MODERN RADAR

CAN ONE RADAR FIT ALL?

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Since World War II, Radio Detection and Ranging (radar) has had a dramatic impact on the way we conduct war and provide for our national defense. There is a growing desire to consolidate radar functions and transition to multi-purpose, single platform radar systems. This paper presents various characteristics of radar systems and explores and discusses key aspects that determine just how far we can (or should) go to achieve that objective.

Today, radar systems are used to provide air, sea, ground and space defense, target tracking and cueing, air-traffic control, weather monitoring, warhead arming and fuzing, environmental sensing and a number of other functions. Military applications can be strategic or, more often, operational and tactical in nature, which then drive the requirements for the radar system and the functions they need to support various weapons systems and platforms. The materiel developers are faced with a wide variety of options and constraints that need to be met to serve various mission needs. In addition, rapid technological advances, both in radar technologies and methodologies to defeat them, drive the need for upgrades to both hardware and software of radar systems.

Several radar technologies have emerged over the years to meet specific performance, cost, size and capability requirements. The cost of these systems, coupled with the increased technological capabilities being developed, cause some military planners to want to consolidate radar systems into common radar platforms capable of performing multiple functions. For example, U.S. Army air defenders must be capable of defeating the full range of enemy air and missile threats in strategic, operational and tactical situations. Threats can include tactical ballistic missiles, cruise missiles (CM), unmanned aircraft systems (UAS), rockets, artillery and mortars (RAM), fixed wing and rotary wing weapons. From a design consideration, the mission of the radar, the characteristics of the target(s) themselves, and the requirements levied upon it, affect the size, weight, and power required to complete the mission. And from a cost consideration, bring us to accept "real life" decisions based upon available budget, or military urgency. Certainly, other factors cause us to accept risk from many of the "ilities," such as mobility, transportability, maintainability, etc. and weigh equally as important in the acquisition of a new radar system. Potentially, as new technologies mature, the ability to combine functions is certainly becoming more of a reality. This paper addresses the questions, "How viable is a single radar solution in meeting current and perceived (future) needs and how far can we really go in developing a 'one solution fits all' radar system?"

Radar history

Early in the 19th century, experiments by Heinrich Hertz showed that metallic objects reflected radio waves. Not until early in the 20th century did German inventor Christian Hülsmeyer design and build a simple ship detection device intended to help avoid collisions in fog. Prior to WWII, radar was first implemented using low frequency radio bands in the 20-30 megahertz range where current AM and FM radio bands reside. At the start of WWII, Great Britain assembled 21 early warning radar sites along its east coast. This network had a range of ~300km with a peak power of 350kW. The system was bi-static, meaning the transmitter and receiver antennae were separate systems. Radar took a giant leap forward with the invention of the multi-cavity magnetron in 1935 by a German electronics specialist. The designs were then refined by British physicist John Randall in 1937.

This invention revolutionized radar systems because it allowed for development of shorter wavelength (X-band) systems that operated at ~10GHz. These systems were much more compact and were easily transported and could be mounted and operated in airplanes. Commensurate with the development of the magnetron, super-heterodyne radio receivers and transmitters were developed that provided the needed means for generating, detecting, amplifying and processing radar signals. Bell Labs used this technology to produce the first active electronically-steered array radar system in 1960. This was another major advance that provided the means to replace the bulky mechanically rotating antennae with smaller electronically-steered arrays. Major advances in signal processing techniques allowed the Bell scientists to perform long-distance detection, generate target track data, discriminate between warheads and decoys, and provide tracking of outbound interceptor missiles. Many of these techniques are still in use today and we owe much of our modern signal processing techniques to their pioneering work.

The next revolution occurred with the invention of the Gunn diode by John Gunn in 1963 followed quickly by the development of microwave striplines and co-planar waveguides circa 1969 by Julius Lange and Cheng Wen respectively. These two inventions resulted in the development of the first chip-scale microwave devices known as Monolithic Microwave Integrated Circuits, or MMICs, by Ray Pengelly and James Turner in 1975. These devices allowed radar developers to reduce the size and weight of systems by more than a factor of 10 and paved the way for developing radars that employed on-board complex signal processing. The final revolution came with the development of solid state phased array radar systems by several groups in the late '70s and early '80s. These innovations are the basis for all modern radar systems.

Fast forward to the present — modern military radar applications are pushed to the extreme and have evolved through a host of technologies that allow operation in several bands that span the electromagnetic spectrum all the way from a few MHz through 100s of GHz frequency range. Radars now perform a wide variety of complex functions such as target detection, classification and discrimination, multi-target ranging and tracking, frequency hopping, jamming, advanced noise and clutter rejection and more. As is the case in commercial electronics and communications, the evolution from purely analog designs to hybrid analog/digital designs continues to drive advances in radar system capabilities and performance.

Radar signals are becoming increasingly agile and signal formats and modulation schemes, pulsed and otherwise, continue to become more complex. As a result, developers are faced with demands for wider bandwidth in more narrow spectrums. This is exacerbated as commercial use of these bands in the private sector increase. Advancements can also be hindered by material limitations. Architectures such as active electronically steered array (AESA), for example, rely on advanced high-speed, low-loss semi-conductors and other materials to implement phased-array antennas that provide greater performance in beam forming and beam steering. Within the operating environment, the range of complexities that must be addressed to achieve mission requirements may include ground and sea clutter, jamming and interference, unwanted wireless communication signals and other

Radar	Mission	Operating Band	Range, kilometers (km), miles (mi.)	Power Required, kilowatts (kW)	Support Required
AN/TPQ-36	Firefinder, counter target acquisition/mortar	X-Band	24 km 15 mi.	10 kW > 23 kW peak transmission	2 HMMWV 9 Soldiers
AN/TPQ-37	Firefinder, counter target acquisition/mortar	S-Band	50 km 30 mi.	60 kW >120 kW peak transmission	1 HMMWV 2 M925A2 12 Soldiers
AN/TPQ-50	Counter target acquisition/rocket, artillery and mortar	L-Band	10 km 6 mi.	5 kW	Man portable 2 Soldiers
AN/TPQ-53	Counter target acquisition/rocket, artillery and mortar	S-Band	**90 degree:** 60 km 36 mi. **360 degrees:** 20 km 12 mi.	10 kW	1 FMTV 5 Soldiers
AN/MPQ-53	Missile/cruise missile, Patriot guidance, electronic counter-countermeasure	C-Band	100 km 60 mi.	2 x 150 kW 100 kW	1 M983 tractor 1 M860 semi-trailer 4 Soldiers
AN/MPQ-64	Low-altitude, medium-range air defense	X-Band	**AN/MP-64** 40 km 25 mi. **AN/MP-64F1** 75 km 47 mi.	10 kW	1 HMMWV 2 Soldiers
AN/TPY-2	Ballistic missile detection, terminal high altitude air defense target and track	X-Band	1000 km 600 mi.	1300 kW	2 HEMTT 8 Soldiers

Figure 1. A comparison of common ground-based air defense and field artillery radar systems.

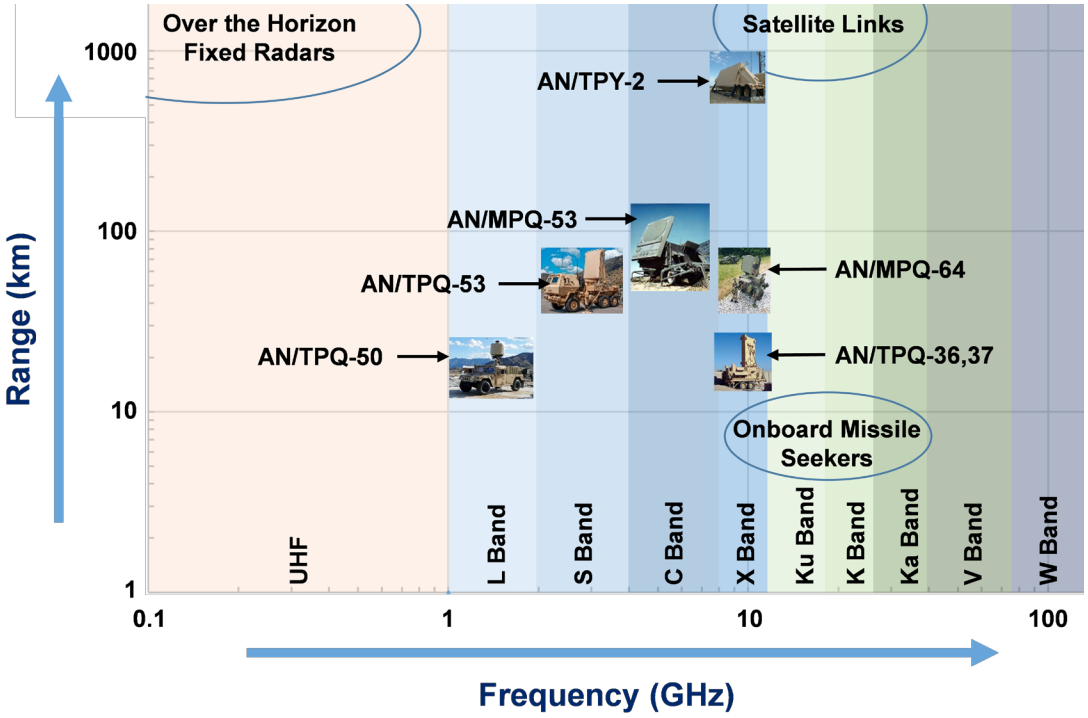
forms of electromagnetic noise. Modern systems must also have the ability to prosecute multiple targets, many of which use materials and technologies that present a reduced radar cross section.

Current radar systems

A wide variety of radar systems are currently in use by the Army. Figure 1 includes some of the more familiar short, medium, and long-range systems currently in our inventory. For this study, we include only the ground-based systems, but it should be noted that different forms of radar are employed in most aircraft systems and in several missile systems. The table shows the types of ground-based radars in use, their effective range, the wavebands in which they operate, and the power requirements and/or peak power output. It should be noted that there are often many variants of these systems and the key parameters listed here are their nominal values for general comparison.

This table shows the ground-based radar systems are generally confined to L, S, C and X-band wavelengths (frequencies) which span the range from ~1GHz up through 18 GHz. Later, we will point out the reason why this is so. The data here also points out that longer detection range requires higher power. One often overlooked factor is the trade-off between range and mobility. Generally, the longer the range required, the larger the power requirements and the less mobile the system becomes. The AN/TPY-2 is a very large system that requires a set of tractor-trailers (heavy expanded mobility tactical trucks) for transport of the radar and separate 1.3MW power generator. It is usually set up for long term operations. Figure 2 shows the relationship between the operating bands and range for

Figure 2. Comparison of operating frequency bands and range for common radar assets.



these systems along with fixed radar sites and missile seekers for perspective.

Historically, each radar was developed to perform a specific mission. As technologies improved, they were routinely upgraded to increase range and resolution on a case-by-case basis. Questions about who has the mission and how those assets are resourced and maintained are all driven by the threat and how we resource to meet those threats. Counter target acquisition (CTA) radars were originally designed to provide counter-battery capability against artillery and mortars. However asymmetric threats such as missiles and UAS have spurred the development of newer systems capable of tracking more types of targets. Communicating in an integrated air and missile defense environment dictates these systems can communicate with other air defense command and control entities in order to "see" the complete air defense operational picture, with the eventual goal that commanders can shoot any weapon available to destroy any target specified.

Real-world budgets, along with resource requirements influence the Army with the goal to increase efficiencies in support, logistics and numbers of systems and to reduce duplication of systems by combining missions. This was envisioned in early 2002 and stated that in the future, the (then) multi-mission radar (MMR) would support air surveillance, air defense, counter-target acquisition (CTA) and air traffic control. The goal of the MMR was to close traditional gaps in current radar applications, including lack of multi-mission functionality, 360-degree coverage with a single radar, precise counter battery/counter mortar capabilities, classification of threats and positive identification. Multi-mode radars continue to develop, although there are none at this time that can accomplish 100 percent of the air defense missions.

An AN/MPQ-64 Sentinel Air Defense System from South Carolina Army National Guard's 263rd Army Air and Missile Defense Command is set up in preparation for the Vigilant Shield Air Defense Artillery Field Training Exercise on August 14, 2016. (Cpl. Joseph Morin/Canadian Armed Forces)

The physics of radar systems

Imagine you decide you want to use your minivan to compete in a Formula One Race. It is doubtful that your van will take corners at over 100 mph more than once. Truthfully, the design of the minivan does not satisfy the physics-based requirements of getting around a corner at those speeds. You need to design a vehicle specifically to meet the requirements of the mission. Similarly, the design of radar systems is governed by physical laws that dictate performance parameters such as transmitter power, gain of the transmitting antenna, radar cross section, size of the radar aperture, required bandwidth, type of radar interrogating signal and the algorithms employed to complete the desired mission. These parameters provide a trade space that determines how well the system will perform. They must be balanced against target type and distance, temperature, radar noise, clutter and environmental effects.

To begin this discussion, we describe the basic radar range equation. It's the basis for understanding the physics of radar systems, their capabilities and resulting decisions that have to be made to ensure optimal performance. The equation has not changed, nor has the physics or mathematical principles since the inception of radar.

The basic radar range equation

Conceptually, each radar consists of a source antenna which transmits a pulse of radio waves outward and a receiver that collects signals reflected off objects within the field of view of the radar. In most modern systems, the source antenna and receiving antenna are one and the same and special switches are used to alternate between transmit mode and receive mode. If all goes well, the transmitted pulse of radio frequency energy reflects off the target and is collected by the receiver and analyzed.

The basic radar equation shows that the size of the returned signal depends on four key variables:

1. Output power of the transmitter
2. Gain of the antenna
3. Operating wavelength
4. Range to the target

This equates to the ultimate signal to noise ratio.

This points out two of the fundamental limitations that drive the size and power requirements of modern radars.

1. The higher the power and gain of the antenna, the larger the return signal (greater signal to noise ratio). Conversely, the farther the object is from the transmitter and receiver, the smaller the return signal becomes. In fact, the return signal drops off as the fourth power of the range. For example, if the radar transmitter puts out a total power of 1kW into an antenna with gain of 100, a 1 m2 target at a range of 1km will at best return a signal of 100 nW/m2. (Essentially for each watt of signal going out, only 1 billionth of a watt gets returned.) In practical terms, this means that we need to have as much power coming out of the transmitter as possible and we need

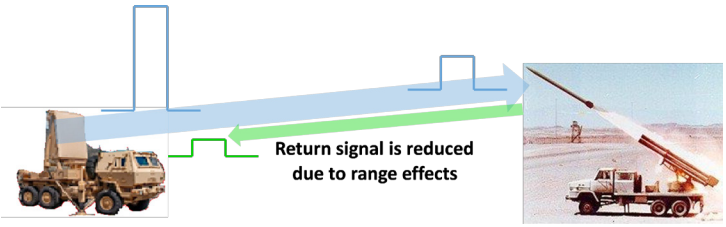


Figure 3. Illustration showing the effect of range on target return signals. (Courtesy Illustration)

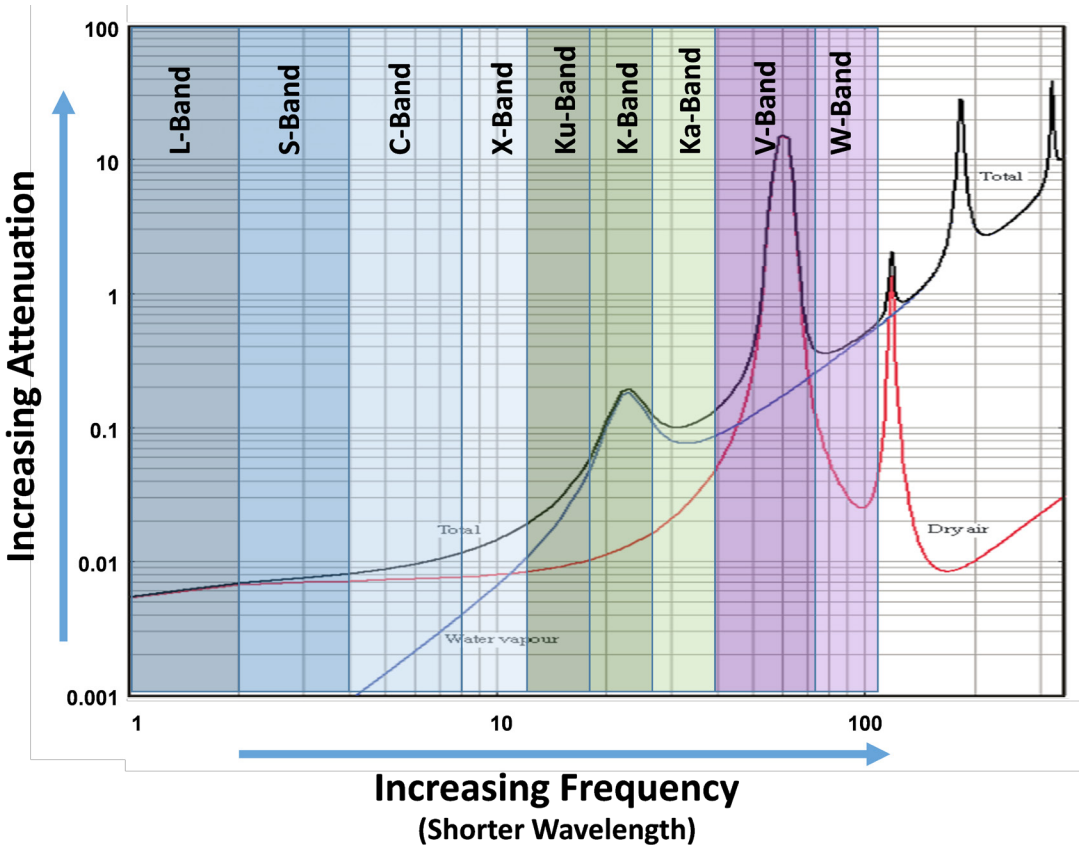
to couple that to an antenna with large gain. (This last fact is what drives us to use parabolic reflectors and phase array antennas for common radar scanning systems.) The larger the gain, the better the radar return signal, but we also have to have as large a receiving antenna as possible to collect the return signal. The effects of range are illustrated in Figure 3. The illustration shows how the signal naturally decreases simply due to the expansion of the radar wave as it exits the transmitter. This effect occurs regardless of the type or size of the radar system. (The blue colored pulse represents the outgoing or transmitted radar signal and the green colored pulse represents the return signal from the target.)

2. The second and less obvious limitation is that the return signal varies directly with the square of the wavelength. This means the range that we can achieve increases by increasing the wavelength, which in turn implies both a larger transmitting and receiving antennae. For instance, an S-Band radar operating from 4 to 8 GHz (with a wavelength of ~8 cm to 4 cm) has inherently less attenuation and capability to detect targets at longer range than an X-band radar operating from 8 to 12 GHz (with a corresponding wavelength from 4 cm to 2.5 cm). However, as a rule the S-band radar components are nearly twice the size of X-band components. Figure 4 shows the reason why this is the case. Two of the major constituents in the atmosphere are oxygen and water and these components absorb radio frequency energy. As shown by the black line in the figure, the higher the frequency, the more they absorb and hence, the less energy our transmitter can place on the target. In order to detect a target at a given range, we either must transmit more power or move to a lower frequency. In addition, there are specific wavelength regions where the absorption is so high that it is impractical to operate a radar system. These are the high spikes shown in Figure 4. This is the reason K and V-bands are not typically used for ground and sea-based radar systems.

As previously stated, these two limitations are the major drivers for the size and power requirements of modern radar systems. Additionally, the size will be dictated by the mission requirements. For instance, the desired detection range for acquiring and tracking incoming ballistic missiles is ~120 miles, while the requirements for detecting rockets, artillery and mortars (RAM) is considerably shorter (12-36 miles). Often, the radar designer must trade size and power (along with operating frequency) for range and resolution. For example, the AN/TPQ-53 is a mobile S-band radar system for RAM and has a nominal output of 8KW. To get better target resolution at ranges needed for detection of ballistic missiles, the AN/TPY-2 operates at X-band frequencies with a larger antenna and a much higher power output (typically ~1.3MW). These two systems also typify the additional problem that the size and power requirements drive the logistics footprint of the RADAR system as well as its maneuverability. The AN/TPY-2 system requires multiple tractor trailers to include power generation trailers, target command module and other ancillary equipment. The AN/TPQ-53 is a highly mobile, self-contained, dual vehicle platform. Note however that it can sometimes be used with a single vehicle however this is not the intended operational configuration.

Another significant limitation is driven by environmental (atmospheric scatter) effects. Generally, rain, snow, dust and smoke in the atmosphere scatters the radar signals and decreases both the strength of the

Figure 4. Atmospheric attenuation of radar signals as a function of frequency. (Courtesy illustration)



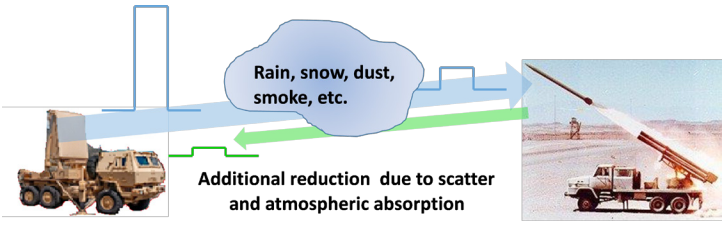


Figure 5. Illustration of additional attenuation due to scatter and absorption due to dust, rain and smoke. (Courtesy illustration)

outgoing (interrogating) signal and the target (return) signal. Figure 5 illustrates how radar signals are attenuated by these effects. The figure illustrates how dust, smoke, rain and snow reduce the transmitted and received signals even further.

Another major driver for radar systems is the ability to accurately determine position and range. Position is largely driven by how tightly the radar beam is formed. Essentially, the higher the antenna gain, the tighter the beam and hence the more accuracy in determining the location of the target. This is another reason why scanning radars for airports use parabolic shaped antennae. The parabolic shape affords a very high gain which in turn implies sharper focus of the radar beam and better target position determination. This same high gain is now achieved using flat panel arrays called phased array antennae. The arrays consist of a series of transmitter modules designed to focus the radar beam down range. The advantage of these systems is that they are much more agile than rotating parabolic reflectors and also support more than one radar function at a time. They also weigh less and take up less space.

The ability to determine the range of a target is governed by two factors. The first factor is how short the radar pulse is and the second factor is the operating frequency of the radar. The shorter the pulse and the higher the operating frequency, the better the range resolution. In addition, the radar designer must also be able to provide the ability to resolve multiple closely spaced targets or discriminate targets from decoys using fine target features. Again, higher frequencies imply better target resolution and better ability to detect structural features on the target. This points out a major trade analysis that needs to be performed for any radar system. One the one hand, we desire to use lower frequencies to get our transmitted signals out as far as possible to obtain better range coverage, but we need higher frequencies to get better target range tracking data. Figure 6 illustrates the effects of frequency on the ability to discern targets. In the upper portion of the figure, a lower frequency signal can detect that some kind of target is there, but a higher frequency signal as shown in the lower portion is needed to resolve the return signal into two separate targets.

These effects are the fundamental drivers that dictate how many and what type of radar systems are needed. For expeditionary and fast moving forces, smaller, lighter and cheaper is better but there is a limit on how small we can go driven by the factors already discussed.

Designing a radar: What is required?

The next consideration for radar systems is their intended mission. We have already pointed out the need for different range capability. What was not discussed is the fact that different radars have different functions and the scope of those functions is constantly increasing. The ability to meet these demands are often driven by technological advances and their maturity level and availability.

When designing a radar system, here are some of the primary considerations:

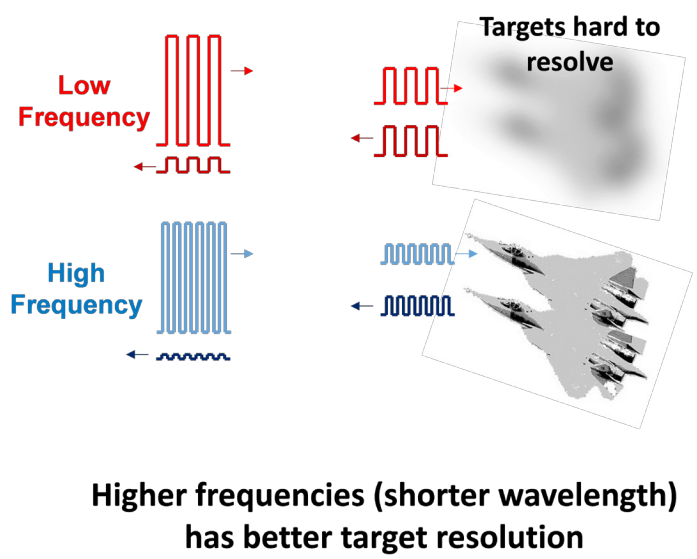
- Mission requirements: Do I require the ability to perform:
  - ◊ Weather monitoring
  - ◊ Fire-control
  - ◊ Target search and track capability
  - ◊ Target illumination
  - ◊ Target discrimination
  - ◊ Target tracking, i.e. single versus multiple targets
  - ◊ Continuous operations or short-lived operation
- Physical system requirements: What capability does the radar need? What are the specifications for:
  - ◊ Scan capability including scan angles and rate
  - ◊ Detection or illumination range
  - ◊ Target resolution at maximum range
  - ◊ Target tracking rate and accuracy, (Do I need Doppler and if so, how accurate?)
  - ◊ Size, weight, and power (SWAP) constraints
  - ◊ Mobility requirements
  - ◊ Platform requirements, etc.
- Support requirements: Do I require:
  - ◊ High mobility, i.e. smaller, lighter, lower power
  - ◊ Large or small support team
  - ◊ Interconnectivity with higher and lower combat units
  - ◊ Continuous, sustained operations
  - ◊ Auxiliary power
  - ◊ Redundancy
  - ◊ Ability to upgrade, etc.

Each of these requirements can and usually is a driver that must be considered in the radar system design. In the following sections we discuss some of these aspects in more detail.

Convergence of military electronics systems

State-of-the-art military sensors have unprecedented requirements to measure and process large volumes of data. To handle this data and provide "actionable intelligence" to the Soldier as soon as possible, sensor system logic requires opti-

Figure 6. Illustration of the effects of frequency on the ability to resolve targets. (Courtesy illustration)



Soldiers assigned to the 1st Battalion, 113th Field Artillery, North Carolina Army National Guard, prepare a radar display at Bulboaca Training Area, Moldova, Sept. 14, 2016, as part of multinational exercise Fire Shield 2016. The exercise, hosted by the Republic of Moldova Sept. 9-25, 2016, is an opportunity for the NCNG's 1-113th FA and 1st Battalion, 120th Infantry Regiment to develop relationships and improve capabilities with European partners. (Sgt. 1st Class Robert Jordan/U.S. Army National Guard)

mized combinations of logic and digital signal processing (DSP) density high-speed transceivers, power-versus-performance design flexibility, and high-assurance design flow to meet end-user requirements. U.S. military systems and vehicles have traditionally housed many separate electronic subsystems associated with radar. Among the most sophisticated of these is targeting radar and surveillance radar. Within the air defense mission, both functions are equally important. The more capable the radar, the greater the range and ability to resolve the target, the faster the enemy can be detected, assessed and prosecuted with the number and type of weapons available. These functions have been slowly converging over time, mainly due to increases in material sciences, and computing (Moore's Law) and other electronic technologies. Many Army radar systems are moving towards the use of multi-mode active electronically scanned arrays (AESA). These AESA systems provide advantages in the ability to quickly form multiple beams and to use each transmit and receive module (TRM) for concurrent roles, i.e. simultaneous scanning and detection, and produce "active arrays." However, as these systems become more complex, there need significantly increases for both the digital- and state-logic requirements of the system, which in turn demands industry responses for more sophisticated software solutions, power generation, and certainly with more sophisticated fixed and programmable logic devices (PLDs).

Technology to meet increasingly difficult missions

Army missions are beginning to overlap significantly, mostly because of an uncertain enemy, and the asymmetric nature of warfare. Set boundaries between traditionally defined front line areas and rear areas have all but disappeared, and the expectation that an agile enemy can attack with a variety of systems, from conventional ammunition such as mortars or UAS of varying sophistication to advanced missiles and fighters, is all within the realm of the possible. Therefore, the explosive growth in memory and semi-conductor capacity capability to perform these activities has enabled the growth of multi-role systems. Field-programmable gate array (FPGA) and structured application-specific integrated circuits (ASIC) continue to play a significant part in building the backbone of solid-state transmit and receive modules used in our most modern radars, i.e. AESA radars, also known as active phased array radars (APARs). Complex phased array radars may have thousands of transmit/receive modules operating in parallel. In addition, these may rely on a variety of sophisticated techniques to improve performance, to include: side lobe

nulling, staggered pulse repetition interval, frequency agility, real-time waveform optimization, wideband chirps and target-recognition capability.

Advanced radar sensor requirements

The challenges in military advanced sensor design are demanding. Below are some examples of some of the technical design constraints that affect the size, weight and power, of the radar and directly influence other decisions, such as cost, supportability, maintainability, agility, etc. Some examples of these technical constraints are:

- High serial data-streaming capacity: Digital antenna technology moves analog-to-digital conversion closer to the receiver, and requires more signal resolution in order to perform digital filtering.
- Complex math operations: Signal pre-processing and matrix operations require large numbers of digital signal processing block elements to assume the roles traditionally filled by digital signal processors.
- Sensitivity to heat dissipation: Sensor systems often have a long, if not continuous, mission life, requiring the dissipation of heat from continuous operation.
- Logic density for multi-role electronics: With so many military missions being performed with the same array, logic requirements are extremely high in transmit and receive electronics.
- Speed and latency performance: The speed grade and latency of the logic devices in a sensor array, as well as all the latency of interfaces between logic devices, affect the reaction times and beam-forming algorithm performance.
- Parts availability: Sensor systems are very complex, and the impact of even one part received behind schedule can have consequences for both operations and sustainment costs and operational readiness.
- Tool-flow ease of use: As millions of logic elements are integrated into a system design, the design, compilation and test of large pieces of logic code is a substantial driver of both cost and schedule.
- Signal integrity: As more receiver elements provide data to be correlated with one another in final processing, small signal errors have larger impacts on sensor algorithms. Signal integrity in digital components is therefore paramount.

One of the major innovations that forever changed the way we think about radar systems is the advent of monolithic microwave integrated circuits (MMIC) technology in the 1970s. It paved the way for reduction of component size and allowed exploration of miniaturized radar systems. Up until this time, radar systems relied heavily on hollow waveguide systems and components resembling square pipes. These "pipes" conduct the radar signals to and from the microwave sources, signal processors and antennae elements. MMIC technology essentially provided low loss waveguides and components at the integrated chip level that reduced the size of microwave systems by more than an order of magnitude. MMIC circuits increase the incoming radar signals while decreasing the signals (noise) coming backwards through the radar amplifier. The key benefit of this technology is the ability to create agile scanning systems (phased array radar) with greatly reduced size, power and weight. Not withstanding, the aperture size of the antennae required remains the same.

Material science improves radar designs

There have been interesting breakthroughs in material science, which have and will continue to enhance radar design and technology. One such example is metamaterials. Material engineers define metamaterials as artificially engineered materials that have properties not yet found in nature. Metamaterials derive their properties not from the compositional properties of the base materials, but from their exactingly designed structures.

Potential applications of metamaterials are diverse and include remote aerospace applications, sensor detection and infrastructure monitoring, smart solar power management, public safety, radomes, high-frequency battlefield communication and lenses for high-gain antennas, improving ultrasonic sensors and even shielding structures from earthquakes.

How do these new materials help? A key feature of radar systems is the ability to scan in two or three dimensions. There are two basic technology choices for scanning radar. Today, radars are migrating (in general) from the older mechanically scanned systems (MSRs) in which an antenna (such as a parabolic dish or slotted wave-guide) rotates to cover a wide field of view, usually 360 degrees to electronically scanned radars (ESRs).

In the older mechanical systems, the rate at which we scan the image is constrained by the speed of the mechanism chosen. In ESRs, beam steering is achieved electronically with a passive or active phased array, as in PESA or AESA. Depending on the frequency and aperture size, there could be thousands of individual amplifiers, phase shifters, and other components spread across the antenna, adding cost and complexity. What the Army needs is a very low cost radar technology that can also deliver wide-angle ESR performance. ESRs are difficult to integrate, hard to thermally manage, extremely expensive and are generally reserved for high-value applications.

Because of the unique advantages of metamaterial, there is an expectation to develop new kinds of affordable, compact and lightweight scanning radar products. As an example, metamaterials surface antenna technology (MSA-T) antenna designs can step-up the antenna's radiated power, and aid applications in radar such as wide-angle beam steering. Why is that important? Conventional antennas that are very small compared to the wavelength usually reflect most of the signal back to the source. A MSA-T antenna behaves as if it were much larger than its actual size, because its novel structure stores and re-radiates energy.

Use of AESAs for design flexibility

As stated earlier, AESAs are a powerful technology for creating highly adaptive steerable beams. In turn, these beams are able to track multiple targets or focus electromagnetic energy in one location. In order to take full advantage of a system's steering capabilities, designers work to move as much signal processing capability as possible into the forward radiating elements of the system. This may include waveform creation and compression, beamforming, correlation, and pre-processing. AESAs perform and optimize more and more functions, parallel FPGA logic, beamforming algorithms and waveform adaptivity can be accelerated, increasing reaction times in the system. High-density series FPGAs are the right tool for optimizing radar system performance. High logic density allows more functions in a single chip. Increased DSP elements streamline matrix mathemati-

cal functions and increase flexibility. Highly flexible 18x18-bit multipliers can be split into 9x9-bit elements, or combined into power and logic-efficient 54-bit multipliers for floating-point operations.

Other technology considerations

The proliferation of active arrays in sensors is the primary technology driver in logic device content. A larger number of array elements equals more design work, more beamforming algorithms, more integration and testing, and a longer logistics tail for the system. In order to meet the diverse computing needs for air defense systems, Army customers have been investing in reconfigurable processors that can perform both front-end and back-end processing. Programmable logic has been the interim design step for critical sensor requirements.

A new dimension to sensor design is experimentation with multiple-input, multiple-output (MIMO) sensor arrays. Receivers in a MIMO system perform phase-delay correlation between multiple orthogonal transmitted waveforms, exploiting advances in electronics density and computing capability. OEMs and developers who will lead in this market will be the ones that best take advantage of the most advanced and logic-intensive devices with the simplest design flow and most efficient compilation profiles.

Radar designers are confronted with a number of tradeoffs. One of the most important is the trade between required range and available resolution. This trade exists because as we stated before, for a given power level, the effective range of a radar decreases with increasing frequency. At the same time, target resolution generally increases with increasing frequency. Hence the designer must pick a frequency which balances the range requirements with the needed resolution. This is depicted in Figure 7. There is usually a "sweet spot" where the range versus frequency curve (shown in blue) crosses the resolution versus frequency curve (shown in red). This "sweet spot" can be moved to higher frequencies by increasing the power output of the radar system. This is the reason that the AN/TPY-2, which operates in the X-band, requires a power output of 1.3 megawatts. The high output power guarantees that the system can maintain the high resolution requirements afforded by operating in the X-band and still achieve ranges out to 1000 km. Said another way, if the system were designed for the L-band, the required power to reach 1,000 km would be much less, but the system would have nearly a factor of 10 poorer resolution.

There are also system level trades (size, weight and power, also known as SWAP) to be made, particularly when we include supporting hardware such as generators, vehicles, and radar pointing and elevation control platforms. Generally, for a given range capability, as the operating frequency increases, the size, weight and power draw of the components decrease. This is largely due to the fact that the wavelength is shorter for higher frequencies so the components are simply smaller than their long wavelength counterparts. As a result, the radar platforms generally get smaller along with the generators needed to power them. In turn, this means that the mobility goes up with higher frequencies. Figure 8 depicts these trends. The blue line shows how the SWAP requirements decrease with increasing frequency. At the same time, the mobility increases. This is one of the reasons that we use K-band radars on the PAC-3 (Patriot) missile system rather than an S-band system for instance. An S-band system is simply too large and heavy to consider for that application. Another example is the difference in support requirements for the AN/MPQ-64 compared to the AN/TPY-2. Both of these radar systems operate in the X-band. The longer range of the AN/TPY-2 over the AN/MPQ-64 (1000 km versus 64 km) requires nearly twenty times the power. Obviously, the equipment is much heavier and as a result, the AN/TPY-2 requires two (2) HEMTTs for transport compared to one (1) HMMWV for the AN/MPQ-64.

Life cycle considerations

The development of these complex radar systems with complex sensors tends to be among the most difficult projects to manage. As shown in Table 1, current radar systems

Figure 7. Illustration of how frequency relates to range and resolution. (Courtesy illustration)

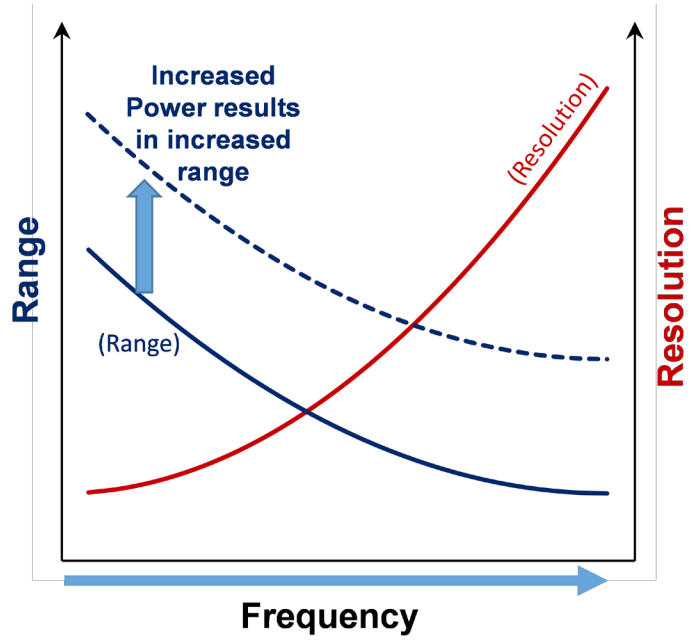
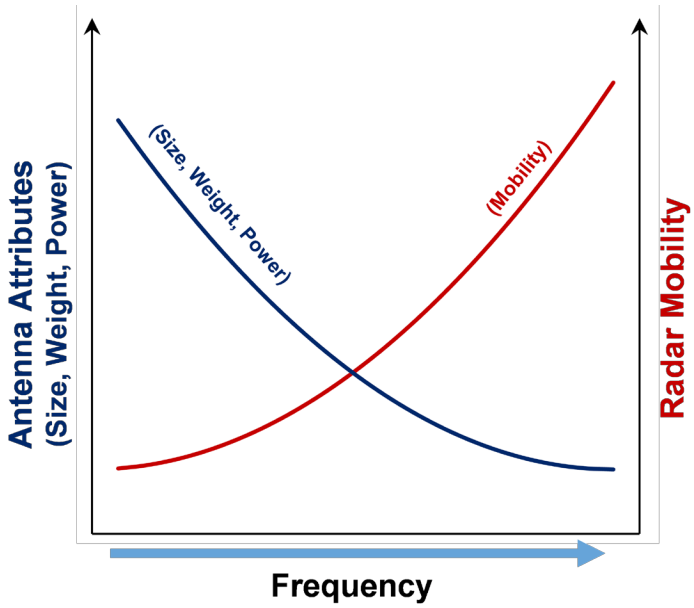


Figure 8. Illustration of how frequency relates to antenna size and mobility. (Courtesy illustration)



From the left, Chief Warrant Officer 2 Chris Fortune, Spec. Mike Stevenson and Warrant Officer Candidate Armand Hunter assemble the AN/TPQ-50 Lightweight Counter-Mortar Radar system, July 23, 2016, as part of annual training with the 1st Battalion, 101st Field Artillery Regiment, at Joint Base McGuire-Dix-Lakehurst. (Staff Sgt. Steven Littlefield/1st BN, 101st FA)

have undergone years of development and testing before their fielding. Over time, those systems continue to improve as breakthroughs in technology continue to make systems more efficient. The Army tends to use their radars for many years, relying on engineering upgrades as technology moves forward. To build a radar today, there are literally dozens of technologies that require integration. Some technologies, such as metamaterials, are untested beyond initial brass board prototypes. The logistics chain, supportability and maintainability are key "ilities" in the consideration of the cost of not only building, but also maintaining a radar system.

S&T and logistics

Clearly, an opportunity exists to continue to work with early developers, including Army Materiel Command and its partnerships with industry and academia, as well as with Army requirements generators in Army Training and Doctrine Command and within the Assistant Secretary of the Army for Acquisition, Logistics and Technology, to determine the relative glide path of future radar technology, and how AMC can best insure we are synchronized to influence the science, but also the transition of technologies in a way that encompasses the best material and technological solutions to support the warfighter once the system is fielded. Considerations to the industrial base requirements may be different for future systems, precious materials, and the development of complex modules and software. Clearly, given a set of clear guidelines, Army Materiel Systems Analysis Activity can help define what "right" will look like from a life-cycle perspective. There should be a logical sequence of meetings within the Army, and with Industry to determine our future for radar.

One radar fits all? Probably not, but...

The radar range equation has not changed, physics has not changed, and the laws that govern electronic signals, wavelengths and frequencies have not changed. It will be hard in the near-term to build radar that meets all the qualifications/Key Performance Parameters (KPPs) of current single systems to any degree of satisfaction. There is no point in designing and building a radar that can't meet all the current KPPs of the radars it is projected to replace. Modern AESA radars have the most design constraints, the longest design cycles and the largest design management needs because of large engineering and verification teams. There are also significant trades in radar design to accomplish in order to size and tailor the radar for its mission. The more capability a single radar must have, i.e. MMR "class" of radars projected to accomplish multiple takes, requires more complex designs, and significantly more complex hardware tooling and accompanying software to test the radar, and will likely increase the per unit cost. Trade space for weight, power, transportability and maintainability become harder to make as the demands on a single system increase. Can it be air transportable, moved by a light vehicle and detect an incoming cruise missile far enough away to react, and at the same time protect a forward operating base from incoming mortar or artillery rounds? Can the radar see through the atmosphere at ground lower angles and be just as successful with smaller targets as it is with higher targets? Can the radar communicate within its mission and communicate with other radar systems in a more strategic view, and with command authorities in a global view? Can your Mini-van compete well in Formula One racing?

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