Radar versus Stealth

Passive Radar and the Future of U.S. Military Power

By AREND G. WESTRA

Sailor monitors radar screen in Combat Direction Center aboard USS *John C. Stennis*

U.S. Navy (Walter M. Wayman)

Faced with the prospect of aerial stealth proliferation, states in the 21st century are looking for antistealth defense options. One such alternative, passive radar, appears a cost-effective counter to stealth. *Passive radar* is a receive-only system that uses transmitters of opportunity.[1] Integrating a system of netted receivers, passive radar can detect, track, and target piloted and unpiloted stealth systems and provide cuing for antiair weapons systems. A passive radar system emits no radio energy and can be well camouflaged in both urban and rural landscapes. The threat system produces no indications on friendly radar warning receivers and is difficult to locate and target. Faced with a passive radar threat, the United States may find itself unable to achieve air superiority at an acceptable cost.

As this article shows, ongoing advances in passive radar will deny traditional means to defeat enemy air defenses, make air superiority difficult to achieve against a passive radar opponent, and require changes in thinking to maintain U.S. power projection capability. In developing this central idea, this article describes the history of the battle between aircraft and radar, the rise of stealth and counterstealth, and the ongoing surge in passive radar and how it relates to advances in signal processing and sensor fusion. Additionally, this article assesses the passive radar threat to stealth, posits implications for future U.S. military power, and recommends a U.S. course of action regarding passive radar.

Aircraft versus Radar

"The defensive form of warfare is intrinsically stronger than the offensive"—so argued Carl von Clausewitz in *On War*.[2] The static warfare of the late 19th century and the

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Great War of 1914–1918 appeared to validate this idea. In 1921, however, Giulio Douhet asserted that the airplane changed warfare "by magnifying the advantages of the offense and at the same time minimizing, if not nullifying, the advantages of the defensive."[3]

Douhet did not envision the many surface-to-air threats that would evolve over the decades after his work was published. Neither did airpower critics. As Sir Stanley Baldwin informed the British parliament in 1932, "I think it is well also for the man in the street to realize that there is no power on earth that can protect him from being bombed, whatever people may tell him. The bomber will always get through."[4]

Yet a few decades earlier in 1904, German engineer Christian Hülsmeyer had patented the *telemobilskop*, an early form of radar. But it was not until 1935 that radar first showed significant operational promise. In the now famous Daventry experiment, Sir Robert Watson-Watt used radar to detect a British Heyford bomber at a range of 8 miles.[5] Notably, the Daventry experiment tested a passive radar system using the BBC Empire broadcast as a transmitter of opportunity.[6] Watson-Watt went on to develop the British Chain Home radar that played a critical role in defeating the German *Luftwaffe* during the Battle of Britain in 1940.[7]

World War II served as catalyst for a second paradigm shift. The overwhelming offensive power of the airplane was largely mitigated by the deployment of radar and modern air defenses. Airpower did not prove an all-powerful offensive weapon that could not be countered, and the bomber did not always get through. Air defenses of both the Axis and Allied opponents proved complex and resilient, and combatants obtained air superiority only locally and for limited durations through the costly reduction of enemy air defenses. This paradigm held firm through World War II and for the duration of the Cold War. For the time being, it seemed that Clausewitz had caught up with the airplane.

Despite Watson-Watt's breakthrough at Daventry, the experiment highlighted passive radar's difficulties, including intermittent signal strength and, at the time, irresolvable locating and tracking ambiguities due to the passive radar geometry.[8] Passive radar is *bistatic*, meaning the receiver is located at a distance from the transmitter.[9] Bistatic radar geometry is shown in figure 1. In 1936, scientists solved the difficulty of geometry by collocating the transmitter and receiver via a shared antenna, a configuration known as *monostatic*, thus creating the conventional radar configuration most commonly used thereafter.

Historically, radar has been the cornerstone of air defense. For example, during the Vietnam War, North Vietnamese air defense radars targeted U.S. aircraft, which, in turn, countered with jamming and antiradiation missiles. Due to the success of North Vietnamese air defenses, the United States was only able to establish temporary air superiority over local areas of North Vietnam. Over the course of the war, the North Vietnamese shot down 190 U.S. aircraft using 1950s-era Russian surface-to-air missiles (SAMs).[10]

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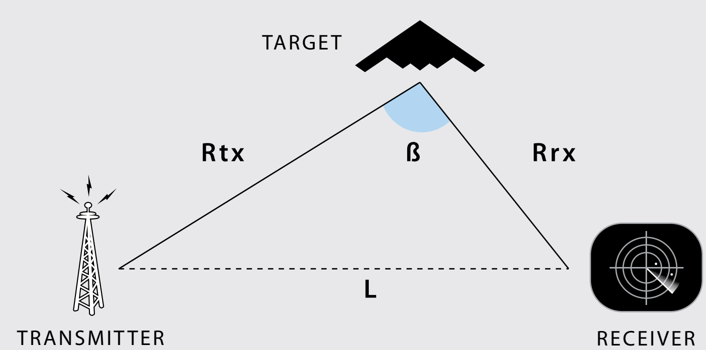
A third paradigm shift began in the 1970s in the "Skunk Works" of Lockheed Martin, where stealth pioneers first created the F–117 "stealth fighter" (more bomber than fighter in usage).[11] Made operational in 1983, the F–117 saw combat in Panama in 1989 and again in the Gulf War in 1990.[12] During the Gulf War, the F–117 was employed against Iraq's most heavily defended targets. In spite of Iraq's robust air defenses, not a single F–117 was lost or damaged during the conflict.[13] By comparison, 32 nonstealth aircraft were lost to antiaircraft artillery (AAA) and SAMs.[14] If Baldwin had witnessed the Gulf War, he might have concluded, "The *stealth* bomber will always get through." Indeed, stealth aircraft have maintained the overwhelming advantage in recent conflicts, including Operation *Allied Force* and the invasion of Iraq in 2003.

Despite the overall success of the U.S. stealth program, in 1999 an F–117 was shot down in the Balkans by a Serbian SAM battery.[15] Although some considered the downing an anomaly, the incident created much controversy. While the Air Force assessed tactical lessons learned, others saw evidence that stealth could be defeated.[16] The incident illustrated what stealth designers already knew: stealth technology does *not* make an aircraft invisible. As a submariner once aptly noted, "Stealth is a zero-sum game. In a given encounter, one platform has it and the other does not. The tactical advantage accrued by being able to detect, close, and attack from a covert stance completely dominates all other factors in any encounter algorithm."[17] In Serbia in 1999, a SAM battery commander attacked from a covert stance and won the tactical advantage. It was a missile shot heard around the stealth world.[18]

The Future of Stealth

If anything, the downing of an F–117 over Serbia only highlighted to the United States the importance of stealth. Increasingly, the U.S. military has made stealth one of its

Figure 1. Bistatic Geometry



Note: L = distance between transmitter and target ("bistatic baseline");
Rtx = transmitter range to target; Rrx = receiver range to target;
ß = bistatic angle.

Source: C.J. Baker and H.D. Griffiths, *Bistatic and Multistatic Sensors for Homeland Security* (London: University College, 2005), 4, available at <http://nato-asi.org/sensors2005/papers/baker.pdf>.

highest priorities, both in terms of new acquisitions and the retrofit of older aircraft. In short, stealth is the centerpiece of the U.S. air superiority strategy.

As stealth grows ubiquitous, nonstealth systems will become rare. Stealth principles are evident in nearly every newly developed military aircraft, ship, and ground combat system. Nations devote large proportions of their military budgets to stealth research and development. And with the Air Force having retired the F–117 in 2008, the United States now has a shortage of operational stealth aircraft.[19] Current U.S. stealth aircraft inventory consists of 20 B–2 bombers and 187 F–22s, with the Joint Strike Fighter projected to become operational in 2012.[20] Planned U.S. procurement for the Joint Strike Fighter is 2,456 aircraft delivered over a 28-year period.[21] Meanwhile, Russia, India, China, Japan, and other countries are attempting to enter the stealth aircraft market.[22] In short, stealth is relevant, in much demand, and continuously evolving.

Stealth Techniques

Stealth is achieved by a broad collection of techniques that render a platform difficult to locate and attack. It requires reducing aircraft signature, generally categorized as either *active* or *passive*:

> *Active signature is defined as all the observable emissions from a stealth platform. . . . Passive signature is defined as all the observables on a stealth platform that require external illumination. . . . The active signature reduction methods are commonly called low probability of intercept (LPI). . . . Passive signature reduction techniques are often called low observables (LO).*[23]

Stealth designers attempt to balance signature techniques.[24] For example, efforts to make an aircraft less visible at 5 miles are somewhat superfluous if it can be acquired by an infrared (IR) sensor at 20. LPI designers focus most of their efforts on reducing the emissions produced by the aircraft's radar and IR sensors.[25] In designing LO, the main concern is reducing reflection in the radar spectrum, also known as the radar cross section (RCS).

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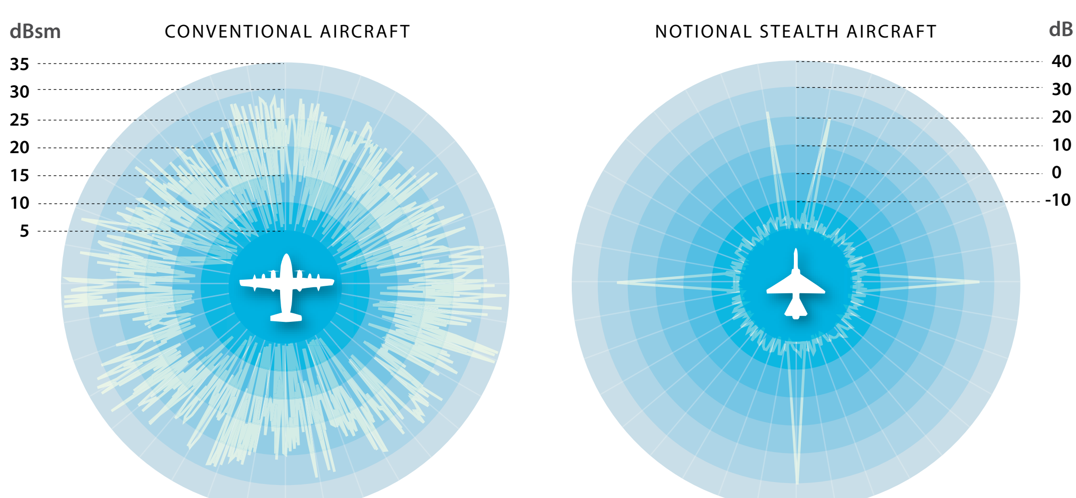
Designers reduce RCS primarily through fuselage shaping and radar-absorbent material. Fuselage shaping, the more important of the two methods, reflects radar energy away from the direction of the emitter.[26] Figure 2 depicts a stealth aircraft RCS versus that of a conventional aircraft. Fuselage shaping works primarily against conventional radars where the receiver is collocated with the transmitter and is less effective against bistatic radar geometry.[27] Radar-absorbent material augments fuselage shaping by absorbing radar energy and reducing the strength of the radar echo.[28] Future innovations may allow stealth aircraft to actively cancel radar echo by retransmitting radar energy and/or by ionizing boundary layer air around the fuselage.[29]

Counters to Stealth

Before discussing passive radar, several other radar and sensor systems are worth mentioning in terms of counterstealth capability. One of the most significant counters to stealth, namely conventional very high frequency (VHF) and ultra high frequency (UHF) radar, has been around since World War II and is still in use today for long-range air surveillance. Most LO techniques are designed to defeat acquisition and fire control radar in the X band, which uses centimeter wavelength. VHF- and UHF-band radar, however, uses decimeter- to meter-long wavelength. In general, the RCS of an aircraft increases as wavelength of the illuminating radar increases.[30] Furthermore, when the radar wavelength is in the same order of magnitude as the aircraft or parts of it, the radar waves and the aircraft resonate, which significantly increases the RCS of the aircraft.[31] It is the physics of longer wavelength and reso-

Figure 2. Conventional and Stealth Aircraft Radar Cross Section Signature



Note: dBsm = decibels per square meter; dB = decibels
Source: David Lynch, *Introduction to RF Stealth* (Raleigh, NC: SciTech, 2004), 6.

nance that enables VHF and UHF radar to detect stealth aircraft. Poor resolution in angle and range, however, has historically prevented these radars from providing accurate targeting and fire control.[32]

Since the Gulf War, the Russian defense radar industry has put considerable effort into digitizing its VHF and UHF radar systems to improve counterstealth capability. Russia's older model radars now have improved resolution and signal processing, and newly developed models, such as the Nebo surface vehicle unit, which is a VHF adaptive electronically steered array radar, likely present significant counterstealth capability.[33]

Other recently developed conventional radars likely to have counterstealth capability include Lockheed Martin's theater high-altitude area defense radar and the Israeli Green Pine radar (recently sold to India), systems with both long range and high resolution in the UHF L-band.[34] The Signal Multi-beam Acquisition Radar for Tracking (L) naval radar manufactured by Thales is yet another system with reputed counterstealth capability.[35]

Passive listening systems, such as electronic support measures (ESM) and direction finding (DF), attempt to detect stealth aircraft radar, radio, and data link emissions and pass this information to surveillance radars. LPI techniques of stealth are designed to reduce or deny ESM and DF, but systems such as the Russian *Kolchuga* remain formidable threats that are likely being updated with digital processing.[36]

Another counter to stealth is IR/electro-optical (EO) systems, which include IR search and track and high magnification optics. Such systems, however, are limited in the ability to scan large volumes of airspace and usually must be cued by other sensors. In addition, most of this spectrum is degraded by clouds, low illumination, and low visibility. Stealth aircraft counter IR/EO through heat signature management, stealthy flight profiles, and LO paint schemes.

Growing in potential as a counterstealth technology is millimeter wave (MMW) imaging, which uses the radiometric signature naturally emitted by all objects. MMW penetrates clouds and low visibility. The waveform can also be transmitted by radar, which then receives and processes the return echo. The A–64 Apache Longbow/Hellfire system is an example of operational MMW radar. The Russian defense industry has developed MMW antiair missile seekers, and other countries are following suit.[37]

While the aforementioned technologies offer important capabilities, they possess limitations that restrict their effectiveness for air defense. Conventional radar is vulnerable to detection and attack by electronic warfare and air-delivered weapons; listening systems do not provide tracking information; and IR/EO/MMW is limited in surveillance capabilities.

In contrast, passive radar is covert, all weather, and capable of medium- to long-range surveillance, and shows strong potential in detecting, tracking, and targeting stealth aircraft. It is thus emerging as a solid competitor in the counterstealth game.

off-the-shelf technology makes them attractive for nonpeer countries as well.

Passive radars use transmitters of opportunity. Potential waveforms include FM and AM radio, television, digital audio/video broadcast, and cellular phone networks.[38] Today, passive radar is often configured as a "multistatic" system using three or more transmitters and receivers.

Passive radar locates and tracks targets through a combination of methods, greatly simplified here for the sake of discussion. First, the radar measures the time difference of arrival between the direct signal from the transmitter and the reflected signal from the target to determine the bistatic range. Bistatic range, expressed as an ellipse, is shown in

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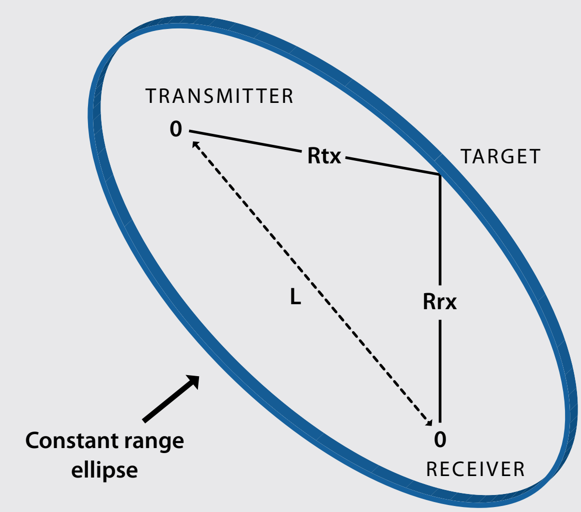
Passive Radar

A new paradigm is emerging, enabled by advances in networked computing and passive radar technology. Because of their potential to counter stealth-based airpower advantage, the use of these technologies by peer competitors is highly likely. That these systems are both low cost and, in part, based on commercial-

figure 3. The radar uses the intersection of the receiver-to-target bearing and the bistatic range ellipse to estimate approximate target location. In a multistatic system, the radar refines target location based on intersecting bistatic range ellipses. The radar further measures Doppler shift—wavelength compression or expansion caused by relative motion—to determine target

Figure 3. Bistatic Range



Note: Rtx = transmitter range to target; Rrx = receiver range to target; L = distance between transmitter and receiver. Bistatic range, expressed as Rtx + Rrx – L, remains constant at all points on the ellipse.

Source: *NationMaster Encyclopedia*, "Bistatic Range," available at <http://www.nationmaster.com/encyclopedia/Image:BistaticRange.png>.

heading and speed. The radar tracks the target by performing regular updates.

Advanced signal processing allows passive radar to integrate data from multiple receivers, cancel signal interference, differentiate real targets from ghost returns and clutter, and establish a target track. Although such processing requires significant computing power, most passive radar systems operate on commercial DOS-based computing technology.

The recent advances of passive radar arise from a confluence of digital processing technology, cheap, sophisticated hardware, and the demand for enhanced surveillance.[39] Moore's law describes the doubling of computer processing speed every 18 months. Meanwhile, designers have made significant advancements in corresponding radar software. What was once thought impossible—that is, integrating signals from multiple receivers and detecting tiny echoes in high-clutter radar environments—has now become feasible.[40]

As a result of this confluence of technology, several systems are now either available off the shelf or are in development. Such systems include Lockheed Martin's "Silent Sentry,"[41] Roke Manor Research's CELLDAR,[42] Thales-Raytheon's Homeland Alerter,[43] and others, including French, Swedish, Chinese, and Russian systems.

Certain commercial waveforms are more suitable for passive radar illumination than others. The most important parameters are frequency, bandwidth, and the presence of continuous wave, which provides Doppler shift for measurement of velocity.[44] Also important is whether illuminators transmit continuously or with significant interruptions (for example, daytime only).

Several waveforms in the HF, VHF, and UHF bands have shown potential for use in passive radar and also exhibit counterstealth properties. In the VHF band, FM radio is broadcast at high relative power and has multiple transmitters available in moderately to heavily populated regions. Analog television (VHF band) also provides useful illumination, as does digital audio broadcast, which is growing in usage worldwide. High-definition (HD) television is spreading globally as well and offers a wideband, high-power waveform in the low UHF band. In the HF band, Digital Radio *Mondiale* (DRM), a digital form of shortwave AM radio, also has passive radar potential.

These waveforms offer differing levels of utility. Analog television and FM radio both offer strong illumination and medium detection ranges—FM out to roughly 120 kilometers (km).[45] Analog television has a strong signal but suffers from interference, while FM is marked by interruptions, such as pauses during human speech.[46] HD television provides an uninterrupted signal with a detection range of 120 km.[47] DRM potentially offers over-the-horizon detection ranges; however, low resolution limits its use to early warning radar. Digital audio broadcast, while a useable waveform, emits at low power, offering only a short detection range of 36 km.[48] Use of more than one waveform is possible, with existing systems touting accurate three-dimensional surveillance capabilities across multiple waveforms, to include FM radio and analogue and digital television.

Most important to this discussion, all of the aforementioned waveforms fall between 3 and 450 megahertz. Based on their decimeter- to meter-wavelengths, these waveforms inherently increase RCS and also interact with an aircraft to create resonance. RCS induced by resonance is largely independent of fuselage shape. In short, radar in this spectrum is inherently counterstealth.

While passive radar can perform detecting, locating, and tracking functions, it may also be able to perform target identification (ID). Under development are methods to conduct target imaging using multistatic UHF-band Inverse Synthetic Aperture Radar.[49] Additionally, existing passive ID measures, such as DF/ESM, will likely augment passive radar.

If successful at creating a target track and ID, passive radar could provide cueing for surface-to-air and airborne weapons systems in order to enable acquisition. Weapons system cueing requires communications infrastructure; for a covert system, this means a local area network for ground-based weapons and an LPI data link for airborne platforms. For

F–117A Nighthawk stealth fighter

U.S. Air Force (Andy Dunaway)

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SAMs with a command guidance mode, the passive radar could provide midcourse guidance via data link. In keeping with the passive radar system, a passive missile seeker—IR, EO, MMW, or perhaps multisensor—would likely be used for end-game guidance in order to complete the kill chain.

Threat Employment

A future adversary will look increasingly to counter the U.S. stealth advantage with passive radar, either as a stand-alone system or in conjunction with active surveillance radars. Passive radar is relatively cheap, and its covert stance lends itself to a strategy of striking from concealment. Moreover, our most likely future opponent—an authoritarian state—already possesses tight control over its commercial media, a situation that requires a relatively small step to optimize broadcasting parameters for passive radar use.

This same adversary will build a passive multistatic receiver network in the VHF and UHF bands, blending the system into the vertical buildup of urban terrain.[50] In remote areas not served by media broadcast, the adversary may disperse a network of inexpensive throw-away transmitters to function as the surveillance area illuminators. He will integrate passive radar and other sensors for rapid, efficient command and control. It is likely that such an adversary will make efforts to develop or acquire passive SAMs with low observable launch signatures and procure and deploy high- and mid-altitude unmanned aerial vehicles—"missile trucks"—to deny flight at those altitudes.

Countering Passive Radar

Countering passive radar will prove difficult. What are the signs that an opponent is using passive radar? Forehand knowledge of the threat may provide an idea of general capabilities. Are friendly air forces losing aircraft to ground fire with little or no threat warning indications? With no radio frequency electronic intelligence available, locating the passive radar receivers will be challenging. Intelligence will face a difficult task of using indirect methods—human intelligence, ground surveillance, computer network operations, and nodal analysis—to collect on sparse information.

If the command and control nodes and receivers cannot be found, targeting planners could focus on destroying suspected transmitters—for example, FM radio, television, and HD television networks. Depending on their location and the potential for collateral damage, however, destroying these targets may result in undesirable strategic consequences, particularly in urban areas.

At the tactical level, friendly forces could employ reactive defenses against SAM launch and fly-out and conduct immediate counterattack of associated threat systems through electronic attack, standoff weapons, directed energy, or other means. This approach, however, would consume time and resources and would likely fail to achieve low- to mid-altitude air superiority.

Electronic warfare (EW) offers the potential to temporarily neutralize passive radar. Standoff noise jamming would have an effect, but because the location of the receivers is unknown, the jammer would need to emit across a wide sector, unavoidably reducing jamming signal density.[51]

Building new generations of stealth aircraft may be feasible, but efforts to improve stealth will eventually reach a point of diminishing returns. Advantages will grow more difficult and expensive to achieve as counterstealth technologies concurrently grow more advanced.


North Vietnamese surface-to-air missile crew in front of SA–2 launcher

U.S. Air Force

basic stealth techniques will be less effective than they once were against passive radar systems that benefit from bistatic geometry and the use of counterstealth waveforms

Moreover, deception jamming may be of limited use against passive radar, also due to the unknown receiver location.[52] Other types of jamming, however, may prove highly effective. Overall, the lack of known threat location bolsters the argument for a robust EW capability that is integral to friendly multirole aircraft. Advocacy for or against a dedicated EW platform, however, is beyond the scope of this article.

Other means of countering passive radar include special operations and computer network attack. In the end, targeting passive radar systems may fall in the "too hard" category for limited warfare. Missile systems—mobile SAMs, UAVs, and even man-portable air defense systems—may be easier to find than passive radar. The adversary will likely deploy substantial passive air defense assets, and U.S. forces will face a long, tedious process of locating and attriting them.

Implications

Passive radar has many implications for future U.S. military power. Stealth will continue to be a critical feature of tactical military aircraft, particularly as a defense against presently fielded weapons systems. As is evident in the continued proliferation of conventional radar SAMs and AAA, these threats are not going away any time soon.

Stealth airframes require long design and procurement processes, whereas avionics and software are more readily modified. This phenomenon is driving a philosophy in tactical aircraft design that basic stealth techniques are the critical solid foundation upon which the aircraft's more malleable offensive and defensive capabilities—sensors, weapons, and communications—are built. The concept of a layered defense will be critical to the survivability of stealth aircraft in the future.

Basic stealth techniques, however, will be much less effective than they once were against passive radar systems that benefit from bistatic geometry and the use of counterstealth waveforms. Increasingly, combatants will use passive radar and weapons systems to detect, acquire, track, and target aerial stealth platforms. Against such systems, stealth on its own will likely provide inadequate protection for manned aircraft, UAVs, and missiles.

This article posits that an ongoing race between stealth and counterstealth is emerging, in which technology will provide only incremental advantage to a combatant until a new counter is found. This assertion does not mean that there are no further opportunities to leverage stealth advantages, but that advances in stealth will be more *evolutionary* than *revolutionary*. The future of stealth and counterstealth will more closely resemble the technological one-upmanship that occurred during World War II and the Cold War than the order of magnitude advantage the United States enjoyed during the Gulf War and the two decades that have followed. Against a passive radar adversary, air superiority will likely only be achieved at significant cost. Forcible entry and amphibious operations will accordingly prove much more challenging. Once again, the defensive form of warfare asserts itself.

Recommendations

To best position the United States for the future, military strategists and operational planners must recognize the counter to U.S. stealth-based air-superiority that is currently unfolding, of which passive radar forms a core technology. These self-same leaders must take appropriate measures to ensure that the United States is not caught off guard by this impending shift in the technological landscape. The following recommendations are in order.

Endeavor to be a leader in the passive radar field. Arguably, the United States has marginalized the passive radar field due to a focus on conventional radar systems. The U.S. military must gain an understanding of passive radar, not merely theoretically, or with minor research and development projects, but with a dedicated effort. But why, one may ask, build a stealth counter when there is no immediate stealth peer competitor? The answer is that would-be competitors in the stealth arena are making a dedicated push to develop this technology. We cannot afford to spend billions on stealth, only to fail to thoroughly understand and counter rival systems. In support of this effort:

- build collaboration between key industry and independent electronic engineers
- increase prioritization of passive radar research and development
- develop and field a passive radar system on a U.S. training range—as a training tool for U.S. stealth pilots and systems to test countermeasures and tactics and assess performance[53]
- work hand in hand with key allies to develop shared capabilities
- explore enhancing parallel technologies (such as disposable transmitters).

Develop methods of degrading enemy passive radar. In support of this effort:

- focus on a multilevel EW capability against passive radar[54]
- continue to develop layered defensive measures for aircraft and UAVs.

Prepare for military operations without air superiority. In support of this effort:

- (again) develop passive radar, but in this case to deny enemy air superiority—future enemy stealth capabilities are ultimately not a matter of *if* but *when*
- continue to integrate complementary piloted and unmanned system capabilities
- plan and train to the contingency of military operations with only local air superiority or with air superiority largely denied.

Passive radar will play a critical role in future conflict. Ongoing advances in passive radar will deny traditional means of defeating enemy air defenses, make air superiority difficult to achieve against a passive radar opponent, and require changes in thinking to maintain U.S. power projection capability.

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F–35 Lightning II flies over Eglin Air Force Base, future home of Joint Strike Fighter training facility

U.S. Air Force (Julianne Showalter)

Will the United States go forward to a future that resembles the past—one in which air superiority is gained only through a gradual and costly reduction of the enemy—or to a future that is worse than the past, in which the use of airpower is denied? Alternatively, can the United States develop advantageous capabilities in passive radar, as well as effective counters to it, and so maintain the airpower advantage? In this alternate future, shaped by awareness of the shifting paradigm posed by counterstealth technology, the United States can become a leader in the passive radar field and, in cooperation with partner nations, position itself to maintain air superiority, accomplish its military campaign objectives, and achieve its political goals. Which future will ours be? **JFQ**

NOTES

[1] Passive radar is also known variously as *passive coherent location*, *passive covert radar*, and *passive bistatic radar*.

[2] Carl von Clausewitz, *On War*, ed. Michael Howard and Peter Paret (Princeton: Princeton University Press, 1976), 358.

[3] Giulio Douhet, *The Command of the Air*, trans. Dino Ferrari (Washington, DC: Office of Air Force History, 1983), 15.

[4] "The Bomber Will Always Get Through," *Air Force Magazine* 91, no. 7 (July 2008), 72, available at <www.airforce-magazine.com/MagazineArchive/Documents/2008/July%202008/0708keeper.pdf>.

[5] Paul Howland, "Editorial: Passive Radar Systems," *IEEE Proceedings Radar, Sonar and Navigation* 152, no. 3 (2005), 105.

[6] Ibid.

[7] "The Radar Pages—Chain Home," available at <www.radarpages.co.uk/mob/ch/chainhome.htm>.

[8] Howland, 105.

[9] Passive radar is considered a subset of bistatic radar. Bistatic radar can also employ cooperative (friendly) or noncooperative (enemy) transmitters. The British Chain Home radar and other radar fences are examples of early bistatic radars that employed cooperative transmitters as dedicated parts of the system.

[10] Craig C. Hannah, *Striving for Air Superiority*, vol. 76, *The Tactical Air Command in Vietnam* (College Station: Texas A&M University Press, 2002), 87.

[11] "F–117A Nighthawk Factsheet," available at <www.air-attack.com/page/44/F-117A-Nighthawk.html>.

[12] "F–117 Site History," available at <www.f117reunion.org/f117_site_history.htm>.

[13] Eliot A. Cohen et al., eds., *Gulf War Air Power Survey* (Washington, DC: Department of the Air Force, 1993), 650, available at <www.airforcehistory.hq.af.mil/Publications/fulltext/gulf_war_air_power_survey-vol5.pdf>.

[14] Ibid., 641.

[15] Benjamin S. Lambeth, "Kosovo and the Continuing SEAD Challenge," *Aerospace Power Journal* 16, no. 2 (Summer 2002), 12, available at <www.airpower.maxwell.af.mil/airchronicles/apj/apj02/sum02/sum02.pdf>.

[16] "Serb Discusses 1999 Downing of Stealth," available at <www.usatoday.com/news/world/2005-10-26-serb-stealth_x.htm>.

[17] Collin T. Ireton, "Filling the Stealth Gap and Enhancing Global Strike Task Force Operations," *Air and Space Power Journal* 20, no. 3 (2006), 69–76, available at <www.airpower.maxwell.af.mil/airchronicles/apj/apj06/fal06/Fal06.pdf>.

[18] In this article, the term *covert* means stealthy or hidden versus the sense of preserving deniability, as in *covert operation*, that is used in joint terminology. In the F–117 downing, covert SAM employment may have been accomplished through mobility, control of radar emissions, camouflage, and/or other considerations.

[19] Ireton, 71.

[20] B–2 and F–22 data are current as of April 2009. Joint Strike Fighter initial operational capability date is from Lieutenant General George J. Trautman III, USMC, *FY2009 Marine Aviation Plan: Supporting Our Most Lethal Asset* (Washington, DC: Headquarters United States Marine Corps, October 1, 2008), 6–3, available at <http://hqinet001.hqmc.usmc.mil/AVN/FY2009%20AVPLAN.pdf>.

[21] Christopher Bolkcom, *F–35 Lightning II Joint Strike Fighter (JSF) Program: Background, Status, and Issues* (Washington, DC: Congressional Research Service, February 17, 2009), 1, available at <www.fas.org/sgp/crs/weapons/RL30563.pdf>.

[22] "J–XX Stealthy Fighter Aircraft—(China stealth fighter)," January 3, 2008, available at <www.sinodefence.com/airforce/fighter/jxx.asp>. See also Mari Yamaguchi, "Japan to Build Stealth Fighter Jets by 2014," *Air Force Times*, December 10, 2007, available at <www.airforcetimes.com/news/2007/12/ap_japan_stealth_071207/>; and "Indo-Russian 5th Generation Fighter to Take Off by 2012," *The Times of India*, October 30, 2007.

[23] David Lynch, *Introduction to RF Stealth* (Raleigh, NC: SciTech, 2004), 3.

[24] Ibid., 8.

[25] Ibid., 46.

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[53] The author attributes the idea of a passive radar training range to Paul Wiedenhaefer, interview by author, Arlington, VA, April 15, 2009.

[54] By *multilevel*, the author means that electronic warfare should be considered tactically, operationally, and strategically. A multilevel electronic warfare (EW) strategy could include both dedicated and nondedicated EW platforms.