The Rules of Stealth

The B-2 bomber first flew on July 17, 1989.   Thirty years on, America counts on low observable stealth more than ever.

Every day, the B-2s provide nuclear deterrence and conventional bomber presence for the United States. The B-2 has also proved itself in combat in five separate air campaigns. Yet the rise of great power competition requires the US military to prepare for facing off with Russia, China – and the military hardware they sell. In the past five years, Russia has sold its advanced S-400 surface-to-air missile systems to China and other nations, and begun tests of its next-generation S-500 missile system. Both Russia and China have increased fighter and bomber flights in Asia and other areas. Some say the value of stealth is fading in the face of these threats.

It's fair to ask: can American stealth still rule air warfare?

Stealth and the Electromagnetic Spectrum

The rules of stealth begin with low observable shaping to elude radar tracking. *Every combat airplane is a group of geometric shapes*, thinks the stealth bomber designer.   Wings, vertical tails, engine inlets, weapons hanging under the wing, cockpit bubble, fuselage: all these are shapes that reflect radar waves back to enemy air defenses on the ground or in the air.

Radar came into widespread use in World War II when command and control centers on land and aboard ships used it to detect incoming formations of attacking aircraft. By the 1960s, radar-guided surface-to-air missiles guarded targets from Moscow to Hanoi. Electronic warfare attempted to artfully blast back energy to fuzz up tracking radars or turn their signals against them. But Vietnam loss rates showed the edge shifting to the defenders.

Then, in the 1970s, research on low observable shapes for aircraft yielded the first stealth fighter designs. Stealth works on a marvelous set of principles. Radar “sees” the returned waves. The area reflected by radar can be much larger or smaller than the physical dimensions of the aircraft itself. Special equations predict how radar waves behave. Analyze a combat plane as a group of shapes and the sum is the radar cross section.

A stealth aircraft’s design reduces the radar cross section. It’s not easy. Radar waves mirror back from vertical surfaces, bounce off tails, travel along edges, scatter around cavities and diffract from wingtips. Angle the surface, and the radar wave reflects off and away from the tracking radar. Put all these principles – and more – into place and with enough mathematics and simulation, engineers can calculate, predict and control radar return.

The net result is “low observables” or stealth. A low observable aircraft renders radar detection and tracking much less efficient. The first purpose-built stealth aircraft was the F-117. The flat plates and angles showed clearly the ideas driving first-generation stealth. To improve its stealth, the F-117 carried weapons inside a bomb bay instead of under the wings.

In 1981, the Air Force commissioned the B-2 bomber. With revolutionary low observable technology, the B-2 could elude the Soviet Union’s air defense batteries and outfox fighter interceptors.

Low observables are optimized to work against the most dangerous element of enemy air defenses: the fire-control radars. These radars emit a low frequency radar wave, the kind with a big wavelength that flows over any shape. The low frequency wave can detect something out there, briefly, then it’s gone. Tracking fast combat aircraft on an attack profile requires more frequent, shorter wavelength pings operating at closer ranges.

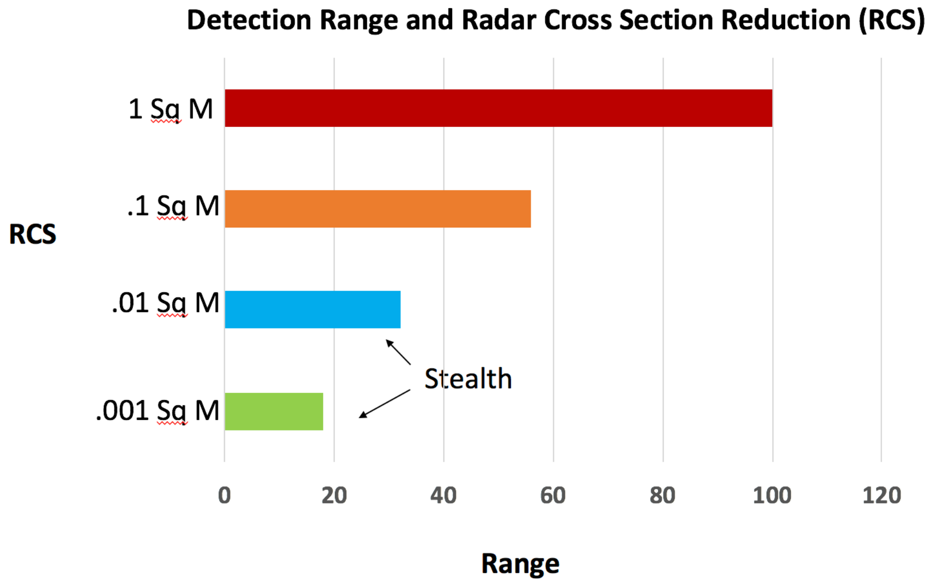
The B-2 bomber took stealth to a new level by introducing large, curved surfaces assisted by complex computer-aided design. And it added range and payload.

Defeating Integrated Air Defenses

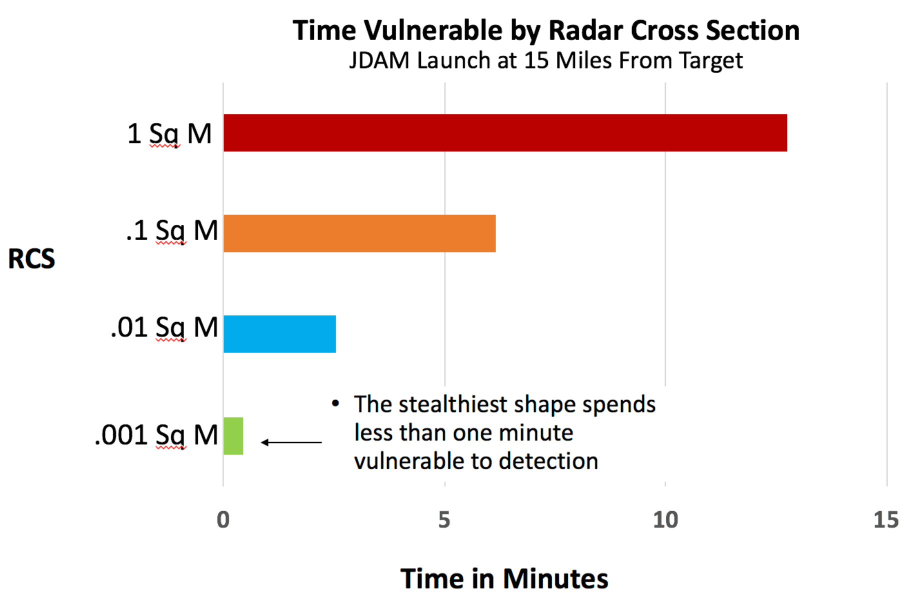
Stealth delivers surprise. Picture the B-2s attacking targets in Serbian airspace in 1999. Pilots reported the eerie quiet. Lights were still on in cities below, with flashes of other combat engagements visible at lower altitudes. Neither integrated air defenses nor the Serbian air force MiG-29s and other fighters interrupted the stealth B-2s on their bombing runs.

Low observables deliver survivability by drastically lowering the number of accurate shots taken by enemy surface-to-air missiles. Step one is reducing detection range. As discussed, the lower radar cross section cuts down the distance at which enemy radars can detect, track and engage the aircraft. Reduce the radar cross section by a factor of ten and the detection range of a radar is cut by 44%, according to the radar range equation.

The first chart shows a detection range for four notional aircraft, starting with a 1-meter square radar cross section and reducing down to very low observable levels. Very low observable radar cross section truncates the enemy air defense radar's effective range. At the lowest shape displayed, the stealth aircraft takes away most of the range tracking advantage. Here is where survivability increases significantly.



As detection range drops, the number of accurate shots taken by enemy air defenses also goes down. This happens in part because the stealth aircraft spend much less time inside the effective threat radius of the surface-to-air missile system. This next chart assumes each of the four notional aircraft is flying at 400 mph and will launch a JDAM at a distance of 15 nm away from the target. The stealthiest shape as depicted in green will be detected only at 18 miles away.



As a result, the aircraft must fly just three miles into the effective threat ring, which takes less than one minute at the given speed. In contrast, the aircraft with the largest cross section in red is detected earlier and spend more time in a zone of vulnerability. Less shots equals more survivability.

Stealth includes more than shaping for low observables against radar. The B-2 design also worked to control electronic, infrared, acoustic and visual signatures. For example, the B-2's four engines are nested inside the bomber with special ducting that reduces detection of engine exhaust heat. The sawtooth trailing edge of the B-2 helps create shed vortices to mix hot and cool air. The B-2's design also minimizes major sources of sound from the engines and airframe.

Updates to Stealth

Stealth is not static. While the rules of stealth apply, there is no question that the threat environment has changed. Today's military doctrine centers on multi-domain operations and tactics for gaining temporary air superiority to carry out missions in denied airspace.

Stealth is more important than ever. The single best proof comes from the national investment in two major fighter programs, the F-22 and F-35.   Both aircraft designs center on low observables and radar cross section reduction. In 2015, the Air Force's decision to build the B-21 Raider stealth bomber for the mid-2020s showed again that stealth is expected to be a dominant force in air combat for decades to come.

However, in the same time period, Russian and Chinese air defense systems have improved in quality and numbers since the original design of the B-2. Regional conflict scenarios once pictured punching through air defenses. Now, the Air Force thinks of penetrating corridors among dense threats that may remain active. Adversary fighters with long-range missiles and sophisticated radars will be in the air. Stealth in this environment relies more than ever on tactics, and in particular, on new technologies for threat emitter location.

The B-2 fleet is in the process of receiving a major Defensive Management System upgrade to improve the threat emitter location systems on the bomber. Active, electronically-scanned radars can assist with finding enemy surface-to-air missile batteries and other threats. For pilots in the cockpit, knowing the threat picture lets them adjust course and tactics, employ electronic warfare when needed, and improve radar cross section management.

Counters to Stealth

The resurgence of Russian and Chinese military modernization has also touched off a new round of debate on how to counter stealth. Not much has changed with physics. But, as it turns out, the counter stealth talk is fueled by hot rivalry among aircraft companies, both domestic and foreign.

Russian military sales brochures account for much of the counter-stealth literature. Here's an example. "With a unique wideband "Kharchenko" square ring element radiator arranged in a diamond lattice pattern, the Vostok E radar is designed to improve its frequency agility against earlier generation stealth fighters," read this one. "Even when facing more advanced stealth aircraft, the Vostok E can detect targets from 57 kilometers away and shoot them down with the S-300 surface-to-air missile. It is a new design to challenge the aerial domination of American stealth aircraft," or so the sales pitch said.

This Russian went on to brag that “Vietnam will probably become the first nation to use the radar system in an asymmetric warfare strategy against stealth fighters from China including the J-20 and J-31 over the disputed South China Sea.”[i]

Counters to stealth try to restore some of the detection range denied by low observable shaping. Since low observables concentrate on countering the short wavelengths for fire control radar, one counter-stealth tactic is to improve low-frequency detection. Improved correlation and analysis of long-range, low-frequency early warning signals might in theory yield better early tracks of stealth aircraft. Networked radars and better computing power are supposed to help compensate for what the low frequency signals can’t deliver.

The second approach is to separate the radar transmitter and receiver into a bistatic radar system. Most radar systems transmit and receive signals back at a single point. The bistatic system transmits radar energy to a receiver in a second location, making a line or barrier for attack aircraft to fly through, like the laser beam scenes in *Mission: Impossible*.

Then there is the old rivalry between stealth and electronic warfare. This one’s really an antique, for the best tactics now combine both. However, even a few years ago stealth was getting rough treatment in the hyper-competitive world of international fighter sales. At one public event, Boeing marketed its non-stealthy F/A-18G Growler electronic warfare fighter with the advertisement phrase “stealth is perishable; only a Growler provides full spectrum protection.” Recently Boeing has advertised its upgraded F-15s have “everything but stealth.”

This critique is a variation on the low-frequency approach. SAM (Surface-to-Air Missile) radars are shifting their frequencies into lower frequency bands where U.S. stealth is less effective,” said one executive.[ii]

Bomber, Not Fighter

Yet another subcategory of the counter-stealth debate spun off from criticism (by other aircraft manufacturers) of the F-35 Joint Strike Fighter. Asserting that the F-35 focused on front-aspect signature reduction, rival marketers suggested again that only electronic warfare could handle the threat. They didn't seem to notice that official Department of Defense strategy included advanced electronic warfare capabilities for the F-35 that are tested and performing well.[iii]

Buried in the mix is a valid point. Russian and Chinese advanced systems have improved their low-frequency, long wavelength. Advanced systems can share networked information to help refine early detection.

But the rules of stealth still apply. Stealth degrades surveillance radar detection and shrinks the effective coverage of fire-control radars. The hand-off from surveillance to fire control to missile shots breaks down. Most important, stealth starts with low observables and combines tactics, electronic warfare, networked information flows, and reductions in infrared to create the package of survivability.

Also, the fighter debate doesn't apply to assessing stealth for the B-2. It's important to remember the B-2 was designed with all-aspect signature reduction: meaning, specifically, that it's not limited to head-on attack. A prime requirement in the B-2 design was minimizing radar return from 360 degrees around the aircraft. Success in all-aspect signature reduction was one of the reasons Northrop won the contract originally. Signature reduction is perhaps not identical from every angle but the holistic design gives the B-2 low observables whether flying towards, around or away from target areas.

Tactics of the Future

Beginning with Operation Allied Force in 1999, American B-2 crews learned to fly the "blue line," carefully planning and updating the route to targets. Tactics of the blue line point the bomber's stealthiest signature aspect toward the threat. By flying the blue line, the bomber stays out of detection range. Altitude adds another advantage. Flying high can work around the strongest zones of radar coverage.

The B-2's stealth relies on more than one type of technology. One enemy breakthrough doesn't shatter stealth.

The B-2 and soon the B-21 can play unique roles in campaigns of the future. The stealth bomber can degrade enemy air defenses and strike other high-value targets. By extension, the stealth bomber's ability to attack any target, anywhere, is the foundation of deterrence. All-aspect signature reduction gives bombers the advantage in the duel with defending IADS and fighters. Only stealth aircraft can attack with maximum efficiency against the most important targets.

"The B-2 bomber, imagine having that come at you," remarked Air Force Chief of Staff General David Goldfein.[iv]

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[i] "Vietnam will buy the Belarus-made surveillance radar Vostok E able to detect stealth fighter," armyrecognitioncom, July 18, 2013.

[ii] Dave Majumdar "Stealth VS. Electronic Attack," USNI, April 21, 2014

[iii] House Armed Services Committee, Air and Land Subcommittee, "Military Services Fifth Generation Tactical Aircraft Challenges and F-35 Program," February 16, 2017.

[iv] Gen. David Goldfein, Remarks, Retirement Ceremony for Secretary of the Air Force Heather Wilson