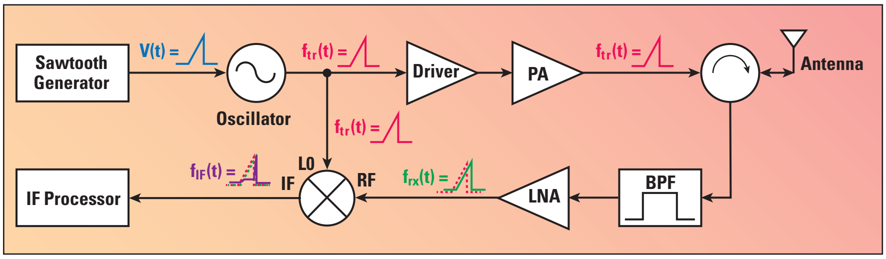


Fig. 1 FM-CW radar block diagram.

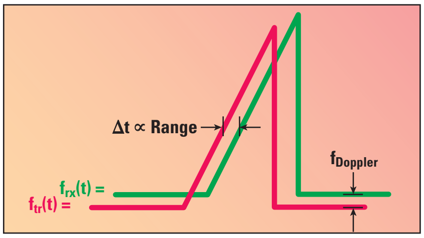


Fig. 2 FM-CW transmit (red) and received (green) signals.

the transmitted and received signals. Therefore, FM-CW radars use a very wideband FM modulation technique.

TECHNIQUES

There are many techniques to generate a WBFM signal: analog based, digitally based and hybrid techniques. In this article the commonly used solutions and hardware are reviewed.

Free Running Voltage Controlled Oscillator

A free running VCO is a device based on an unstable transistor circuit. The frequency of oscillation depends on the resonance frequency set by its equivalent capacitance and inductance. By applying variable bias voltage to a varactor diode, the capacitance is changed and the oscillating frequency is changed accordingly. A simplified schematic is shown in ***Figure 3***.

The VCO is a very low cost method of generating WBFM signals, such as chirp signals. The VCO has some important properties that are common to all frequency sources. The definitions of these properties are detailed below and will be used for the rest of the article:

Frequency range is defined as the lowest and highest frequencies generated by the VCO. A VCO may cover a full octave band.

Settling time is defined as the time it takes the VCO to reach the final frequency within an allowable window. Typical values are 50 ns to ±10 MHz and 1 μs to a ±4 MHz for a 12 to 18 GHz jump.

Post-tuning drift: After a VCO reaches what seems to be its final frequency it may slowly drift until it reaches the real final value. This post-tuning drift may cause an additional few MHz of deviation after a few micro-seconds.

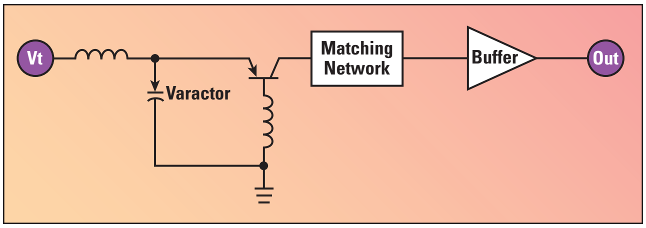
Sensitivity and maximum sensitivity ratio (MSR) is defined as the "voltage to frequency" transfer function of the VCO and is measured in MHz/Volt. A perfect VCO will have a constant sensitivity throughout its range of operation. Unfortunately there are no ideal VCOs and therefore the sensitivity varies across the VCO frequency range. The maximum sensitivity divided by the minimum sensitivity is defined as MSR. Using a VCO with poor MSR (>>1) will yield a wide range of problems. Some examples:

Applying a perfect saw-tooth waveform as the tuning voltage will not generate a perfect chirp. Range measurements in altimeters, for example, will become inaccurate as a result.

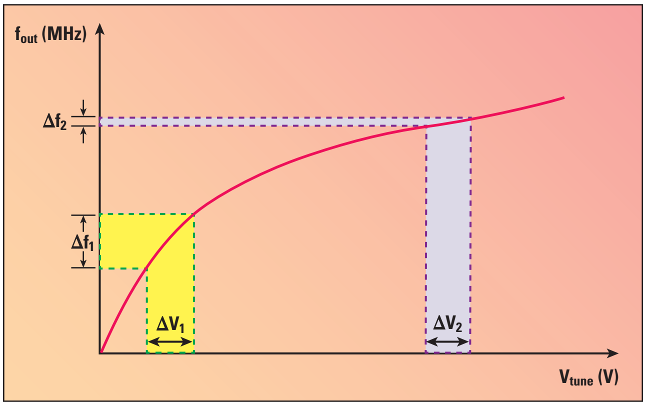
The same modulating waveform, for different center frequencies, will result in different frequency spans. This is demonstrated in ***Figure 4***.

Different modulating waveform amplitudes, for a constant offset voltage, will result in different center frequencies. This is demonstrated in ***Figure 5***.

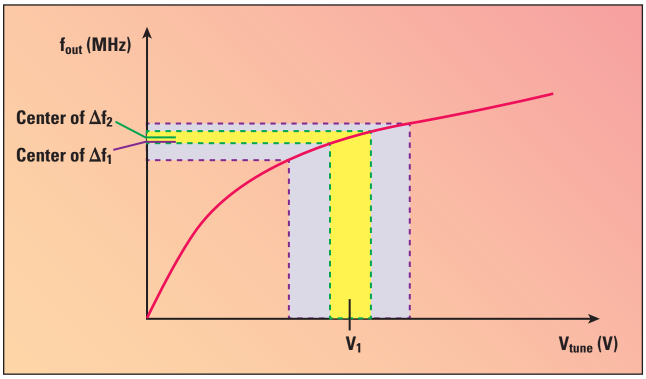
Frequency total accuracy is defined as the maximal frequency error that will be measured after a "voltage to frequency" calibration table has been established. The frequency error is mainly effected by temperature and aging. This is the major drawback of the VCO as a frequency source. A system using a simple VCO as a WBFM generator may end up with a signal that has some deviation in its center frequency and also in its span. For example, an EW system may jam the wrong frequency band reducing its effectiveness and its coexistence capabilities.



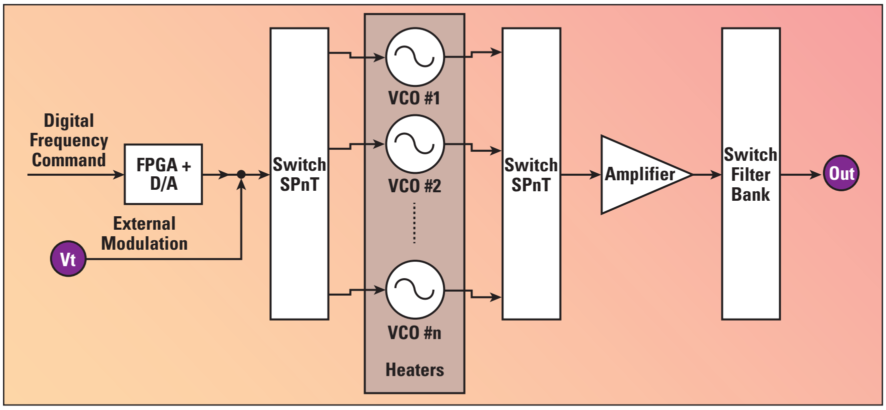
▲ *Fig. 3 VCO simplified schematic.*



▲ *Fig. 4 MSR effect on frequency span.*



▲ *Fig. 5 MSR effect on center frequency.*



▲ *Fig. 6 Multi-octave DTO conceptual block diagram.*

Frequency modulation span is defined as the maximal frequency span that a VCO may cover when driven by a modulating signal. With VCOs there is no actual limit to the span and a VCO can support WBFM starting at its lowest frequency and ending at its highest frequency. For example, a 4 to 8 GHz VCO will support modulation with a span up to 4 GHz. As will be shown later, this is not the case for other devices.

Modulation frequency bandwidth is defined as the maximal modulation frequency or modulation rate that may be applied to the modulation control pin before the span droops by more than 3 dB. For example, a VCO is being modulated by a very slow changing control voltage to generate a 1 GHz span. The control voltage is then changed to be a fast sine-wave. The frequency of this control voltage is increased until the span starts to become less than 1 GHz. The frequency that causes the span to be 707 MHz is the 3 dB modulation bandwidth. A typical value for a VCO would be 250 MHz.

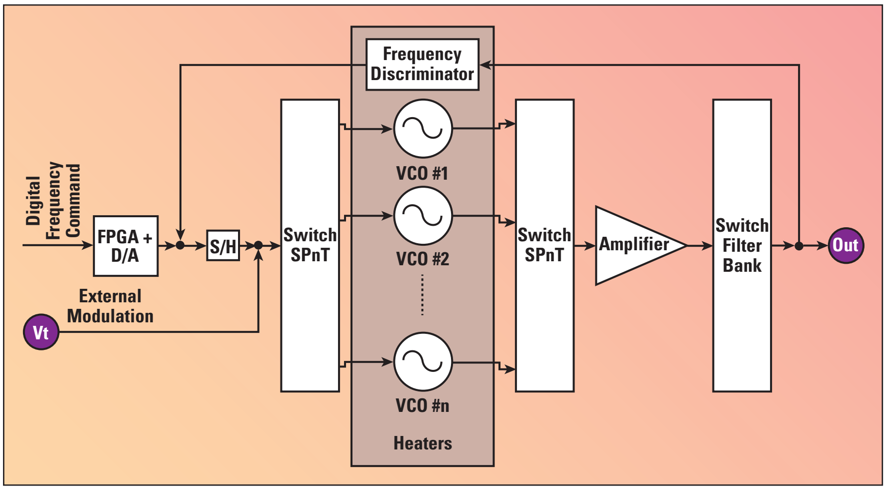
Digitally Tuned Oscillator

Since the VCO requires the user to prepare a look-up-table in order to know what voltage to apply to get the desired output frequency, a more convenient approach is to have this look-up-table stored within the module. This allows the user to input a digital command and the pre-calibrated information is used to generate the correct frequency. Since the transfer function of a VCO is greatly dependent on the temperature, a heater connected to the VCO is used to produce a constant VCO temperature. For supporting frequency ranges of more than an octave, several VCOs may be housed within the same DTO. The basic block diagram of a multi-octave DTO is shown in ***Figure 6***. The main advantages of the DTO are its multi-octave frequency range and its relatively low price. The main DTO disadvantage is the need for an elaborate calibration process.

When modulating the DTO by the external modulation signal, only one of its internal VCOs is being modulated and therefore the modulation span is limited. The same problems of changing modulation spans and shifting center frequencies with different modulation voltages exist when using a DTO as well.

Frequency Locked Oscillator

To improve the frequency accuracy of a DTO, a correction circuit is used. The output signal is sampled and its frequency is measured with an accurate frequency discriminator. The output of the discriminator is used as feedback to the tuning voltage of the VCO. The VCO is said to be frequency locked and its accuracy is as good as the discriminator's ability to measure frequency. When commanded to jump to a new frequency, the FLO's control circuit applies a tuning voltage to the VCO according to its internal look-up-table. This is



▲ *Fig. 7 Multi-octave FLO conceptual block diagram.*

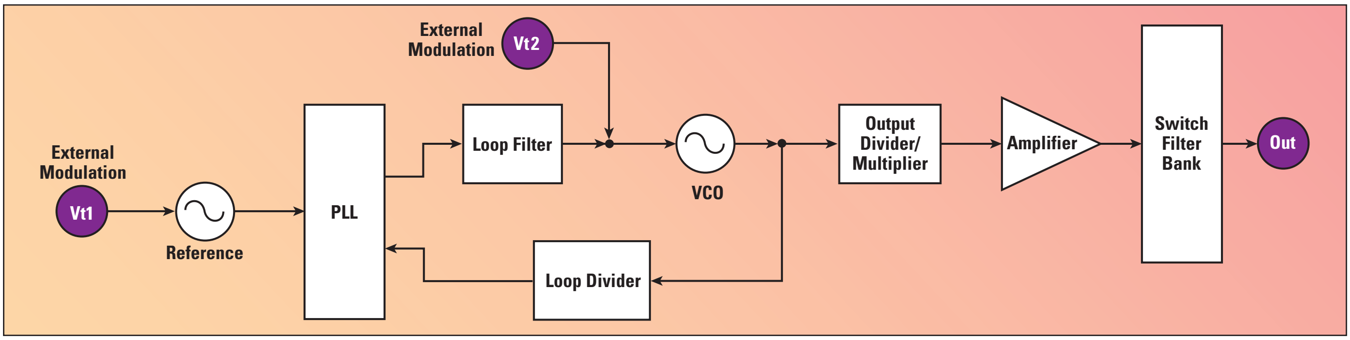
called a "DTO Mode" since this is exactly what is being done in a DTO. Once the VCO converges to the vicinity of the final frequency, the discriminator reading is connected with a closed loop to the tuning voltage in order to achieve enhanced accuracy. This is called "FLO Mode". As with the DTO, the FLO output signal may be modulated. For NBFM the module can still be in "FLO Mode" during the modulation and the center frequency accuracy is guaranteed. However, for WBFM the frequency locked loop must be opened (due to the limited BW of the discriminator) and the module works in a "DTO Mode" with reduced accuracy. Usually, for the same frequency range of operation, the FLO is larger and more expensive than a DTO. The basic block diagram of a FLO is shown in ***Figure 7***.

Fast Indirect Synthesizer

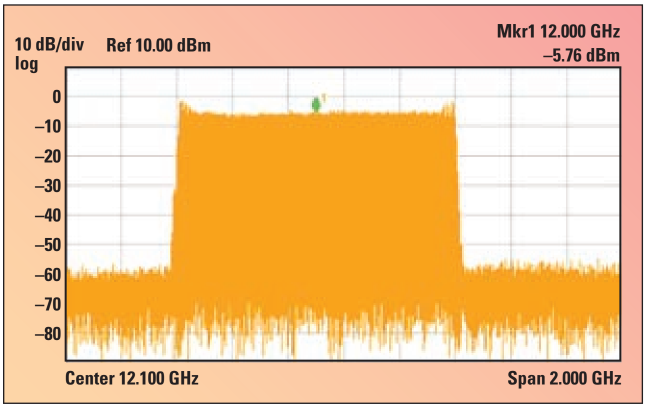
A cost effective solution for generating wideband signals is the indirect synthesizer. With the indirect synthesizer the VCO is phase-locked to a reference oscillator. That is why the indirect synthesizer is also known as a PLL based signal generator. The frequency accuracy of the output signal is the same as the reference signal used to lock the synthesizer, and is several orders of magnitude better than all the previously described solutions. The basic block diagram of an indirect synthesizer is shown in ***Figure 8***.

The indirect synthesizer has been widely used in the market for many years and is successfully supporting many non-modulated frequency applications. To add modulation ability to the indirect synthesizer, there are several approaches.

NBFM techniques: Two major techniques are commonly being used. The first is to inject the modulating



▲ *Fig. 8 Indirect synthesizer conceptual block diagram.*



▲ *Fig. 9 Model SM6220 spectrum plot.*

voltage directly to the tuning voltage of the VCO. This solution is effective as long as the modulating signal is a relatively higher frequency than the loop BW (also known as AC coupling). Otherwise the loop will be able to detect and remove this modulation. The second technique is to modulate the reference signal to the PLL. This technique is effective as long as the modulating signal is within the loop BW so that the loop will cause the VCO to follow the changing frequency of the modulated reference. Other methods are also being used, such as hybrid methods (two and three point modulation) but they are behind the scope of this article.

WBFM techniques: Two major techniques are commonly used. The first is to use the PLL in order to jump to the new center frequency, then to keep the tuning voltage to the VCO at a constant value (e.g., by a S/H) and inject the modulating voltage directly to the tuning voltage. This technique is called "DTO Mode" since the loop is open during the modulation and the VCO is actually in free running mode. This technique suffers from all the drawbacks explained previously for the "DTO Mode" in DTOs and in FLOs.

The second technique is to use a "pure locked mode" (PLM). Using PLM the reference signal to the PLL is modulated and the synthesizer is always locked, similar to the NBFM case. This technique is very challenging due to the fact that the loop elements of the PLL need to support extremely high rates of voltage changes (both voltage and frequency). But the advantages of the PLM are quite clear, perfect center frequency and well known modulation spans, without the need for factory or customer calibration. The PLM supports modulation waveforms from DC to high rates (DC coupled).

PRODUCT EXAMPLE

There are many benefits of using the indirect synthesizer technology to generate WBFM especially when using it in PLM. The Model SM6220, offered by General Microwave Israel (GMI), is a 2 to 20 GHz synthesizer that has a very fast settling time; less than 1 micro-second. This settling time is guaranteed for any jump between any two frequencies, including end-to-end. The SM6220 is also capable of WBFM in PLM with up to a 1 GHz span. The 1 GHz span can be located anywhere within the 2 to 20 GHz range (no "sub-bands"), thus enabling continuous coverage. The 3 dB modulation bandwidth is 10 MHz. A spectrum plot of a 1 GHz WBFM span is shown in **Figure 9**. This state-of-the-art product is compared to other solutions in **Table 1**. ■

TABLE 1
COMPARISON OF MODELS THAT SUPPORT WBFM

Model	V6120A	D6218	FL6218	SM6220
Technology	VCO	DTO	FLO	Synthesizer
Frequency Range (GHz)	12 to 18	2 to 18	2 to 18	2 to 20
Settling Time (µs)	1	1	1	1
Modulation Span (GHz)	6	0.5	1	1
Modulation BW (MHz)	250	10	10	10
WBFM Mode	Free Running	DTO Mode	DTO Mode	PLM
Steady State Accuracy	±4 MHz	±2 MHz	±1 MHz	±200 kHz

ACKNOWLEDGMENTS

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INVITED PAPER

Silos of Inefficiency: Overcoming Closed RF Design and Development Practices

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Within the defense industrial base, adherence to standards such as IEEE and ISO are nothing new. However, there has been little standards-based activity born out of defense; nearly all standards activity emanates from the commercial sector. This is not surprising, since much of the work within defense electronics is centered on platforms designed to meet very specific applications, where standards-based solutions are difficult to design, engineer and develop. This is especially true within RF and microwave-based defense applications where, to date, little to no progress has been made in developing electronic warfare (EW) applications based on open systems architectures (OSA).

How did it get this way? Historically, each branch of the armed services would typically develop their own systems for specific platforms. Even worse, systems on similar platforms in each branch were often incompatible. One explanation for this "siloed approach" was that different platforms targeted different threats, an argument still used today in many circles. However, regardless of the platform, the mission is really the same: controlling the electromagnetic spectrum, which requires RF and microwave technology.

This article outlines a new vision for an OSA approach within the RF and microwave industry, explores the need for such an architecture, discusses what it will take and ways it can be implemented.

BREAKING DOWN THE SILOS

The stovepipe approach completely contradicts the U.S. Department of Defense's (DoD) mandate that all systems move toward open architectures in order to lower costs and facilitate ongoing upgrades to essential electronic systems, so they remain on the cutting edge of technology. In 2013, then Deputy Secretary of Defense Ashton Carter opined in the DoD Electromagnetic Spectrum Strategy, "DoD systems must become more spectrally efficient, flexible and adaptable, and DoD spectrum operations must become more agile in their ability to access spectrum in order to increase the opportunities available to mission planners." In essence, that means systems must be designed so they can be reused or repurposed for various missions and platforms. That means scaling systems from surface vessels, long-range bombers, armored vehicles and strike aircraft to remotely piloted vehicles (RPV). As RPV use increases, the systems must be scaled down in size, weight, power and cost (SWaP-C), as well as adapt to mission parameters and the ever-evolving threats from adversaries. In order to realize the DoD's vision, the next steps in eliminating silos must mimic the commercial industry's recent rapid advances in cellular network, smartphone and other technologies.

To simplify the discussion, the focus here will be on a single domain: cellular networks. The use of mobile devices has exploded over the past decade, and today they are used in virtually every aspect of life. Their rapid adoption was accelerated by an infrastructure designed to support the vast amounts of data being communicated. At the heart of this infrastructure are RF and microwave transmitters and receivers. While the RF equipment may have different frequencies, the same essential building blocks are used across the network, in a sense providing multi-function RF equipment in a system. Providers use common equipment with tailored software to add user features and

ensure quality of service (QoS). Software-defined radios (SDR) are used to adapt to various protocols. The use of SDR equipment allows software to be easily uploaded to address features needed in order to scale or adapt a system.

Another important aspect that leads to the rapid deployment of the infrastructure that supports all of these disparate devices is the use of common control and data transport protocols, such as Ethernet. In summary, common, modular "building blocks" are used throughout the system. Multifunction RF building blocks provide the heart of the communication between mobile devices and the base stations. The flexibility and adaptability around the commercial equipment controlled by common software protocols led to the deployment of a scalable, cohesive and affordable solution for the telecommunications industry (see ***Figure 1***). This type of system is essentially an open systems architecture approach.

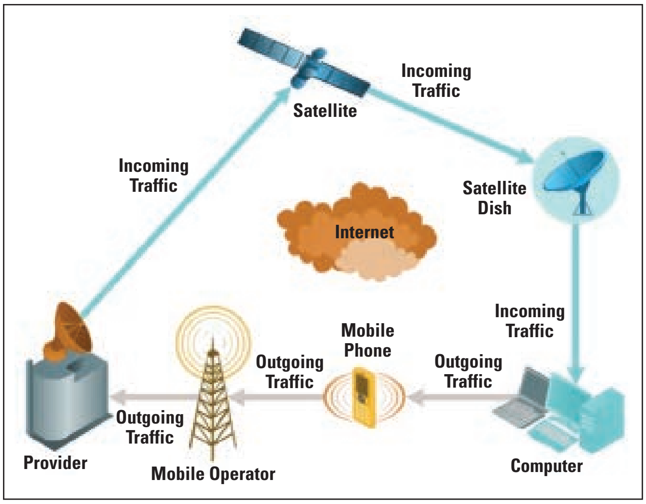
OPEN SYSTEMS ARCHITECTURE FOR RF/MICROWAVE

Why would an open systems architecture be valuable to the RF and microwave industry supporting the Department of Defense? There are several major reasons:

- Provides scalability for common hardware blocks
- Reduces integration schedules
- Reduces program risk
- Provides maximum flexibility and rapid adaptability
- Eliminates duplicate efforts
- Restores productivity and creates an ecosystem of affordability

Scalable hardware building blocks provide the framework for any open architecture. The real key is to have a common framework that also provides adequate freedom for creative developments within the framework. Reducing the time developers need for integration is essential in any open architecture. This reduction in the integration schedule mitigates program risk caused by using known intellectual property. The flexibility of using a common infrastructure allows new technologies from new or previously unused companies to be inserted rapidly into various systems. This flexibility provides a new level of adaptability for enhancing and maintaining a system. The aforementioned benefits all lead to a reduction in duplicate, custom efforts. The reduction of duplicate efforts leads to a new level of productivity and yields maximum affordability for developers within the ecosystem. All of these points are evident in the wireless infrastructure example from the previous section. Given this, how can an open systems architecture approach to RF and microwave be implemented to provide these benefits to the DoD?

Developing an open systems architecture requires working with existing standards. Open architectures such as OpenVPX (VITA 65) have brought rapid integration of digital subsystems under common hardware and software protocols into the realm of the possible. Of course the ecosystem did not develop overnight. OpenVPX started as an architecture and turned into a high-level system specification defined by common modular hardware. The system specification enables scalability and flexibility at the system level. The next step is to bring RF/microwave (RFM) into this ecosystem. This seamless integration of RFM into consolidated systems provides the first step to a new era of multi-function systems.



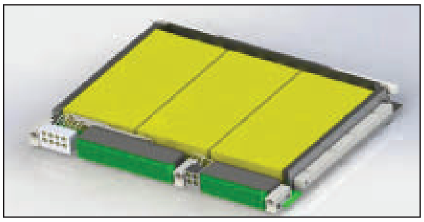
▲ *Fig. 1 Wireless network infrastructure.*

This is the intent of Mercury Systems' proposed OpenRFM™ initiative – an affordable, modular open systems architecture that standardizes the electromechanical interfaces and control planes to drive affordability, ease of integration and interoperability within the RF/microwave domain. It is ideally suited to EW applications. Its modular approach and leverage of commercial technology enables scalability, adaptability, high channel density and export features.

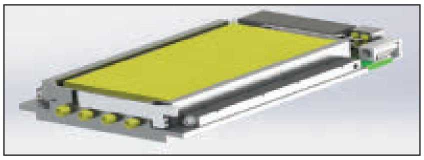
OpenRFM MODULE PARAMETERS

To begin the OpenRFM architectural design, a mechanical structure and connectivity must first be developed. To enable a scalable architecture from 6U OpenVPX to 3U OpenVPX, a mechanical volume that permits use in both ecosystems must be adapted. The concept of supporting both ecosystems is shown in ***Figures 2*** and ***3***.

Starting with the smallest common denominator, the module must have an outline that fits within 2.7 × 5.6 inches. The height may vary depending on the module design but must not violate the pitch set forth by the existing VITA standards. The next step is to define the electrical connectivity for power and control. The architecture uses a very high-speed connector with an abundance of connections for power and grounding. The connector must be capable of high data rate signaling, such as set forth in the JESD204B standards, be rugged and easily placed by automated manufacturing equipment.



▲ *Fig. 2 6U OpenRFM payload.*

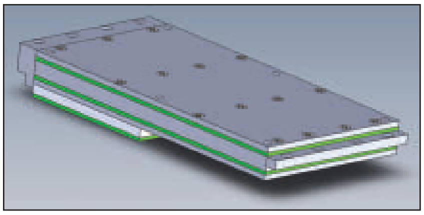


▲ *Fig. 3 3U OpenRFM payload.*

The control signals to the OpenRFM modules have to serve a myriad of purposes. There must be a low-speed diagnostic type path for module identification and basic operational parameters as well as a high-speed path to provide a standard control and data path. The high-speed control and data path used for OpenRFM is a multiplexed address and data path, used to preserve signals and to provide general purpose input-output (GPIO) signaling to the RFM module. A small complex programmable logic device (CPLD) within the OpenRFM module is sufficient for more complicated modules requiring many control signals. The power rails provided to an OpenRFM module are standard voltages such as 5 V and 3.3 V. The OpenRFM connector also provides some modules with power directed at RFM circuitry. The voltages are ± 8.5 V and an adjustable low voltage supply for special biasing and control circuitry.

To allow direct control of the OpenRFM module's RF circuitry, a hardware abstraction layer has to be developed to enable control from various protocols, such as Ethernet, PCI Express or Serial RapidIO. These are all control or data protocols within the VITA standards outlined for OpenVPX. The hardware abstraction layers can be implemented by various circuits. In a fashion similar to the use of SDR for easy upgrades in a wireless network infrastructure, a system on a chip (SoC) device is used in the OpenRFM architecture to enable protocol agnostic communication. Developing a hardware abstraction layer also relies on a level of software sophistication to prevent bottlenecks in control and status of an OpenRFM module. The application program interface (API) is used to simplify the application level software access to the OpenRFM modules. This RFM "middleware" provides a common software interface to OpenRFM modules, enabling easy system integration of RFM modules into a system.

The OpenRFM architecture does not restrict any RF or microwave circuitry within the modules. This allows RFM designers to be as creative as needed to solve the system problems for communication through the electromagnetic spectrum (EMS). The OpenRFM module (see ***Figure 4***) can consist of any RFM assembly – from a high frequency receiver, transmitter, local oscillator generator or power amplifier to a complete SDR with data conversion by an analog-to-digital converter (ADC) or digital-to-analog converter (DAC). The only restrictions are the power consumed within the module. An exact number has not been set for the OpenRFM module; as the architecture matures, the power within a module will be confined by the VITA standard in which it resides. The modules are designed to be compliant to the VITA 48 – VPX ruggedized enhanced design implementation (REDI) specifications.



▲ *Fig. 4 Typical OpenRFM module.*

CONCLUSION

The proposed OpenRFM approach is the first step toward enabling a new, affordable open systems architecture in the DoD RF/microwave industry. Breaking down the siloed approach to design and following the open approach used in the commercial industry should enable the rapid deployment of a multi-function RFM ecosystem that can tackle even the toughest problems. The mechanical envelope and electrical connectivity enables a flexible and scalable architecture. The hardware abstraction layer and RFM middleware provide a highly adaptable architecture that will address the next level of sophistication in DoD RFM systems. This flexibility, scalability and adaptability should provide the means to reduce duplicate custom design efforts and enable maximum productivity and a new level of affordability. Equally important, this approach aligns with the DoD directives to lower costs and increase the ability to rapidly and continuously upgrade critical defense electronics systems, thereby keeping pace with emerging EW threats. ■

Signal and Spectrum Analyzer for Long Radar Pulse Sequences

Rohde & Schwarz
Munich, Germany

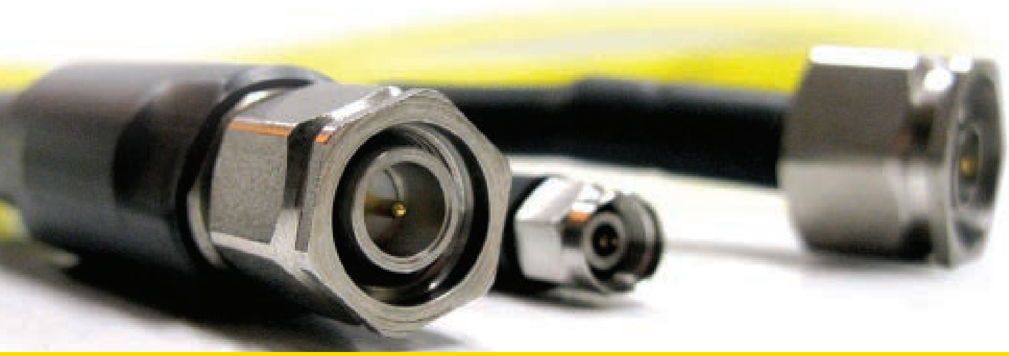
Pulsed radar systems transmit high power signal pulses followed by a pause during which echo signals are received. In many pulsed radar systems, the radio frequency of the emitted pulses remains constant, while the pulse repetition interval (PRI) and the pulse width (PW) vary.

The PRI determines the unambiguous range; the longer the PRI, the higher the unambiguous range. The width of an unmodulated pulse determines the minimum distance to the target and the range resolution. Shorter pulses allow detection at shorter distances and improve the range resolution, i.e., to resolve objects as separate items, but they require more spectral bandwidth. Longer pulses emit more energy per pulse and therefore reach higher ranges.

PULSE ANALYSIS

Spectrum analyzers have become the tool of choice for analyzing radar signals. They provide a wider frequency range than oscilloscopes and allow detailed in-pulse measurements of phase and frequency, which cannot be achieved by simple, power-based pulse analyzers. Spectrum analyzers have made huge leaps in bandwidth analysis over recent years. The R&S FSW signal and spectrum analyzer from Rohde & Schwarz now features up to 2 GHz bandwidth analysis and a frequency range of up to 67 GHz. This makes it possible to analyze even very short pulses.

To analyze radar signals in the modern world the R&S FSW signal and spectrum analyzer needs to offer flexibility. For instance, marine and air surveillance radars regularly change their operation modes. They use different PRI and PW in search mode, acquisition mode or tracking mode where different trade-offs between measurement accuracy, minimum and maximum range and range resolution are required. Further techniques include modulation of



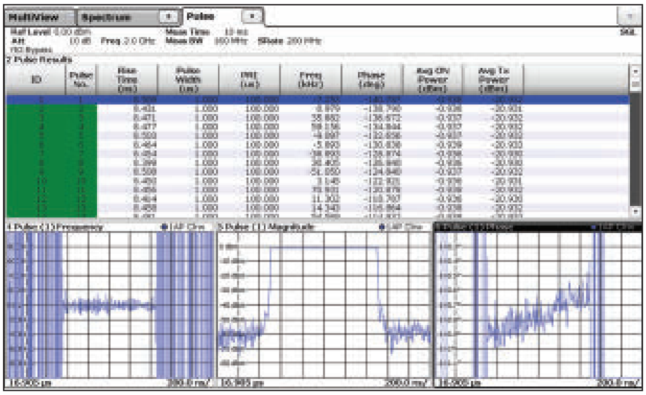


Fig. 1 *Result table of the R&S FSW-K6 pulse analysis software, displaying key parameters for each pulse, such as rise time, pulse width, PRI and frequency.*

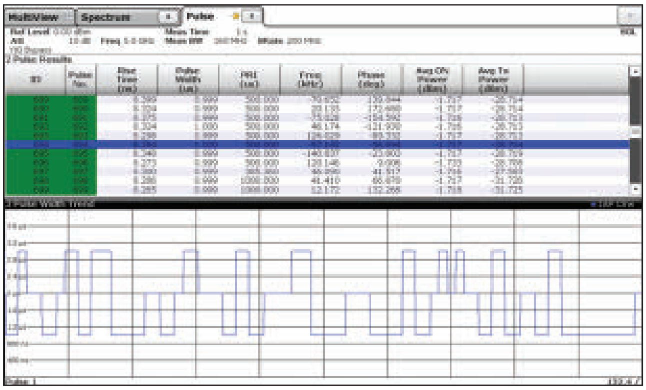


Fig. 2 *Display of 20s capture time, revealing that the analyzed radar system operates in three different modes.*

phase or frequency during a pulse, which encompasses pulse compression.

For development, optimization and troubleshooting of radar transmitters, pulse trains have to be characterized over long periods. To detect sporadic events or small but continuous effects like temperature drifts, it is desirable to contiguously capture and observe all emitted pulses over a period of up to several minutes.

Furthermore, a common means of influencing radars is range gate pull-off. The radar pulses are recorded and played back delayed, at higher power and probably with a changed pulse shape or frequency than for the naturally scattered pulses from the subject aircraft. The other radar receiver may lock onto the stronger echo return and the resolution cell eventually moves completely away from the subject aircraft. If the play-back is then suddenly stopped, the other radar receiver needs to readjust the leveling and go back through search, acquisition and tracking mode again. Development and optimization of such intelligent influencing techniques and countermeasures also requires the recording and analysis of long radar pulse sequences.

To address such issues, features such as rapid identification of spurious emissions, low phase noise and extensive pulse analysis functions running as software tools on the analyzer provide in-depth signal analysis possibilities, making the R&S FSW an essential tool in the development and production of radar systems.

Figure 1 shows the result of an analysis of radar pulses with the R&S FSW equipped with the R&S FSW-K6 pulse analysis software. Pulses of 1 µs width with a PRI of 100 µs were captured at a 200 MHz sample rate. The table highlights the pulse of interest and displays key parameters for each pulse such as rise time, pulse width, PRI and frequency. The graphs show frequency, magnitude and phase versus time of a single pulse. The analysis software allows further in-depth analysis of pulse parameters such as rise and fall times, dwell time, settling time, overshoot and undershoot.

SEGMENTED CAPTURE

The required high sample rate in combination with a limited capture buffer, however, reduces the total seamless capture and analysis period. As a solution, the R&S FSW-K6 pulse analysis software has been equipped with efficient memory management for analyzing pulse trends over long periods. It is in the nature of pulsed signals that during pauses only noise can be received. This makes it possible to extend the total capture time by omitting the noise during pauses.

A simple but effective algorithm to increase the total observation period is to store and time-stamp I/Q samples over a user-defined period once a certain power level triggers the capture. In addition, a certain number of pre-trigger samples are also stored. All other samples are omitted until the next trigger event. With typical duty cycles of 1 percent, the maximum observation period can principally be extended by up to a factor of 100.

Practically, with 50 percent pre-trigger capture and a capture time per pulse of twice the pulse period, the maximum recording time is extended by a factor of 50. Lower duty cycles extend the maximum recording time even further. The segmented I/Q capture can be triggered by an external trigger as well as by an IF power trigger.

EVALUATION OF PARAMETER TRENDS

Capturing many consecutive pulses makes it possible to analyze parameter trends and track changes that occur from pulse to pulse. ***Figure 2*** displays the pulse width versus the pulse number over 20s capture time. This reveals that the radar system operates in three different modes (1, 2 and 3 µs pulse width), which appear in a random order. Without segmented capture, the maximum capture time for this signal at 200 MHz sample rate was only 2.3 seconds, not enough to see the pattern of different modes.

Segmented capture increases the total analysis period by omitting the pauses between pulses. Effects that occur over many pulses, like changing modes, become visible, making it easier to analyze complex radar systems with changing parameters.

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Handheld VNA Delivers Benchtop Performance to 40 GHz

Anritsu
Morgan Hill, Calif.

The Anritsu Microwave Site Master™, model S820E, is a handheld two-port cable and antenna analyzer designed for field use yet delivering benchtop performance. Five models covering 1 MHz to 8, 14, 20, 30 or 40 GHz are available. An optional VNA mode provides fully reversing S-parameter measurements. An optional vector voltmeter (VVM) mode, with standard A/B and B/A ratio capability, may be used as a drop-in vector voltmeter replacement.

Key specifications of the Site Master are:

- Dynamic range: 110 dB typical from 20 MHz to 40 GHz, 100 dB specified
- Sweep speed: ≤ 650 µs/point
- Frequency resolution: 1 Hz from 1 MHz to 40 GHz
- Simultaneous extended USB sensor transmission and error-corrected reflection measurements
- Field-proven design: explosive atmosphere MIL-PRF-28800F Section 4.5.6.3 compliant
- Coaxial and waveguide measurements
- USB/Ethernet connectivity, full remote control capability
- Intuitive, menu-driven 8.4 inch touchscreen with daylight/nighttime viewable modes
- Standard three-year warranty

Two decades ago, in 1995, the world's very first handheld one-port vector network analyzer was introduced by Anritsu. Considered unbelievable by many, the measurements were initially challenged until proven to be highly accurate and repeatable. That product still exists in many forms and is universally recognized as the de facto industry standard, known as Site Master.

The standard Site Master is ideal for applications up to 6 GHz. However, there are needs for higher frequency coverage. Until recently, no product on the market offered VNA capability beyond 26.5 GHz. The Anritsu S820E Microwave Site Master breaks through that barrier and delivers benchtop performance up to 40 GHz.

To understand how the S820E is capable of delivering up to 110 dB of dynamic range, even at 40 GHz, consider the advanced technology that is deployed inside the S820E. The traditional VNA is comprised of a source, transfer switch, couplers or bridges, and reference/measurement receivers. Measurements are typically down-converted to an intermediate frequency (IF), where the signal is processed. The most common method for conversion uses mixers. However, mixers typically do not have sufficient bandwidth to directly down-convert signals higher than just a few GHz. Higher frequency signals, which exceed the funda-

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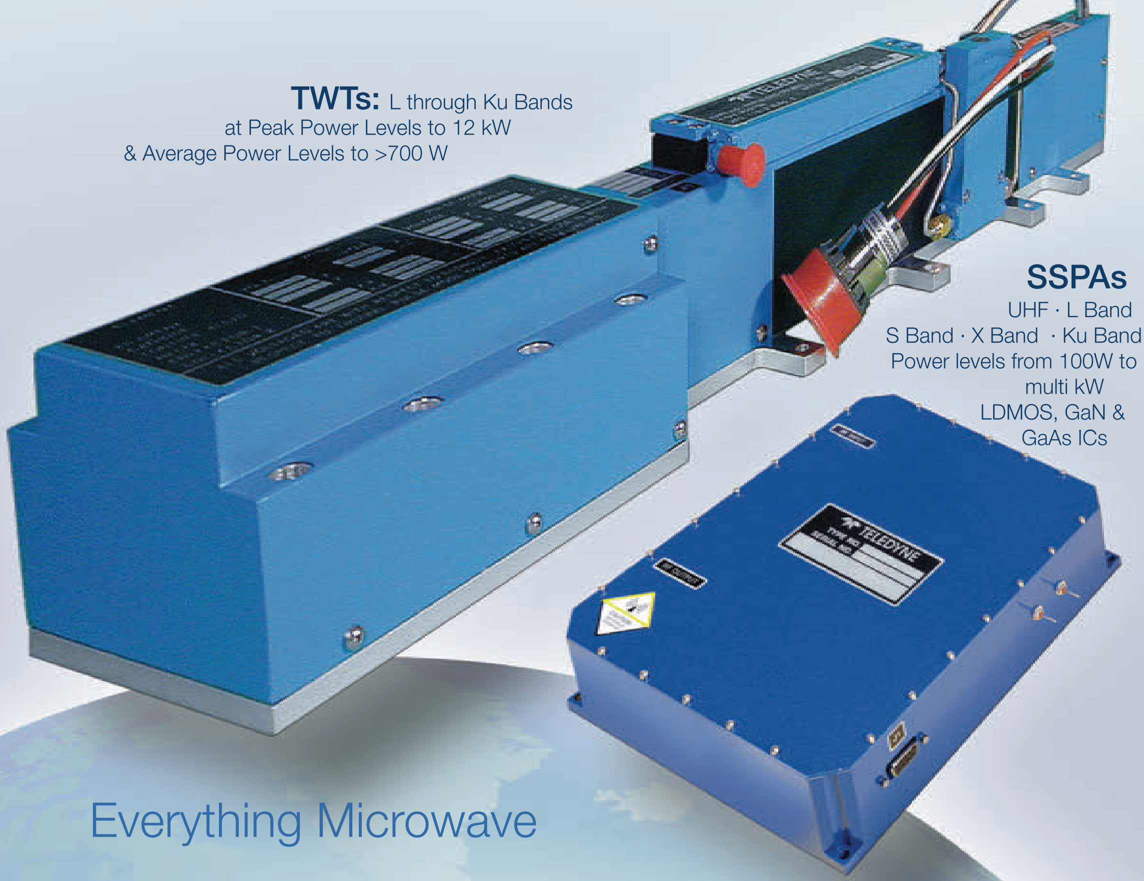

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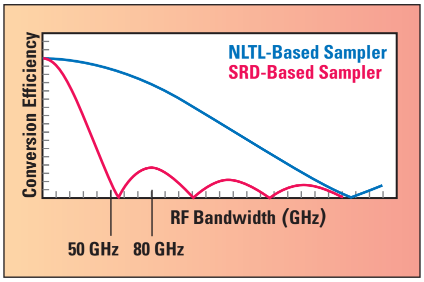
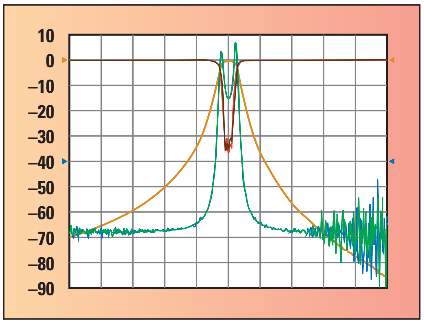


▲ *Fig. 1 The NLTL sampler exhibits much wider bandwidth than one using SRDs.*

mental mixer band, must be downconverted using harmonics of the mixer. The disadvantage is that the conversion efficiency rapidly declines as the harmonic order increases. The consequences are reduced dynamic range, elevated noise floor and often degraded sweep frequency resolution. Very large amounts of IF gain are required to compensate for the reduced conversion efficiency, often adding undesirable side effects, such as increased noise, higher nonlinearity, additional heat and thermal drift and increased power consumption. Mixers with good high frequency performance typically perform poorly at low frequencies, so the problem is simply shifted, not resolved.

An alternative method is a sampler using step recovery diodes (SRD). SRD samplers are widely deployed and offer many advantages over mixer-based methods. However, the SRD sampler method also suffers from declining down-conversion efficiency.

The most efficient down conversion method is the nonlinear transmission line (NLTL) sampler. Historically, it has been challenging to mass produce this technology with reasonable price and consistency. Anritsu engineers have successfully overcome these challenges with newly developed "VNA-on-a-chip" monolithic microwave integrated circuit (MMIC) devices. These devices are establishing new benchmarks in the high performance/price ratio for VNA instruments such as the S820E. These highly integrated MMIC devices have the performance advantages of NLTL technology and additional benefits, such as unmatched temperature stability and no degradation of frequency resolution. The extremely high conversion efficiency enables the S820E to deliver 110 dB of dynamic range up to 40 GHz. Since

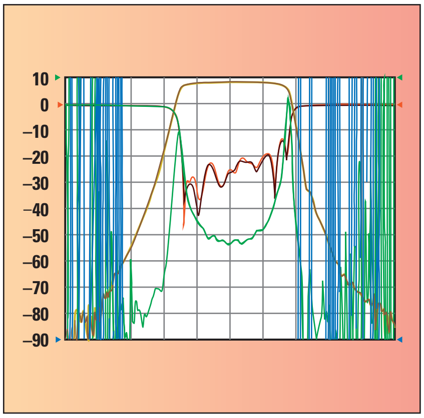


▲ *Fig. 2 S820E measurement overlaid with ShockLine measurement of a 1.95 GHz bandpass filter.*

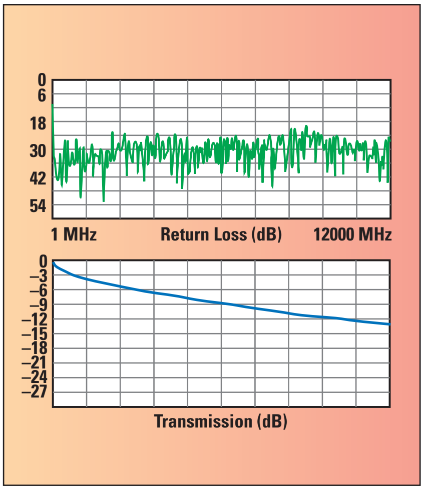
lower IF gain is required, longer battery life and better linearity are additional benefits. ***Figure 1*** compares the NLTL-based sampler technology to the SRD-based sampler.

Equipped with NLTL technology, the handheld S820E is able to correlate with Anritsu's premium VectorStar™ VNA and Anritsu's ShockLine™ series of benchtop VNAs with uncanny precision, bringing true benchtop performance from the lab to the field. ***Figures 2*** and ***3*** show examples of measurement correlation.

Although capable of providing benchtop quality measurements, the S820E is designed to handle the unique challenges of the field. Measurements on long transmission lines are a fine example, where the ends of the line are far apart and not reachable with conventional test port cables. Examples include communication or signaling cables that are embedded in aircraft wings or the fuselage, long waveguide runs in Navy vessels and satellite ground stations, and long microwave coaxial cable runs in the elevator shafts of high-rise office buildings. Historically, these measurements have been performed using scalar network analyzers (SNA). Detector modules could extend the transmission measurement capability using long extender cables, providing a scalar (magnitude only) response. S_{11} of the device being tested could also be measured using a calibrated auto-tester module. Today, VNAs have replaced SNAs for most measurements, and the SNA instrument is no longer readily available. Fortunately, the S820E can make these measurements with ease. Combining unique "USB Sensor Transmission" and vector error-corrected S_{11} measurement



▲ *Fig. 3 S820E measurement overlaid with VectorStar measurement of a WR28 waveguide 39.6 GHz bandpass filter. The slight variation is mainly due to the repeatability of the waveguide connection.*



▲ *Fig. 4 Simultaneous vector, error-corrected S_{11} (return loss) and USB sensor transmission measurements.*

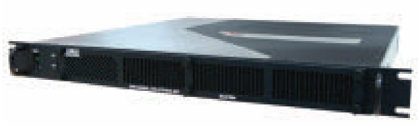
capabilities, the S820E measures both required parameters simultaneously with one user calibration. The USB sensor measurement is made using USB extenders. Anritsu provides a passive, plug-n-play USB extender kit. Users simply add a suitable length of CAT5e or CAT6 cable between the two USB extender modules. ***Figure 4*** shows a measurement example.

The Anritsu S820E is a rugged, handheld solution, allowing users to confidently make VNA measurements in the uniquely challenging field environment and achieve benchtop performance to 40 GHz.

VENDORVIEW

Anritsu
Morgan Hill, Calif.
www.anritsu.com

Eight-Channel Narrowband High Frequency Tuner Subsystem



DRS Signal Solutions
Germantown, Md.

Thousands of individual signals are present in the high frequency (HF) spectrum. Often, the most difficult problem is to discern and capture a small signal in the presence of large interfering signals. DRS Signal Solutions' SI-8728A HF tuner is a best-in-class RF front-end for receiving small signals in dense signal environments. The SI-8728A is operationally proven, with several hundred units deployed on program platforms.

The SI-8728A is capable of continuous 1 Hz tuning resolution over the frequency range of 100 kHz to 30 MHz, while each of its tuner channels provides an instantaneous IF bandwidth of 25 kHz. The SI-8728A's very high density design, high dynamic range, VITA radio transport standard precision time-stamped I/Q data and non-blocking switch options, coupled with an easy-to-use graphic user interface (GUI), make the unit a best-in-class HF tuner.

The SI-8728A provides up to eight digital HF tuner channels in a compact 1U rackmount chassis, half the size of the nearest competing unit. Its attractive low size, weight and power (SWAP) design includes a weight of less than 18 pounds and an internal power supply that accepts 100 to 250 VAC. This design and its extended temperature range of -20° to +60°C allow multiple units to stack for high-density systems.

With its eight channels, the SI-8728A can be remotely configured for independent or phase-coherent operation to support a variety of system applications. Possible applications for the SI-8728A include a high density HF monitor system, a phase-coherent tuner for super-resolution DF systems and a front-end for HF systems based on software-definable radio. The tuner provides flexibility to operate up to eight channels independently, up to eight channels phase-coherently or with a mix of some channels operating independently and the remaining phase-coherently. Simultaneous control of the SI-8728A's multiple tuner channels is controlled remotely using a Gigabit Ethernet interface and TCP/IP.

The SI-8728A features high dynamic range and low phase jitter. Amplitude and phase distortion within each channel are minimized as well as amplitude and phase mismatch among channels. The tuner is designed to expend very low emissions for operation in electromagnetic interference (EMI) sensitive environments. It may also be configured and used for precision direction finding and rapid signal analysis. A built-in self-test calibrator ensures that the unit functions properly.

Each channel's IF output is processed digitally and made available as baseband in-phase and quadrature-phase (I/Q) data. The

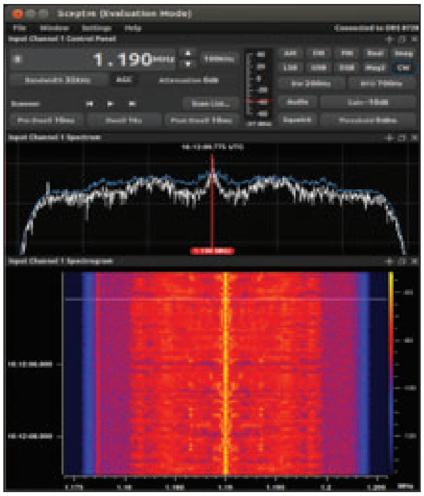


Fig. 1 *Graphical user interface for the SI-8728A.*

tuner features an analog-to-digital converter (ADC) that digitizes data that is passed to the digital signal processor (DSP), where it is filtered and decimated, resulting in a complex data output. The processed data outputs are packaged according to the packet structure of VITA 49.0 for output via the Ethernet interface. A real time clock is maintained for time-stamping the processed data. This clock may be synchronized to an external one-pulse-per-second (1 PPS) reference input.

The SI-8728A control GUI interface is simple to use and allows for easy signal detection, signal analysis, signal recording and digital playback. Its narrowband real time continuous fast Fourier transform (FFT) is shown with a spectral display and a waterfall display that depicts a spectrum's activity over time using color to indicate signal strength (see ***Figure 1***).

OPTIONS AND AUXILIARY EQUIPMENT

The 8728A/MULTI Switch Matrix option adds an 8×8 fully non-blocking matrix internal to the SI-8728A chassis. It allows any combination of eight antennas to be connected to any combination of tuner channels. The switch matrix is controlled through the same 1000Base-SX or 1000Base-T interface as the tuner, for ease in deployment. This switch matrix option limits its RF output power when a large RF input is applied, protecting sensitive RF input circuitry from high voltage transients and nearby lightning strikes.

Four SI-8728A units can be combined with one SI-9332, 32×32 HF fully non-blocking switch matrix. The SI-9332 receives up to 32 HF inputs in the 0.5 to 30 MHz range and provides up to 32 outputs. Any of the 32 SI-8728A channels can access any of the 32 SI-9332 inputs, allowing operational flexibility. The switch matrix provides near unity (0 dB) gain so that it is virtually transparent in system operation. The unit offers excellent intermodulation, noise figure and internal spurious performance.

DRS Signal Solutions
Germantown, Md.
www.drs.com

Compact 1 kW Power Amplifier for HF Applications

Delta-Sigma Inc.
Riverside, Calif.

While the focus today is primarily on devices, subsystems and systems for wireless frequencies, there are still many systems that operate within the HF band from 1 to 50 MHz. They include long-range radar, commercial and military communications, and scientific and industrial equipment, many of which require a combination of high RF output power and high linearity. As with their higher frequency counterparts, HF power amplifiers must be as small as possible to accommodate space constraints, while delivering rated performance with minimal cooling. The VEGA Series of RF power amplifier modules is designed to meet these requirements, delivering more than 1 kW CW in enclosures typically measuring only 4" × 2" × 1.2" and weighing about 1 lb.

The VEGA Series can be used either as standalone amplifiers or as building blocks in a higher power amplifier system controlled via RS-422, RS-232 or Ethernet. Delta-Sigma has used amplifiers in this series to create systems that deliver CW output power up to 4 kW over portions of the HF region and wider bandwidths.

The amplifiers achieve small size through a combination of very efficient, rugged LDMOS RF power transistors, low loss combining networks and precise impedance matching, using design techniques to achieve full rated RF output power with minimum heat sinking and external convection cooling. The amplifier's efficiency is between 65 and 68 percent depending on frequency, and it draws 27 A from a +50 V DC supply.

Over-temperature protection is integrated in the amplifier, and other protection circuits can be supplied depending on the requirements of the application. Key amplifier specifications include 26 dB gain, harmonic rejection up to -37 dBc, spurious rejection of -70 dBc and third-order intercept point of +69 dBm. More detailed specifications are shown in ***Table 1***. The gain, efficiency and return loss of a VEGA Series 1 kW RF power amplifier from 5 to 25 MHz are shown in ***Figure 1***.

Although they are specified for Class AB CW operation, the VEGA Series amplifiers are suitable for pulsed modulation, AM or FM and digital modulation schemes. Specifications can be modified to meet requirements from the standard broadband design to narrower or wider frequency ranges up to 230 MHz, RF output power, and mounting and connector types. The amplifiers can be specified to meet a variety of military specifications. One example is airborne operation, with an operating temperature range of -40° to +55°C, altitudes up to 10,000 ft., and shock and vibration per MIL STD-810F Method 516.5.

Other models in the series include:

- VEGA6 driver amplifier, delivering 6 W CW from 20 to 88 MHz or 20 W CW from 30 to 150 MHz or 1.7 to 30 MHz
- VEGA50, providing 50 W CW from 100 to 500 MHz
- VEGA100, with 100 W CW from 10 to 175 MHz
- VEGA150, delivering 150 W CW from 20 to 150 MHz
- VEGA200, providing 200 W CW from 30 to 88 MHz

The company has designed and manufactured solid-state RF power amplifiers that deliver extremely high power levels required for scientific and radar applications with RF

TABLE 1

TYPICAL VEGA SERIES AMPLIFIERS SPECIFICATIONS

Frequency range (MHz)	1.5 to 30
RF Output Power, CW or P1dB (W)	≥ 1000
Gain (dB)	26
Efficiency (%)	65
Harmonic Rejection Second (dBc) Third (dBc)	 -37.3 -13.3
Spurious Rejection (dBc)	-70
Third-Order Intercept Point (dBm)	+69
Return Loss (dB)	Input: -14 Output: -20
Switching Rise and Fall Times (ns)	200
Environmental Operating temperature Range (°C) Humidity (%) Altitude (ft.) Shock and Vibration	 -40° to +55° 95 non-condensing 10,000 Meets MIL-STD-810F Method 516.5
Operating Voltage, Current (VDC, A)	+48 to +52, 27
Dimensions (in.)	4.1 × 2.6 × 1.2
Weight (oz.)	17
Connectors	SMA Female (input), Type-N (output)
Protection	Over-Temperature

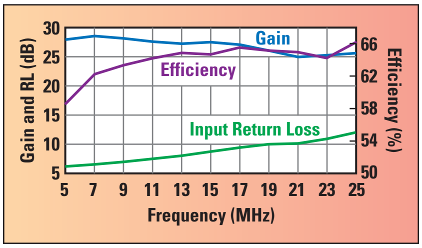
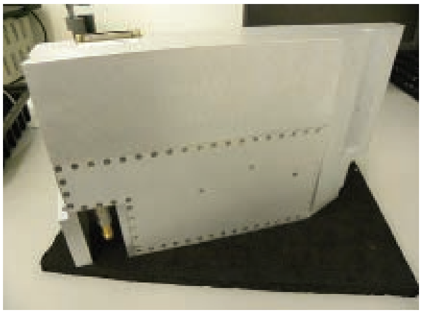


Fig. 1 Gain, efficiency and return loss of a VEGA Series 1 kW RF power amplifier.

outputs as high as 350 kW. A recent example is an amplifier system that powers the Doppler radar wind profiler (DRWP), recently deployed at the Kennedy Space Center. It consists of 20, 16 kW subsystems, each consisting of 10 hot-swappable LDMOS RF power amplifier modules for a total output per module of 2 kW. The subsystem can produce RF output power greater than 16 kW. The output of each subsystem is then combined to produce power up to 350 kW.

The DRWP power amplifier has a soft fail capability that allows it to continue to operate if one of the modules fails, after which a new module can be "hot swapped" for the failed one while the system is running. This quickly returns the system to full-power. Efficiency of the DRWP amplifier is about 75 percent, 45 percent from AC to RF output. The total combining losses for the entire amplifier system is only 0.3 dB, including the 40 final-stage transistors, absorptive lowpass filters, and a patented transmit/receive solid-state switch.

Delta-Sigma Inc.
Riverside, Calif.
www.111rfpower.com



1200 W, High Efficiency S-Band PA

Using GaN technology, Delta Microwave has developed a 1200 W high efficiency power amplifier (PA) for S-Band pulsed radar applications. The PA delivers a minimum of 1200 W across 2.9 to 3.1 GHz with 40 percent power-added efficiency and 45 dB minimum gain. The amplifier will handle pulse widths up to 100 µs and 10 percent duty cycle, with a maximum droop of 0.5 dB. Harmonics are -50 dBc maximum, and input VSWR is 2:1 or better. The signal interfaces to the PA are a female SMA at the input and female Type-N at the output.

The operating temperature range is -30° to +70°C, with integrated protection for over-temperature, high duty cycle and high pulse width conditions. The amplifier is biased with 32 V DC and includes over-current protection. SSPA includes internal microprocessor for TIA-485 data interface.

Delta Microwave
Oxnard, Calif.
www.deltamicrowave.com

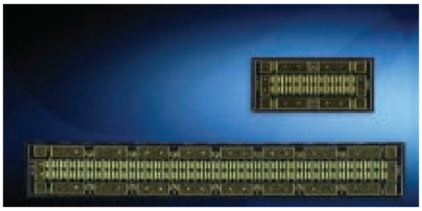
0.1 to 18 GHz, 80 x 5 Distribution Matrix

For airborne surveillance and similar applications, Custom Microwave Components offers a broadband distribution matrix that switches any of 80 octave-band inputs to any of five outputs (non-blocking). The output frequency range covers 100 MHz to 18 GHz. The signal path from input to output has a nominal gain of 0 dB with less than 14 dB noise figure. Leakage across any of the channels is less than 60 dB. Paths can be grouped into sets that amplitude and phase track. Channels can be selected within 2 μsec, and output blanking occurs in 100 nsec.

The 12U rack-mounted unit's environmental operating range is 0 to +55°C, up to 95 percent relative humidity, vibration meeting Mil-STD-810F Method 514.5 and 50,000 foot altitude.

First developed in 2003, the distribution matrix has a history of reliable service. The RF units are line replaceable, enabling field service and upgrades, if required. The design allows user-defined controls, which provides additional flexibility.

Custom Microwave Components Inc.
Fremont, Calif.
www.customwave.com



High Power 50 V GaN HEMT

Cree has extended its family of 50 V discrete GaN high electron mobility transistors (HEMT) with three new die products: a 320 W transistor, usable to 4 GHz; and 75 and 20 W devices, usable to 6 GHz. These three new products join two others – with 170 and 40 W output – to comprise the only 50 V GaN HEMT die product portfolio on the market.

The 320 W device is the industry's highest power 50 V GaN die product available. It typically provides 19 dB small-signal gain with 65 percent power-added efficiency at 4 GHz. The 20, 40, 75 and 170 W devices in the family operate to 6 GHz, with typical performance of 17 dB small-signal gain and 60 percent power-added efficiency. At 4 GHz, the devices deliver 18 dB small-signal gain with 65 percent power-added efficiency.

All devices in the family are fabricated with Cree's 0.4 µm, 50 V process and offer hybrid amplifier designers higher gain, efficiency and power density with wide instantaneous bandwidth. With its high breakdown voltage, thermal conductivity and saturated electron drift velocity, GaN is an effective alternative to silicon (Si) and gallium arsenide (GaAs). The 50 V product family is suitable for various market applications, including two-way private radio, broadband amplifiers, cellular infrastructure, test instrumentation, tactical and satellite communication and industrial, scientific and medical (ISM) amplifiers.

Cree's GaN HEMT die are supplied in Gel-Pak® Vacuum Release™ trays, a non-tacky membrane that immobilizes the components to ensure damage-free transportation and storage.

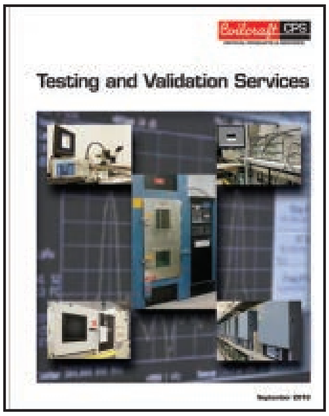
Cree Inc.
Durham, N.C.
www.cree.com/RF/Products/General-Purpose-Broadband-50-V

RF and Microwave Technology

VENDORVIEW

Anaren Inc. is a Syracuse-based, global leader in RF and microwave technology used in wireless infrastructure, satellite, defense and consumer-electronics applications. The company has approximately 1,000 employees and five state-of-the-art facilities worldwide. Product lines include: standard passive components (e.g., couplers, power dividers, baluns, resistors, attenuators, terminations), RF multichip modules, high-reliability softboard and ceramic PCBs, and complex assemblies (e.g., switching, beamformers, antenna feed networks, DRFMs, IMAs).

Anaren Inc.
www.anaren.com



Testing & Validation Services

Coilcraft Critical Products & Services (CPS) offers a full range of product testing and validation services to help electronics manufacturers determine the reliability, repeatability and/or compliance of the electronic components and assemblies they manufacture or procure. Coilcraft CPS's testing capabilities include vibration and mechanical shock to MIL-STD-202, as well as complete electrical testing, elemental analysis, radiographic inspection, thermal shock and cycling, and other environmental and analytical lab services.

Coilcraft CPS Inc.
www.coilcraft-cps.com/pdf/testing.pdf

RF and Microwave Products

CPI's Beverly Microwave Division (BMD) designs and manufactures a broad range of RF and microwave products for radar, communications, electronic warfare and scientific applications. BMD has been located in Beverly, Mass. since 1947. CPI BMD is the world's largest manufacturer of receiver protectors and magnetrons. They also manufacture TWTs, CFAs, transmitter assemblies, scientific systems, high-power solid state switches and switch assemblies, pressure windows plus a wide variety of multi-function components and integrated microwave assemblies.

Communications & Power Industries
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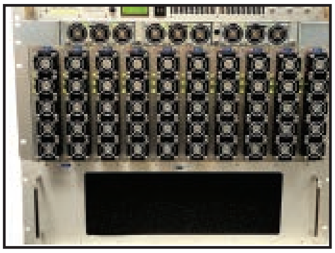
www.cpii.com/bmd

Power Amplifiers Catalog

CTT announced a new four-page power amplifiers short form catalog. The catalog features more than 75 models developed for radar, EW and multi-function systems design. The amplifiers feature narrowband CW, narrowband pulsed, wideband (CW) and ultra-wideband (CW) coverage. Frequency coverage is 0.1 to 18 GHz. CTT's family of solid-state amplifiers are finding applications in many of the next generation of high-performance communications, instrumentation and medical systems where high power is required.

CTT Inc.
www.cttinc.com



High-Power Amplifier Showcase

Delta-Sigma Inc. has expanded its website with greater detail about its custom high-power RF amplifier modules, subsystems and complete systems (such as the 16 kW amplifier shown) for commercial, medical and scientific applications. The site describes the company's ability to design and manufacture unique RF power amplifier systems that combine high efficiency and linearity in compact footprints with CW or pulsed RF power output from 1 kW to more than 250 kW at frequencies up to 3 GHz.

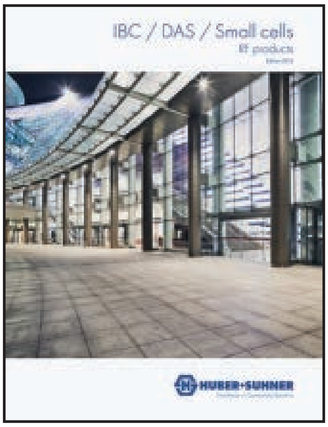
Delta-Sigma Inc.
www.111rfpower.com

RF Relay Switches

Fairview Microwave recently debuted a new portfolio of electromechanical RF relay switches that cover ultra-broadband and millimeter wave frequencies up to 40 GHz. These high-reliability RF switches are guaranteed to perform up to 2 to 10 million life cycles, which make them an ideal solution for demanding industries and applications related to military/defense, aviation, radar, wireless communications, satellite communications, and test & measurement. Available in multiple varieties from SPDT (Single Pole Double Throw) to SP12T (Single Pole 12 Throw) and designed with either SMA, Type-N or 2.92 mm depending on frequency range.

Fairview Microwave
www.fairviewmicrowave.com

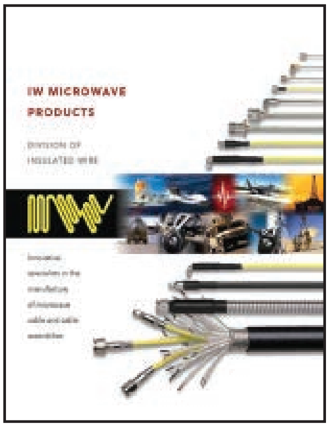
COMPANY SHOWCASE



IBC/DAS/Small Cells Catalogue

When it comes to availability and quality of wireless data communication services, the high coverage requirements apply equally both outside and inside buildings. With the implementation of dedicated solutions like distributed antenna systems (DAS), additional capacity for voice and data channels can be created as required. The HUBER+SUHNER IBC/DAS/Small Cells product catalogue contains a wide range of radio frequency solutions that support all applications in the deployment of the mobile communication network in urban environments. Visit HUBER+SUHNER's microsite at www.wireless-infrastructure.com/solutions for a closer look.

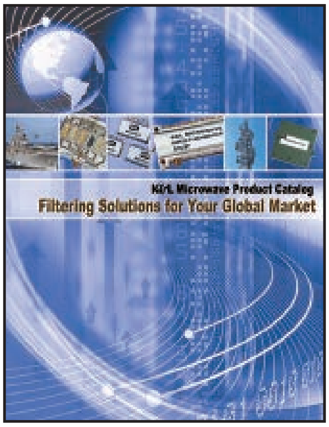
HUBER+SUHNER
www.hubersuhner.com



New 2015 Catalog

IW presents their new catalog for 2015. The latest edition features a new data sheet format with increased technical content including tabulated and graphical data for all cables including stranded center conductor, expanded Re-Flex™ options, attenuation values in dB/m, useful cable handling instructions and new product specifications – IW introduces 0471, 170 series and RF250 following customer demand for smaller diameter cable, improved attenuation and extended frequency range for SATCOM applications, and the most versatile RG401 replacement available, respectively. IW – We're Flexible!

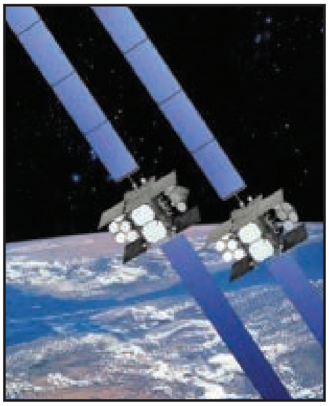
Insulated Wire Inc.
www.iw-microwave.com



2015 Product Catalog

K&L designs and manufactures a full line of RF and microwave filters, duplexers and subassemblies, including ceramic, lumped element, cavity, waveguide and tunable filters. The catalog shows filter responses, loss calculations and standard packages for all products. K&L supplies many of today's most significant military and homeland security electronics programs. Applications include space flight, radar, communications, guidance systems, mobile radio base stations as well as air traffic control and communications. Visit www.klmicrowave.com to download the complete catalog.

K&L Microwave
www.klmicrowave.com



Success in NewSpace

The space industry is in the midst of dramatic change. NewSpace is driving disruption that hasn't been seen since the original space race in the 1960s. Developing new strategies, processes and requirements – especially those associated with electronic design, development and production – will be critical to working in NewSpace. Keysight's latest white paper, "Utilizing Commercial Best Practices for Success in NewSpace," describes the challenges that these business models put on electronic design and test strategies and processes.

Keysight Technologies Inc.
www.keysight.com/find/satellite-focus

Indirect Synthesizer with Frequency Modulation

Kratos General Microwave enhanced its family of indirect synthesizers with the addition of model SF6218 with frequency modulation capability. It can provide a frequency deviation of 1 GHz at up to a 10 MHz rate and can be controlled with either analog or digital inputs. Of special significance, the synthesizer output frequency remains fully locked even while in the FM mode. Its small size and high reliability make it ideal for use in demanding airborne environmental conditions as well as test systems.

Kratos General Microwave Corp.
www.kratosepd.com/solutions/kratos-general-microwave

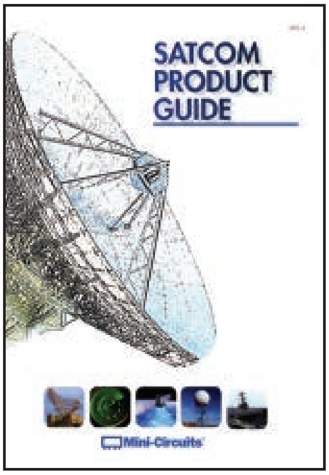
Advanced Microelectronics Centers

Mercury's Advanced Microelectronics Centers offer state-of-the-art design and manufacturing for RF and microwave components and subsystems. They offer capabilities designed to reduce costs and drive affordability. Highlights include: streamlined supply-chain with one-stop shopping from design through manufacturing, decreasing supply-chain complexity, significantly reducing risk; world-class automation – from production through testing – lowering costs; co-located design and manufacturing engineering assets to optimize on-board and build-to-print work; plus redundant, state-of-the-art manufacturing capabilities scale from design to full-rate production. ISO 9001 certified.

Mercury Systems Inc.
www.mrcy.com

AEROSPACE & DEFENSE ELECTRONICS

COMPANY SHOWCASE

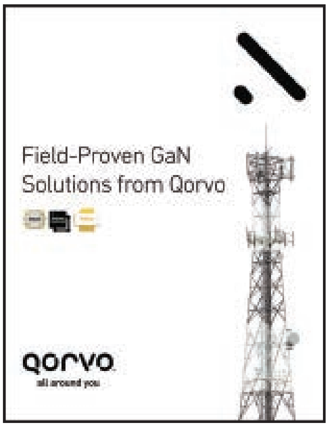


SATCOM Product Guide

VENDORVIEW

Mini-Circuits has released a new SATCOM product guide in print and for download from their website. This 32-page guide features a full survey of components and assemblies for satellite and earth station systems. With selected products from over 20 different product types to 40 GHz, the guide provides key performance parameters for each product and serves as a handy reference for engineers evaluating parts for their design needs.

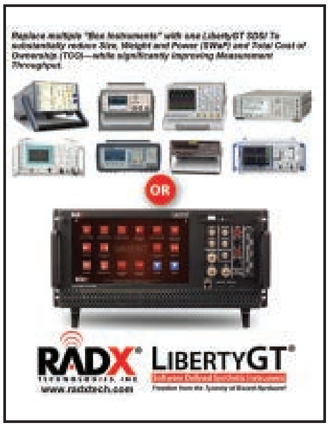
Mini-Circuits
www.minicircuits.com



Field Proven GaN Solutions

Qorvo's high-performance GaN technology supports products from DC through Ka-Band for military and commercial applications. Qorvo continues to build on its 15-year GaN legacy of innovation and reliability by offering new products and foundry services that strive to meet their partners' demanding system requirements. Their partners benefit from the 'trusted' supplier status and MRL-9 classification. Only Qorvo delivers performance, quality and reliability that sets the standard in the industry. For more information visit www.qorvo.com/defense.

Qorvo Inc.
www.qorvo.com/defense



RADX LibertyGT 1211B

Replace multiple "box instruments" with one LibertyGT SDSI to substantially reduce size, weight and power (SWaP) and total cost of ownership (TCO)—while significantly improving measurement throughput. The RADX® LibertyGT® 1211B is a modular, COTS, multifunction, programmable, upgradable software defined synthetic instrument (SDSI®) that supports a broad range of real time RF and microwave stimulus, test and measurement applications.

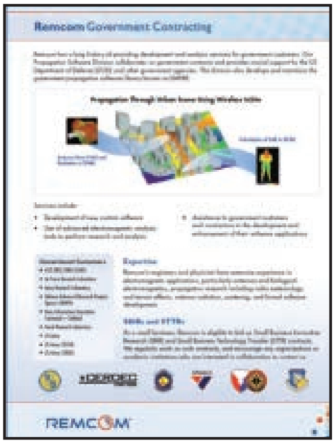
RADX Technologies Inc.
www.radxtech.com/lgt1211b

Filters, Multiplexers and Multi-function Assemblies

VENDORVIEW

When being first to react makes all the difference in the world, choose Reactel for your mission-critical filter requirements. This catalog features RF and microwave filters, multiplexers and multi-function assemblies for the military, industrial and commercial industries. To request your copy, please email reactel@reactel.com, or visit www.reactel.com.

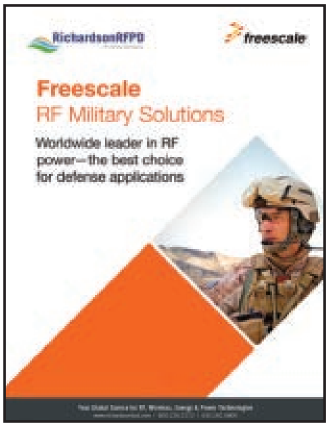
Reactel Inc.
www.reactel.com



Government Contracting

Remcom has a long history of providing development and analysis services for government customers. Their propagation software division collaborates on government contracts and provides crucial support for the U.S. Department of Defense (DoD) and other government agencies. The division also develops and maintains the government propagation software library known as EMPIRE. As a small business, Remcom is also eligible to bid on small business innovative research (SBIR) and small business technology transfer (STTR) contracts.

Remcom
www.remcom.com



Aerospace and Defense Portfolio

VENDORVIEW

Freescale's RF aerospace and defense portfolio encompasses a range of high-power solutions, including GaN, GaAs and LDMOS transistors and ICs, that support a wide variety of needs for military applications, such as avionics, HF through L- and S-Band radar, communications, electronic warfare, and identification, friend or foe (IFF). With leading-edge products and technology, a dedicated military products team, and its product longevity program, Freescale is your go-to source for aerospace and defense application needs. Brought to you by Richardson RFPD.

Richardson RFPD
www.richardsonrfpd.com

AEROSPACE & DEFENSE ELECTRONICS

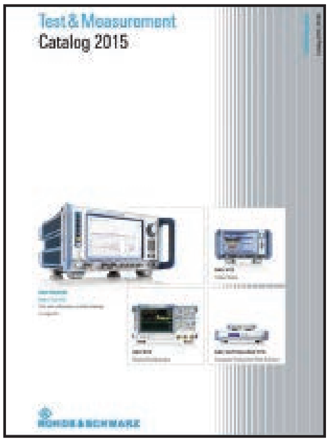
COMPANY SHOWCASE

Coonrod's Corner Video Series

VENDORVIEW

John Coonrod hosts Coonrod's Corner, a series of videos approximately 5 minutes in length each, that will teach you about popular topics in the PCB industry. Become a member of the Rogers Corp. Technology Support Hub today to watch the video series, access Rogers' calculators, literature, technical papers and download the free ROG Mobile App for Apple and Android smartphones and tablets. Register for free at rogerscorp.com/techub.

Rogers Corp.
www.rogerscorp.com



Test & Measurement Catalog 2015

VENDORVIEW

Rohde & Schwarz' Test & Measurement Catalog 2015 features more than 200 pages of information about Rohde & Schwarz test & measurement instruments, systems and software. It includes a short description and photos of each product with important specifications and ordering information. You can download this catalog as a PDF from the Rohde & Schwarz website or order a copy from customer support (order number: PD 5213.7590.42 V 05.00).

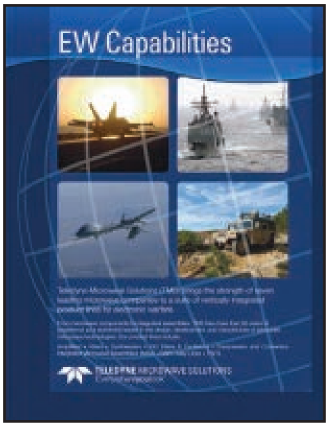
Rohde & Schwarz GmbH & Co. KG
www.rohde-schwarz.com

Real-Time Spectrum Analyzer/RF Recorder

VENDORVIEW

The BB60C is a broadband real-time spectrum analyzer and RF recorder that captures and displays RF events as short as 1 µs. It has selectable IF streaming bandwidths from 250 kHz up to 27 MHz. With accurate operation from 9 kHz to 6 GHz over its entire temperature range (-40° to +65°C available), the BB60C is well-suited for lab or field use. It sells for $2879 USD, and includes an API for custom software development.

Signal Hound
www.signalhound.com



EW Capabilities

Teledyne Microwave Solutions (TMS) has deep experience providing a wide range of products and capabilities for the EW, ESM / ELINT and radar markets. They have worked with most of the large OEM system manufacturers to develop custom SSPAs for EW needs; produced a wide variety of high performance receivers based on their patented IFM and unique wideband super-heterodyne technology for specific RWR, EW, SIGINT and ELINT applications; and developed TWTs, TWTAs, YIGs, filters and other products for today's modern war-fighting systems.

Teledyne Microwave Solutions
www.teledynemicrowave.com

Harness Informational Briefing

Harnesses provide a multi-channel connectivity solution that requires minimal installation tools, delivers a compact connector footprint, removes the risk of crossed channels and misconnection, enables fast installation or replacement, and simplifies wire management and routing. This briefing discusses benefits, applications, design components, qualification testing and range of tailored harness solutions—both flexible and semi-rigid—that are available from Teledyne Storm.

Teledyne Storm Microwave
www.teledynestorm.com

GORE-FLIGHT™ Microwave Assemblies

GORE-FLIGHT™ Microwave Assemblies, 6 Series are lightweight cable solutions for airframe assemblies in military and civil aircraft applications. These new assemblies deliver the lowest insertion loss before and after installation, ensuring reliable performance for the life of the system. Their robust construction reduces total costs by withstanding the challenges of installation, reducing costly production delays, field service frequency and the need for purchasing replacement assemblies. The 6 Series are also lightweight, which improves fuel efficiency and increases payload.

W. L. Gore & Associates
www.gore.com/simulator

ADVERTISING INDEX

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