

SPECIAL TOPIC

STATE OF STEALTH





Dear Reader,

When the U.S. flew the first stealth aircraft in the early 1980s, it revolutionized air warfare. More than three decades later, the science of reducing detectability to radar remains vital to the balance of military airpower. At least eight countries have developed or intend to develop stealth fighters, and the technology has been incorporated on almost every major combat aircraft in production today. But even as stealth technology advances, so do efforts to defeat it.



For more than 100 years, *Aviation Week & Space Technology* has reported on cutting-edge developments in aircraft technology. In that tradition, the magazine published “State of Stealth,” a seven-part series in 2016-17 designed to offer its readers a comprehensive understanding of stealth technology: the science, the platforms and the most extensive compilation of public data yet assembled. The articles contain over a dozen original illustrations and photographs, which are complemented by an online gallery. The pages include in-depth explanations of the physics, discussions of the history, revelations of new developments and quantitative analysis of progress.

We’ve compiled the entire series in this eBook, exclusively for *Aviation Week & Space Technology* subscribers. The chapters include:

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Meanwhile, Aviation Week’s global network of bureaus continue to provide close-up coverage of important developments in the defense sector. You can access our full coverage daily online at AviationWeek.com and catch up in print every other week.

And as always, I welcome your personal comments on our coverage; I can be reached directly at joe.anselmo@aviationweek.com.

Joe Anselmo
Editor-in-Chief
Aviation Week & Space Technology



Measuring Stealth Technology's Performance

Dan Katz

This is the first article in a series. For the non-U.S. nations buying the Joint Strike Fighter, Lockheed Martin's F-35 will be their first experience operating stealth aircraft. Since development of the aircraft began 15 years ago, radar technology has advanced and debate over the value of stealth has escalated. But several nations have now selected the F-35 in open competitions, citing in part the combat capability enabled by low observability. As the F-35 debuts at air shows outside the U.S., Aviation Week reexamines the fundamentals of stealth and whether it provides an advantage over the latest adversary radars.

Stealth Basics

Stealth is the science of reducing an object's detectability to radar. The goal is to minimize the electromagnetic energy reflected back to a radar so it cannot distinguish the return from the signals created by environmental clutter and noise of its internal electronics.

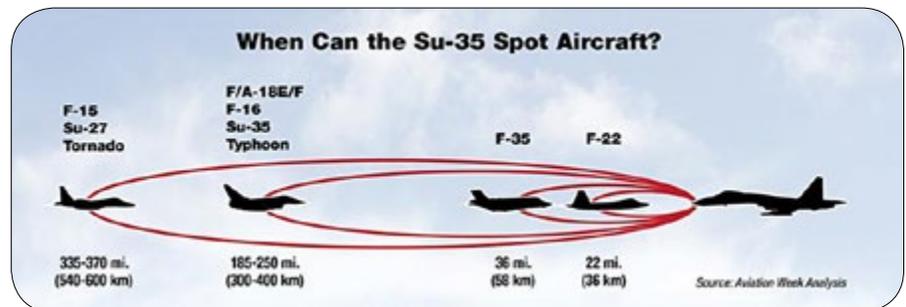
The metric of detectability is called radar cross-section (RCS), which normalizes the reflectivity of targets by comparing them to metal spheres. Human beings have an RCS of about 1 m²— they return as much radar energy as a sphere with a geometric cross-section of 1 m². Since RCSs vary by orders of magnitude, it also is common to use the logarithmic unit “decibel square meters” (dBsm), in which 100 m² converts to 20 dBsm and 0.1 m² to -10 dBsm.

RCS varies with the angle and frequency of the radar signal. The sector of greatest interest is ± 45 deg. in azimuth and ± 15 deg. in elevation, and the frequency band of greatest concern is X-band (8-12 GHz), where most fire-control radars operate. “All-aspect stealth”—minimizing detectability from any angle—and “broad-band stealth”—reducing observability over a broader frequency range—can be achieved with greater cost or engineering tradeoffs.

Stealth technology reduces RCS by shaping an aircraft to “scatter” radar waves away from the emitter and using radar-absorbent material (RAM) to reduce reflections by turning the energy into heat. Traditionally, shaping accounts for 90% of stealth's RCS reduction and materials 10%.

Shaping starts with a focus on “specular” scattering, in which waves bounce off a structure like billiard balls. Flat surfaces reflect most energy at an angle equal to the incident wave and are therefore preferred and oriented to minimize returns to the radar.

Engine intakes, cockpits, 90-deg. corners and other “multiple-bounce structures” reflect the most incoming energy back to their sources. Right angles are avoided entirely. Cockpit canopies are “metallized” with a few nanometers of gold or indium tin oxide to make them reflect radar energy. Engine fan faces can be shielded from radar illumination by external screens (F-117 and RQ-170), internal blockers (F/A-18E/F) or



Large “fourth-generation” fighters such as the F-15, Su-27 and Tornado have radar cross-sections (RCS) of 10-15 m². The F-16 and “Gen-4.5” fighters—Typhoon, Rafale, Su-35 and Super Hornet—are believed to be in the 1-3-m² range. The F-35 and F-22 RCSs are said to equal a golf ball and marble, respectively. Based on Sukhoi's claims that its Su-35 can detect 3-m² targets at 400 km in a narrow-angle, maximum-power search, Aviation Week estimated how far away it can detect these fighters. Note the detection range in a standard search is half as much.



serpentine-shaped inlets (B-2, F-22 and F-35), all of which incorporate RAM.

Weapons and other stores are carried internally. Missiles, bombs and fuel tanks increase RCS with their pylons, round bodies, cruciform tailfins and sensor apertures. They also create multiple-bounce geometries with the airframes, which can increase RCS.

Edges diffract radar energy in a narrow, fan-like pattern but still at an angle equal to the incoming wave, and wing and tail tips diffract waves in all directions. Both are kept narrow to minimize RCS, and edges are angled away from the direction of the threat.

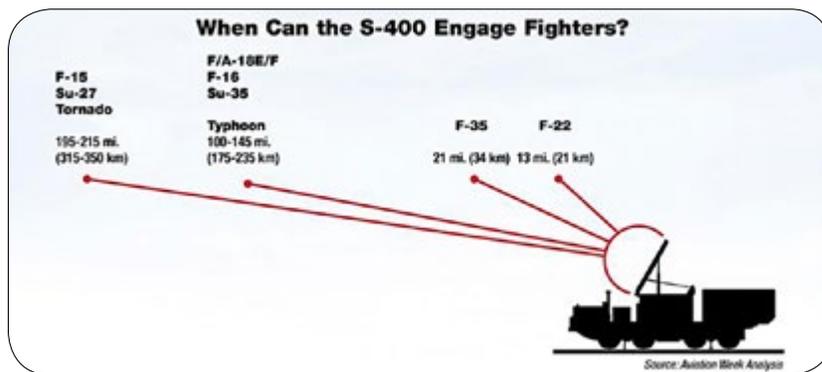
This front view of the F-117 shows the screens covering the engine intakes. The screen blocks most radar waves and traps the rest inside. Note also the hexagonal auxiliary intakes with edges aligned with the main intakes and side of the fuselage and the sawtooth pattern surrounding the canopy.



U.S. AIR FORCE

Fuselage facets, control surfaces, leading and trailing edges, and gaps are oriented to concentrate reflections into a minimum number of angles. This “planform alignment” reduces detectability at every other angle. The surface is then covered with RAM, with special treatments for edges and tips.

When waves strike surfaces at grazing angles, they induce currents that travel until they hit a discontinuity, where they radiate waves and bounce back to radiate again. The longer they travel, the weaker they become, particularly if the surface contains RAM, but any discontinuity—an edge, gap or step in the surface, or a material change—reflects them. Gaps around access panels must be covered with conductive tapes or caulks to bridge any electromagnetic discontinuities. Access panels and doors that open in flight, such as those for landing gear and weapon bays, have edges angled to reflect traveling waves away from the threat sector, often creating a “sawtooth” appearance.



Almaz-Antey says the S-400's 92N6E “Gravestone” fire-control radar can detect a 4-m² radar-cross-section target at 250 km. Based on this figure, Aviation Week estimated its detection range against modern fighter aircraft.

Estimating RCS

There are formulas to calculate the RCS of simple shapes and computer programs to

estimate those of more complex structures, but due to the difficulty in accounting for nonspecular mechanisms, interaction among structures and RAM, it is better to rely on RCSs determined by testing. Those numbers, sometimes cloaked in terminology of objects, have been discussed publicly.

Conventional aircraft of similar geometries and size tend to have similar RCSs. The Boeing F-15 has a frontal RCS of around 10 m². The Sukhoi Su-27 RCS is also in the 10-15-m² range and the Panavia Tornado



is likely in this neighborhood as well. The figure is larger if external stores are carried. The initial Boeing F/A-18's RCS is believed to be in the 10-m² realm, but F/A-18C/Ds began incorporating RAM in 1989. The smaller Lockheed Martin F-16's RCS is believed to be around 1-3 m²; the later C model is slightly stealthier than the F-16A, and signatures have also been reduced under Have Glass programs, which include application of RAM.

Later "Generation 4.5" fighters all employ RCS reduction to some extent. The Eurofighter Typhoon program sought to reduce RCS by a factor of four compared to Tornado. The Sukhoi Su-35 claims reduction of 5-6 times over the Su-27. This likely puts the Su-35, along with Dassault Rafale, in the 1-3-m² range. The F/A-18E/F, which Boeing says employs the most extensive RCS-reduction measures of any nonstealth fighter, is reported at 0.66-1.26 m².

While low observability is a spectrum and not a binary quality, "stealthy aircraft" usually implies an RCS of less than 1 m². Russia's new T-50 PAK FA is believed to be in the 0.1-1-m² range. Cruise missiles come in at 0.1-0.2 m². The F-117 was said to have an RCS equal to a small bird (0.01-0.01 m²). The F-35 RCS is compared to a "golf ball" and the F-22's to "a marble"; these objects have RCS of 0.0013 m² and 0.0002 m², respectively.

Detectability vs. Radar

How does stealth affect survivability? Since radar waves expand spherically going to and returning from targets, the range at which an aircraft can be detected is proportional to the fourthroot of its RCS. Every tenfold reduction decreases detection range by 44%.

The most advanced Russian fire-control radars yet deployed are the Irbis-E on the Su-35 and the ground-based 92N6E Gravestone, part of the formidable S-400 surface-to-air missile (SAM) system. The manufacturers of the Su-35 and S-400 claim good performance against "stealthy" targets, but their own numbers do not substantiate this.

Sukhoi states the Su-35 can detect a 3-m² target at 400 km (250 mi.). That is a good range against an F-16 or Typhoon, but it means this newest Flanker cannot detect an F-35 until it is within 36 mi., and inside 22 mi. for an F-22. And the U.S. fighters can launch their medium-range AIM-120 AMRAAMs from more than 60 mi. away. Also, that detection range is for a maximum-power, narrow-angle search. In conventional search mode, the detection range is half as much.

Almaz-Antey's S-400 is feared for many reasons, including its longest-range (380-km) missile, but it cannot fire until its Gravestone radar has a target. According to the manufacturer, Gravestone detects a 4-m² target at 250 km (155 mi.). Again, good against "reduced RCS" fighters, but the F-35 would not be seen until 21 mi. away and the F-22 13 mi. away. The U.S.'s internally carried Small Diameter Bombs can be dropped from more than 40 mi. away.

Much of the debate over the continued value of stealth has been generated by developments in lower-frequency radars (to be addressed in the next installment of this series), able to detect aircraft optimized for X-band stealth at longer range. But these are search radars that lack the resolution to provide targeting data. The S-400's 91N6E "Big Bird" search radar can detect 1-m² targets at 338 km (210 mi.), almost twice the range of the Gravestone, but its batteries cannot launch until the fire-control Gravestone has a target.

These figures are only estimates, but they are based on established formulas and public data from manufacturers and specialist engineers. The numbers convey the continuing advantage of stealth fighters, which can remain undetected until well within weapons range, even against top-end fire-control radars. These numbers suggest stealth remains a strong contributor to survivability against state-of-the-art weapon systems. 🗨



Physics And Progress Of Low-Frequency Counterstealth Technology

Dan Katz

This is the second article in a series. Since the advent of stealth technology, claims have abounded about ways low-observable aircraft can be detected. Chief among these are radars that operate at lower frequencies than those stealth aircraft are designed to defeat. With digital electronics technology overcoming some of the performance limitations inherent in VHF and other low-frequency radars, can they render stealth obsolete?

To understand the current balance of stealth versus counter-stealth as the Lockheed Martin F-35 joins the F-22 in operational service requires a closer look at how radars work, at the effect of wavelength on radar reflection, and at the capabilities of advanced lower-frequency systems now being deployed.

Lower-frequency radars are better for detecting stealth aircraft because of their longer wavelengths, which are inversely proportional to frequency (see table, Radar Band Frequencies and Wavelengths). Most fire-control radars operate in X-band (8-12 GHz), although some short-range systems use higher-frequency Ku-band (12-18 GHz). Search radars are typically S-band (2-4 GHz), for longer range. Some surface-to-air missile (SAM) systems use C-band (4-8 GHz) for both search and fire-control, as a compromise between range and resolution. Long-range early warning radars typically operate in L-band (1-2 GHz) or lower and it is these frequencies that have counter-stealth properties. The reason lies in the behavior of radar waves as they reflect off structures, which can be divided into three regimes based on the size of the structure relative to the wavelength.

Radar Band Frequencies and Wavelengths		
Band	Frequency	Wavelength
K _u	12-18 GHz	2.5-1.67 cm (1-0.66 in.)
X	8-12 GHz	3.75-2.5 cm (1.5-1 in.)
C	4-8 GHz	7.5-3.75 cm (3-1.5 in.)
S	2-4 GHz	15-7.5 cm (6-3 in.)
L	1-2 GHz	30-15 cm (12-6 in.)
UHF	300 MHz to 1 GHz	1-0.3 m (3.3-1 ft.)
VHF	30-300 MHz	10-1 m (33-3.3 ft.)
HF	3-30 MHz	100-10 m (330-30 ft.)

High-Frequency Scattering

A high-frequency regime (not to be confused with the HF radio band) applies when the structure is at least 10 times longer than the incident radar wave. In this regime, specular mechanisms dominate the radar, in other words the angle of reflection equals the angle of incidence, like billiard balls colliding. “Backscatter” – reflection towards the emitting radar – is reduced by angling surfaces so that they are rarely perpendicular to radars and suppressing the reflections from re-entrant structures such as engine intakes and antenna cavities with combinations of internal shaping, radar absorbent material (RAM) or frequency selective surfaces.

In this regime, “surface wave” mechanisms are small contributors to RCS, but are still present. These are the electromagnetic waves created by the currents induced in a surface when radar energy strikes it. As these currents move back and forth across the surface, they emit electromagnetic energy known as “traveling waves.” If the wavelength is small relative to the surface, these waves are weak and their overlap will generate maximum backscatter when the radar signal is at grazing angles.

When these currents encounter discontinuities, such as the end of a surface, they abruptly change and emit “edge waves.” The waves from different edges interact constructively or destructively due to their phases. The result is they strengthen the reflection in the specular direction and create “sidelobes” – a fan of returns around the specular reflection which undulate rapidly and weaken as the angle deviates from the specular direction. The currents can also swing around to a structure’s back side, becoming “creeping waves” that shed energy incrementally and contribute to backscatter when they swing back toward the radar.

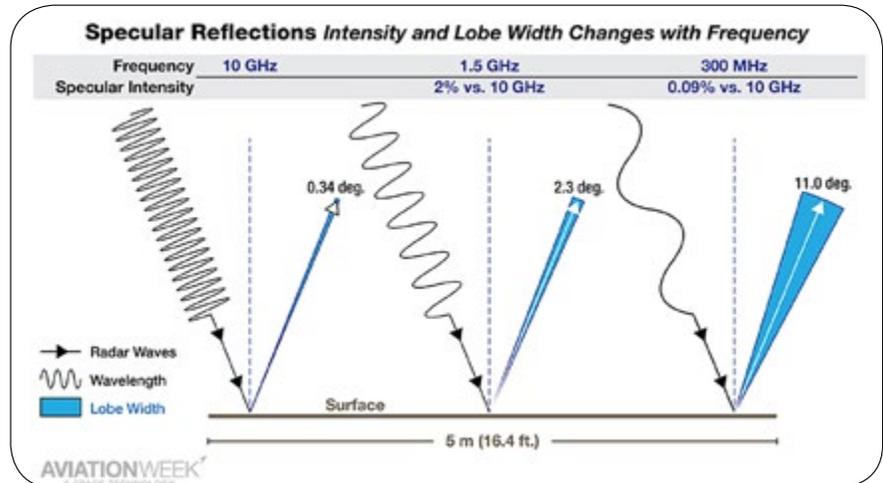
While small at high radar frequencies, surface waves still require attention on stealth aircraft. Aligning discontinuities to direct traveling waves towards angles of unavoidable specular return, such as the wing



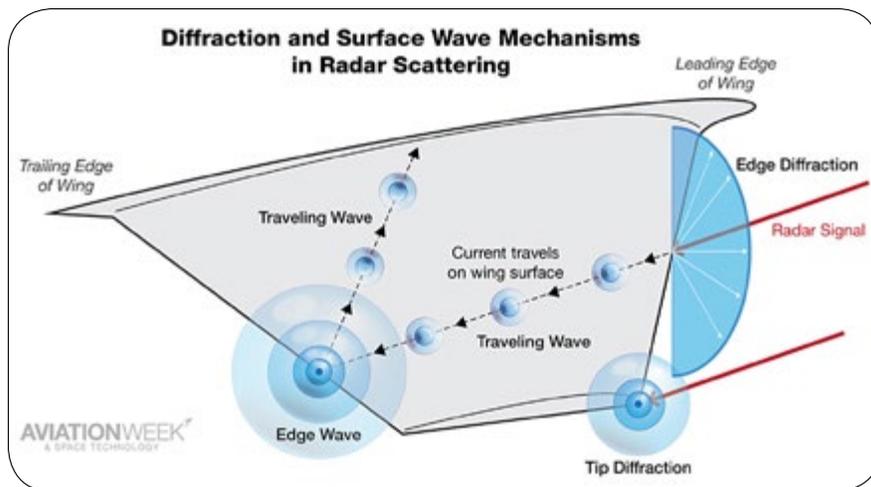
leading edge, can limit their impact at other angles. Designing airframe facets with non-perpendicular corners and so radars view them along their diagonals, at low angles and across from the facets' smallest angles, limits the area of edge-wave emission. At high relative frequencies, surface waves can also be suppressed with RAM.

They can also be reduced by blending facets. The first stealth aircraft, the F-117, was designed with a

computer program that could only predict reflections from flat surfaces, necessitating a fully faceted shape, but all later stealth aircraft use blended facets. Shapes composed of blended facets are more aerodynamic, but also allow currents to smoothly transition at their edges, reducing surface-wave emissions. Therefore, blended bodies have the potential for a lower RCS than fully faceted bodies. And blending the curves around an aircraft in a precise mathematical manner can reduce RCS around the azimuthal plane by an order of magnitude. The penalty is often a slight widening of the specular return at the curves, but in directions at which threat radars are less likely to be positioned. This was one of the great discoveries of the second generation of stealth technology.



DAN KATZ/AW&ST



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are almost 6 deg. wide. In addition, most RAM types become less effective as wavelength increases. For all these reasons, stealth specialists say the RCS of a stealth aircraft grows approximately with the square of wavelength from the lowest frequency for which it was designed, and that above-mentioned effects become significant when the wavelength reaches about 1/10th the size of a structure.

But aircraft RCS does not necessarily grow linearly. As surface-wave effects grow, their phases can interfere constructively or destructively with specular reflections. This phenomenon is illustrated in simple

The Resonance Region

As the radar wavelength grows, non-specular reflections intensify and specular reflections widen. For flat surfaces, traveling waves grow with the square of wavelength and their angle of peak backscatter rises with the square root of wavelength: at 1/10th the surface length, it is over 15 deg. Tip diffractions and edge waves from facets viewed diagonally also grow with the square of wavelength. Specular reflections from flat surfaces decrease with the square of the wavelength, but widen proportionally: at 1/10th the surface length, they



form with a sphere (see figure below). As wavelength grows relative to the circumference, the creeping wave circling the sphere grows continuously, but its phase interference with the specular return varies. This causes the sphere's RCS to undulate, with successively higher peaks corresponding to phase matches between the specular return and the strengthening creeping wave. This phenomenon is known as "Mie scattering" and this regime —where the wavelength is between one and 1/10th the size of the structure—is known as the "resonance region." Maximum RCS is often reached when the wavelength reaches the approximate size of the structure.

Rayleigh Scattering

Once the wavelength grows past this point, the specifics of target geometry cease to be important and only its general shape affects reflection. The radar wave is longer than the structure and pushes current from one side of it to the other as the field alternates, causing it to act like a dipole and emit electromagnetic waves in almost all directions. This phenomenon is known as "Rayleigh scattering." At this point, the RCS for many shapes will then decrease with the fourth power of the wavelength.

Net Effects

These effects occur individually for every shape on an aircraft and their reflections interact with those of every other shape. Smaller shapes exhibit the behavior before larger ones, but also have a lower maximum RCS. The behavior can also vary with changes in aspect angle.

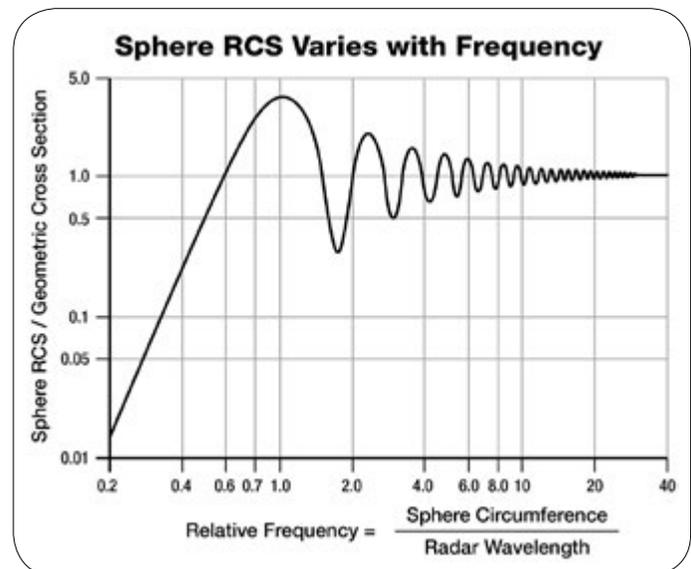
No RCS figures for fighters outside of X-band are publicly available but the above phenomena make low-observable aircraft more detectable as shaping and most RAM become less effective. The sizes of wings and tails on fighter aircraft are on the order of one to several meters.

This means these shapes might enter the resonance region in L-band and reach Rayleigh scattering in VHF, although the specific angle, frequency and geometry can still matter.

Lower-Frequency Systems

So why not build every radar for lower bands? Because they are less accurate at lower frequencies. Every antenna generates a beam pattern with a central cone called a main lobe within which most of its energy is emitted and reflected energy detected. The main lobe's width depends on the ratio of the antenna's aperture size to its wavelength. Longer wavelengths require bigger apertures, increasing cost and decreasing mobility, and even large antennas struggle to generate fire-control-level accuracy. Early in the Cold War, the Soviets developed the first mobile VHF systems, such as the P-12 "Spoon Rest," but its accuracy was so poor that target handoff to higher-band fire-control radars was difficult. Fighter radars have been largely restricted to X-band due to the need to fit in small noses.

But with the advent of active, electronically scanned array (AESA) antennas and improvements to computers and signal processing, lower-band radars have become more accurate and their range has increased. The state-of-the-art ground-based VHF system is now Russia's 55Zh6UME, produced by Nizhniy Novgorod Research Institute of Radio Engineering (NNiIRT). And the radar suite in Russia's new Sukhoi T-50





fighter includes N036L-1-01 L-band AESA antennas in the wing leading edges. These could be integrated into Sukhoi's Su-35 as well.

The 55Zh6UME may be able to detect stealth aircraft at far longer ranges than contemporary higher-band search radars. NNiiRT states a VHF detection range of 265 mi. for a 1m² RCS target, albeit at the curious altitude of 98,000 ft. No reference range has been released for the N036L-1-01. L-band might put the wings and tails of the F-35 and F-22 in the upper resonance region and possibly generate greater returns from their engine intakes and certain small shapes. The N036L-1-01 has a smaller aperture and likely less power than nose-mounted radars, but the advantages of L-band could be enough to detect stealth fighters farther away than the main radar.

From Detection to Engagement

Using lower frequencies can extend detection range against stealth aircraft, and provide early warning, but to engage them an adversary has to guide a missile accurately enough to put the target within the lethal radius of its warhead. The volume available inside missiles restricts onboard radars to higher C-, X- or Ku-band, so how to guide them?

One approach is to use VHF command terminal guidance. The idea is to link the 55Zh6UME search radar to the S-300/400 weapon system and use its data to direct the missiles all the way to their targets. According to data released by NNiiRT, however, the 55Zh6UME is not accurate enough for this. The manufacturer claims a root mean square error of 0.25 deg. in azimuth and elevation against a 1 m² RCS target. This means for targets only 20 mi. away it could be off by more than 460 ft., and proportionally more for more distant targets. This is inadequate to guide a missile. As for the N036L-1-01, Sukhoi does not claim the T-50 can engage targets with it and, being restricted in height to the thickness of the wing, the system likely has poor elevation accuracy.

Another approach is to use lower-frequency systems to cue fire-control radars and extend their range against stealthy targets. This theory digs into how radars detect aircraft. A radar must discern a target's return from environmental clutter and noise generated by its own electronics. Designers chose a ratio between signal and noise (S/N) at which the radar has an acceptable probability of detecting real targets, typically 90%, and an acceptable rate of false alarms, usually one per minute.

To improve S/N ratio, radars integrate the returns from numerous pulses. Since a target will be present at every pulse, but noise varies randomly, the signal builds up until the S/N ratio is achieved and the computer declares a target. Therefore, if a radar knows roughly where to look, it can send more pulses into a restricted search cone and increase the S/N ratio from farther away.

Theoretically, this technique can increase fire-control radar ranges up to those of the cueing sensors, but in practice it has limitations, such as signal processing hardware. A radar must generate enough pulses to cover its entire field of view, which means several thousand combinations of azimuth and elevation for regular search and even dozens to hundreds for a restricted search. For each angle, the radar must break up every return into dozens of range bins and each range-bin must be broken up into many velocity bins. Complex mathematics must also be performed for the bins and their resulting values before a target can be declared. So processing and memory requirements build up quickly.

In addition, signal processing is best done digitally, but that requires quantizing the analog signal into series of bits called words. The sensitivity of this analog-to-digital converter must be set so that above-average signals do not saturate the converter. But this means that low-end signals can register as zero, and stealth fighters reflect less than 1/1000 the energy of conventional fighters. Larger words can be used, but every bit increases processing and memory requirements, increasing cost, size, weight and complexity.



While the processor details for the S-400 SAM and Su-35 fighter are not known, the manufacturers' information suggests the ranges of their X-band fire-control radars cannot be extended significantly. Almaz-Antey's quoted range for the S-400's Gravestone radar of 250 km for a 4m² RCS target is specifically stated as with designation from the Big Bird search radar. The S-400's Big Bird can detect 1m² targets at 338 km (equivalent to 478 km for a 4m² target) and designate 4m² targets at 390 km, and still Gravestone's detection range is less. As for the Su-35's Irbis-E, it only detects a 3m² target at 400 km in a special narrow-angle, maximum-power search mode; detection range in standard search is half that. This suggests the higher figures for both systems are achieved only when the radar already receives external cueing.

Furthermore, extending radar range with external cueing would apply to conventional as well as stealth targets. The RCSs of conventional aircraft also grow with longer wavelengths and increasing signal integration time would be effective for a non-stealthy target. Therefore, this capability would likely be reflected in a greater detection range against higher RCS targets.

A third approach to engaging stealth aircraft is to combine VHF-command mid-course guidance and X-band active terminal guidance. In this scheme, a lower-frequency radar directs a missile towards a stealthy aircraft until the onboard X-band radar acquires the target. The U.S. Navy, for example, plans to use UHF-band AESA radars on its E-2Ds to provide mid-course guidance to SM-6 SAMs.

The concept holds promise, but would first require the lower-frequency radar to be able to localize the target enough for the missile to detect it. Missile sensors cannot match the range of fighter radars because they have far less power and gain. They only have to acquire targets towards the end of the flight, but against an F-35 or F-22 they will be looking at aircraft detectable at less than a fifth of the usual range. In addition, even if detected by the missile, stealth-fighter electronic countermeasures are made more effective by their low observability. This is because spoofing techniques, such as range- or velocity-gate pull-off, require the jamming signal to overwhelm the aircraft's real radar return, which is smaller for a stealth fighter.

When questioned about lower-frequency radar, some F-35 program officials concede detection is possible, but dismiss the possibility of engagement. This assessment appears to accurately reflect the state of the stealth-counterstealth balance – for now. But faster processors, smaller memory chips, stronger transmitters, better signal processing and superior antenna technology all have the potential to erode the advantage current stealth aircraft enjoy. When it comes to the state of stealth, neither side can claim final victory yet.

Anatomy of a Stealth Fighter Shootdown

Perhaps the best cautionary tale against assuming stealth fighters are invulnerable is the story about how one has already been shot down. Four days into NATO's air campaign over Serbia, an F-117A was brought down by an SA-3 northwest of Belgrade. The alliance's air forces assumed Serbia's outdated equipment posed a minimal threat to the Nighthawk. They didn't even mind the crowds, which are believed to have included Serbian agents, outside their airbases watching planes takeoff.

The stealth fighters flew the same routes every night on their way to Belgrade. On the ground, Lt. Col. Zoltan Dani, commander of the 3rd Missile Battalion, 250th Air Defense Missile Brigade, was able to eavesdrop on the unencrypted radio traffic between fighter pilots and the E-3 AWACS directing them. Colonel Dani had studied the F-117's technology and positioned his unit where he determined to be the optimum position from which to detect it.

On the night of March 27, 1999, weather had forced the cancellation of all NATO strike missions with the exception of eight F-117s. A little after 8pm, radar units in northern Serbia reported they had detected a target with a small RCS. At 26,000 ft., an F-117 was heading northwest from Belgrade after striking its target.

Col. Dani ordered his P-18 search radar (a 1970s upgrade of the P-12) activated. Initially, it detected nothing.



ing, but then he instructed the operator to activate an “innovation” and a target appeared on the screen at 31-37 mi. Colonel Dani has declined to detail the “innovation” but it’s believed to have enabled operation at an even lower frequency than normal. When the target closed adequately, the SA-3 operators began turning on their radars for 20-second intervals, to minimize exposure to NATO’s anti-radar missiles. On the third try, they locked on a target from 8-9 mi. away and fired off a pair of missiles at its 4 o’clock. The first flew over the F-117, failing to detonate, but the second struck, blowing off its left wing and sending it uncontrollably towards the ground.

The first lesson of this incident is that survivability is a combination of technology and tactics. When militaries use advanced technology without regard for tactics, a tactically skilled opponent can exploit a weakness, particularly if combined with a bit of technical ingenuity. Col. Dani knew the F-117’s flight path and the Nighthawks were the only aircraft around. That makes detection a lot easier than when an aircraft that can approach from any direction in a crowded sky. Hence the importance of tactics and also an underrated part of stealth technology: the electronic receivers that detect radar emissions and the computers that chart courses which minimize the chances of detection.

The second lesson is the continuing importance of combined arms operations. Stealth fighters might be able to do some jobs alone but they are more effective, and survivable, when combined with broadband stealth aircraft, jamming, anti-radar missiles, decoys and stand-off weapons. After the F-117 was shot down, it is believed U.S. EA-6B electronic attack aircraft began supporting the F-117s and strike aircraft gave more attention to search radars.

The third lesson is the potential vulnerability of stealth aircraft to lower frequencies. It is possible though that the F-117 is more susceptible to them than its successors. While it has a flat bottom, its fully faceted airframe might be more vulnerable than a blended shape at lower frequencies, because of surface wave effects, and the modified P-18 may have caught it an angle to exploit that. It also used early RAM. On the other hand, today’s lower frequency radars have far greater detection ranges than the P-18 and if they can solve the engagement problem they may be able to engage modern stealth fighters. To paraphrase the words of Col. Dani: there is no such thing as “invisible to radar,” there is only varying degrees of visibility. 🌐





The ‘Magic’ Behind Radar-Absorbing Materials For Stealthy Aircraft

Dan Katz

This is the third article in a series. Stealth is traditionally associated with aircraft shaping, but as more nations field low-observable aircraft and counter-stealth sensors, radar-absorbing materials (RAM) may take on increasing importance.

Typically, shaping accounts for 90% of the radar cross-section (RCS) reduction of a stealth aircraft and RAM the remaining 10%. And where RAM might reduce RCS by an order of magnitude, shaping can shrink it by three or four orders. But RAM reduces radar returns from certain features more than these guidelines imply and, while progress in shaping may be plateauing, in materials it is advancing rapidly.

Electromagnetic Materials

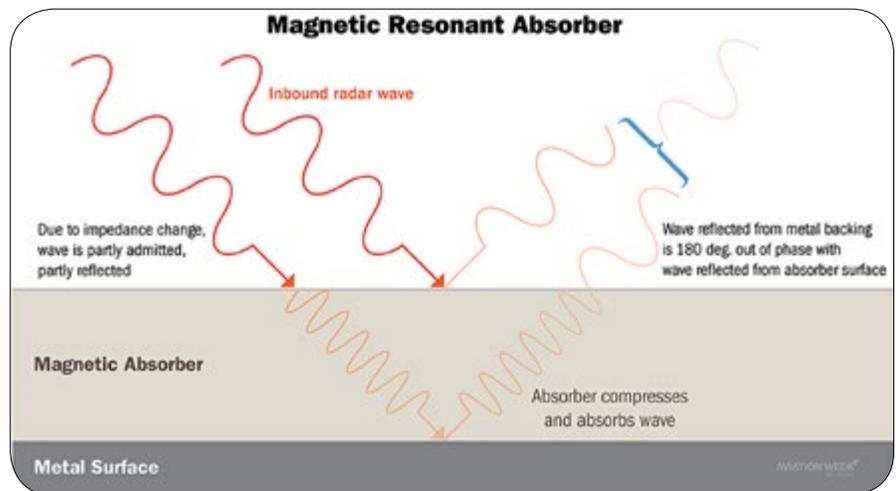
The ability of a substance to absorb electromagnetic (EM) waves depends on two material properties called permittivity and permeability, which are the capacity to store electrical or magnetic energy, respectively. The source of both is the existence of electric or magnetic dipoles at the atomic, molecular or crystal lattice level.

When an EM wave passes through the material, these dipoles orient opposite to the field's direction. In some materials, the dipoles effortlessly return

to neutral after the EM field returns to zero. In other materials, the dipoles are “sticky” and require energy to orient them or return them to neutral. That additional energy is lost and the material's permittivity or permeability is said to have a loss component.

RAMs are composites made up of a matrix material and a filler. The matrix is a low-loss dielectric material with appreciable permittivity and negligible permeability. They are effectively “transparent” to EM waves and are usually chosen for their physical properties. Typically, they are insulating polymers like plastic, glass, resin, polyurethane and rubber. Ceramics have higher permeabilities and heat tolerance. Foams and honeycombs have especially low permittivity—electrical energy storage—because they contain a lot of air. One might be tempted to construct an aircraft skin from such “transparent” materials, but radar would then reflect off objects beneath the surface such as sensors, fuel, metallic airframe and engine parts and the pilot. In practice, the bottom layer of a stealth skin is a highly conductive material, such as metal, which strongly reflects radar waves before they reach the complex reflecting environment below.

The RAM filler, meanwhile, is typically particles composed of or coated with a lossy material. Carbon is the material of choice for dielectric absorption because electrical lossiness is proportional to conductivity and carbon's conductivity is below metals but above insulators. Magnetic absorbers, which have some permittivity but far greater permeability—magnetic energy storage—are typically carbonyl iron (a pure powdered form of the metal) or iron oxides, also called ferrites. These materials can be impregnated into rubber or dissolved into a paint and ferrites are often sintered into tiles.



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As its permittivity, permeability and loss components increase, a material can absorb more EM energy because EM wavelengths shrink as these values rise. But when waves reach a boundary between two mediums, energy can be reflected rather than admitted. The amount reflected depends on their impedances—the square root of the ratio between each material’s permeability and permittivity. The greater the impedance change, the more energy is reflected before it can be absorbed. So RAM design must balance absorptivity with surface reflectivity to maximize absorption.

A material’s EM properties also vary with frequency. At higher radar bands, no magnetic materials have permittivity and permeability in a ratio close to that of air, so high surface-reflection is inevitable. But if the material is a quarter-wavelength deep, reflection from the metal backing partially cancels the surface reflection. Because of the high permeability of magnetic RAM, the depth required is small. Absorption performance of 20 dB (99%) is achieved by commercially available “resonant absorbers” with resonant frequencies of 1-18 GHz and thicknesses of 0.04-0.2 in. The technique is inherently narrowband, however, with significant absorption extending perhaps 15% from the resonance frequency.

Given this limited bandwidth, as well as higher weight and cost, dielectric absorbers are preferred for wideband absorption at high frequencies. Since dielectrics have no magnetic properties, their impedances never match air, but by using layers of materials—each with an increasing concentration of carbon particles—permittivity, conductivity and dielectric losses all gradually increase while impedance gradually decreases. Layers can also be adjusted to maximize cancellations. These graded dielectric absorbers can reduce reflection by 20 dB, and their bandwidth easily covers higher frequencies. However, they require significant depth to achieve lower-frequency performance: 1 in. for X-band and 4.5 in. for 500 MHz.

Another approach is to use a physical gradient. These “geometric transition” absorbers use pointed objects of homogeneous material oriented perpendicular to waves. The most common application is the pyramidal absorbers that line anechoic chambers used for RCS testing. At high frequencies, waves bounce among these structures, losing energy with each strike. If the wavelength is large relative to the structure, the waves act as though encountering a gradual change in material properties rather than a geometric shape. Absorbers of this type can reduce reflection by 60 dB, but require structures 15-ft. high for effectiveness at 30 MHz.

Counterintuitively, at lower bands, some magnetic materials become more effective because their energy storage—permeability—increases. At frequencies of 30-1,000 MHz, certain ferrites exhibit extreme wave compression and impedance close to air. Commercial ferrite tiles can achieve over 20 dB reduction in VHF band and 10 dB reduction through UHF, with a thickness of only 0.25 in. and a weight of 7 lb./ft.².

Thus far, what has been discussed is reducing specular reflections—those that bounce off an object like light off a mirror—but RAM is also particularly effective at reducing surface waves. These are the waves emitted by currents induced in a conductive surface when struck by radar. As they move along the surface they emit traveling waves, usually at angles close to grazing, and when they encounter discontinuities—an airframe edge, a gap or step in the surface or a change in material—they emit edge waves, concentrated closer to the specular reflection. Surface currents travel along a material’s length rather than through its thickness, and the RAM acts as a waveguide, trapping the currents and absorbing them. Magnetic RAM can suppress surface currents well in a thickness of only 0.03 in.

There are ways to combine techniques. Layered magnetic materials can reduce RCS by 10 dB from 2-20 GHz with 0.3 in. of depth. Hybrid RAMs can be created with a front layer of graded dielectric and a back layer of magnetic material to attenuate radar reflections from VHF to Ku-band.

Dirty Birds and Pie Panels

RAM has been part of RCS reduction efforts since they began. In 1943, Germany’s Horten brothers de-



signed their HoIX flying wing with wings of plywood sandwiched around a mixture of glue, sawdust and granulated charcoal. RAM would see service in the war aboard German submarines, on which a material called “Sumpf”—rubber infused with carbon granules (some sources say a magnetic filler)—was applied to snorkels and conning towers. By 1945, MIT’s Radiation Laboratory had developed a rubber material infused with disc-like aluminum flakes called MX-410 which exhibited anti-radar properties.

Lockheed’s Skunk Works and MIT radar experts tried many configurations of “Dirty Bird” U-2s, hoping to reduce RCS. The final approach was a paint loaded with carbonyl ferrite, which lowered RCS by an order of magnitude. However, none of these configurations prevented Russia from tracking the overflights.

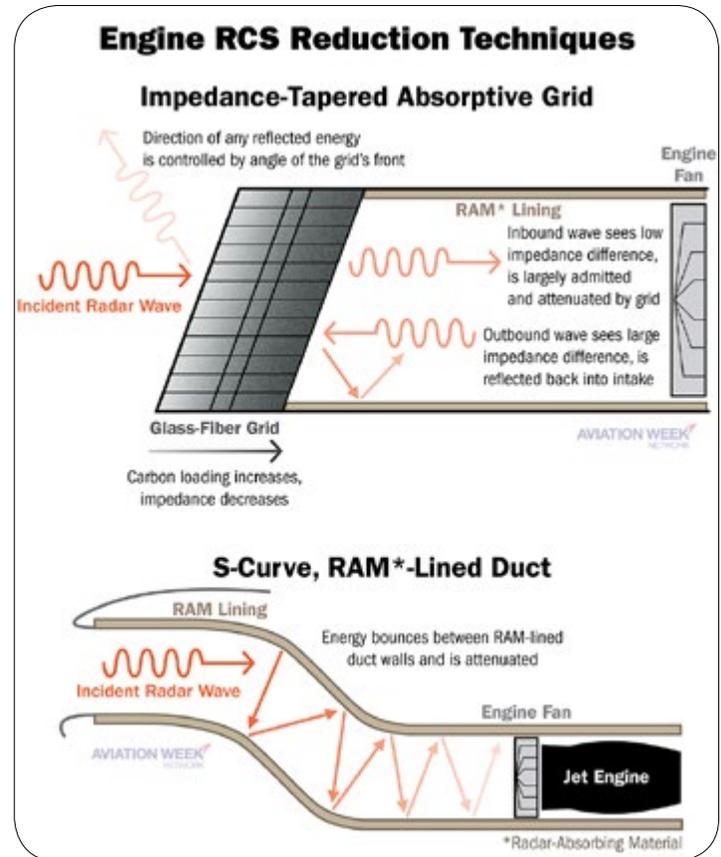
The U-2’s successor, the CIA’s A-12 and U.S. Air Force SR-71, would use speed and altitude for protection, but the agency still insisted that Skunk Works reduce the aircraft’s RCS. The most important breakthrough came in shaping. The aircraft received a thin, curved extension to the nacelles, leading edges and fuselage. This “chine” created a continuously curving airframe with sharp edges and a largely flat underside that reduced RCS by 90%.

In addition, around 18% of the aircraft’s material was RAM. There was a coating loaded with iron ferrites and laced with asbestos to withstand the high surface temperatures at Mach 3. The vertical tails were composed almost entirely of RAM and canted inward 15 deg. The A-12’s outer edge originally consisted of triangular pieces of titanium called fillets, but in later aircraft triangles of resistive plastic honeycomb with glass-fiber surfaces, called “pie panels,” were inserted into the wing’s titanium sawtooth edges and the fuselage chines. The Blackbird ended up with an RCS equal to that of a Piper Cub, which is about 4 m².

The Roach Motel

Unless RAM is integrated into a radar-absorbing structure, the material adds weight and volume without aiding structural integrity. Stealth design has therefore dictated using shaping to control the largest contributor to RCS, specular reflections. The first true stealth aircraft, the F-117, employed a fully faceted shape to control these and saved RAM largely to deal with cavities and surface waves.

The F-117’s skin was aluminum coated almost entirely with RAM. Originally, the material came in linoleum-like sheets of a ferrite-loaded polymer. They were bonded to the airframe’s skin in different thicknesses at different locations. Putty or paint RAM was used to cover fasteners, seal gaps and smooth uneven surfaces. Doors and access panels were sealed before every flight with metallic tape and covered in RAM. Initially, use of RAM paint was minimized as it is hard to apply at accurate thickness and requires the use of toxic solvents. Cockpit windows were coated with gold to minimize the impedance transition from the skin and block radar from penetrating the cockpit, where the pilot’s head would have an RCS 100 times larger than



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the aircraft.

Special attention had to be paid to engines and inlets because from the front these contribute most of a fighter's RCS. Engineers placed a glass-fiber, absorbent-impregnated grid on the intakes that acted like a "roach motel." Energy was absorbed on the way in and could not get out. Conveniently, the material was conductive so it could be heated to prevent icing. The filler was likely carbon, its concentration increasing from front to back. Inbound radar waves would see gradually decreasing impedance, be admitted and absorbed on the way through, and when bounced back toward the grid would see a severe impedance change and be reflected back into the ducts, which may also have been lined with RAM.

Several improvements were made to the F-117's RAM scheme during the program. The primary coating method switched to a robotic system in which a cradle positioned the aircraft while computer-controlled nozzles applied the radar-absorbent paint. There were efforts to reduce "leading-edge RCS" and develop new RAM skins. For a time, the fleet contained multiple RAM configurations before a program launched in the late 1990s standardized them.

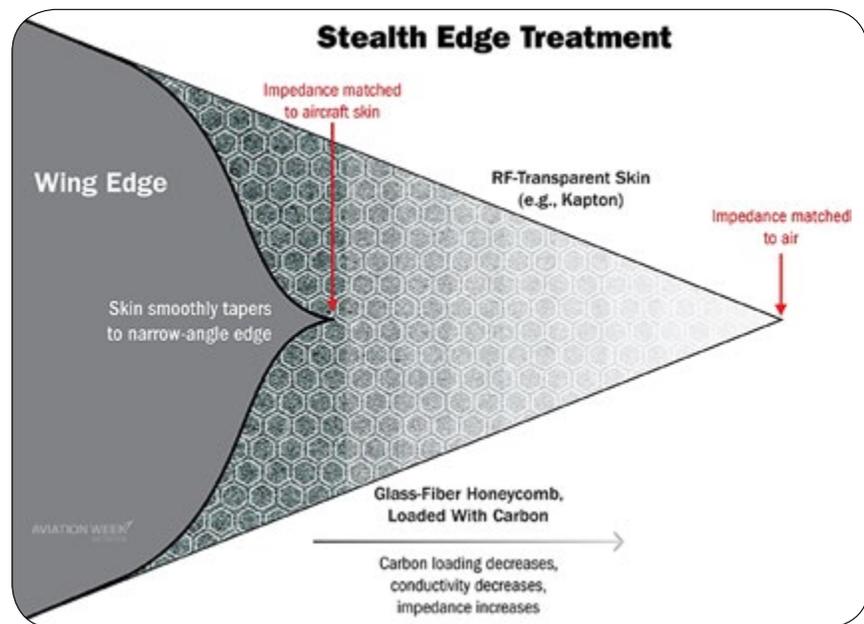
Edge Treatments, Silver Paint and S-Curves

The next stealth aircraft, Northrop Grumman's B-2, was said to rely more on shape and less on RAM than the F-117. Since the stealth fighter's fully faceted shape dealt well with specular reflections, this likely referred to surface-wave suppression. With upper and lower surfaces composed entirely of curves, the stealth bomber's shape has no discontinuities to create strong surface waves except for the edges of the aircraft.

But engineers now had a fix for this edge issue. Beginning with the B-2, all U.S. stealth aircraft have sported a distinctive "edge treatment," visible as a different-colored band around the perimeter of the airframe. Theory suggests what lies beneath. Within the triangular wedge is a lightweight material, such as glass-fiber honeycomb, loaded with carbon in a concentration that increases from tip to base. Impedance therefore decreases from air at the tip to zero at the conductive surface behind it. This allows surface currents to transition slowly rather than abruptly, as well as be absorbed. This arrangement suppresses three contributors to RCS: edge waves by slowing surface current transitions; traveling waves by absorbing the currents; and edge diffraction by absorbing incident radar waves. RCS drops significantly from every angle and particularly at off-normal angles.

The B-2 has considerable depth for an effective absorber made of dielectric materials alone but reports also indicate the incorporation of a magnetic material for better VHF-band absorption. To enhance taper and minimize diffraction, the conductive surface beneath may also slowly transition into a narrow wedge.

While edge treatments can absorb surface currents, those currents have to reach the edges and any surface discontinuity can prevent that. The B-2 airframe used as few panels as possible to minimize gaps, but



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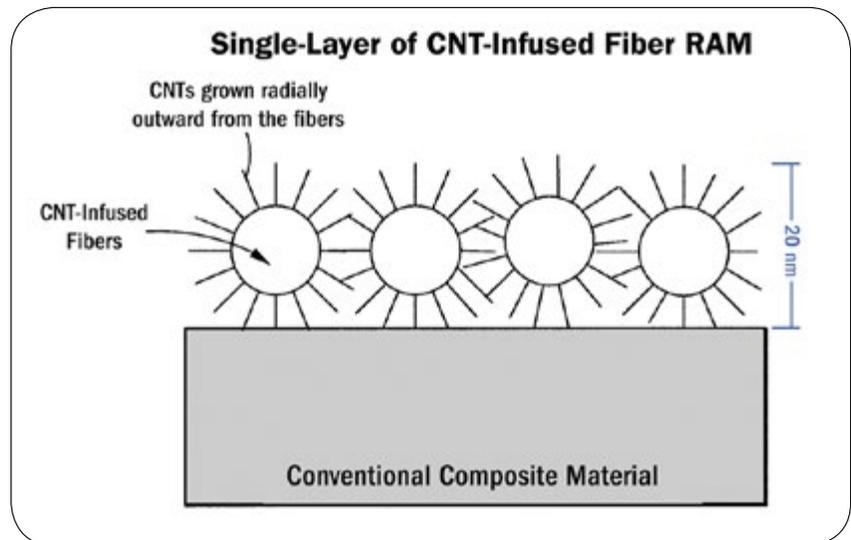


channels around doors and access panels were inevitable. Radar energy can even induce surface currents in the doors and panels themselves and, if those currents encounter discontinuities, they emit strong edge and traveling waves because the features have small dimensions. Therefore, those gaps must be bridged with conductive caulks or tapes. Around 3,000 ft. of tape was originally required for each aircraft. In addition, the B-2's coating included a silver paint. The effect of a discontinuity depends on its size and the conductivity of its sides. Silver is the most conductive metal, so its application might minimize the effect of gaps while also absorbing currents and blocking radar penetration.

To suppress engine returns, the B-2 used a serpentine duct lined with RAM. Both shape and material are vital to this RCS reduction technique. The RAM is thin, but the inlet's curve causes waves to bounce so many times the absorption adds up. Compared to a notional straight duct, an untreated serpentine inlet might achieve a reduction of 30 dB at boresight, but the advantage is zero outside 5 deg. off centerline. Add RAM, and RCS drops another 30 dB at boresight and stays 30-40 dB below unlined ducts, straight or curved, past 10 deg.

Changes to the B-2's RAM scheme since the 1990s have focused on reducing the maintenance burden, as well as RCS. Better tapes were introduced along with stronger caulks with shorter curing times. In 2003-10, B-2s also received the Advanced High-Frequency Material: a magnetic RAM robotically applied to access panels to reduce time required to restore stealth after routine maintenance. Flexible "blade seals" became the conductive bridge for some panels and certain gaps were surrounded with narrow bands of magnetic RAM called "picture frames."

The F-22 continued use of many RCS reduction techniques from the B-2. Its shape is composed of blended facets to minimize surface waves. Edge treatment is evident around wings, control surfaces and engine inlets. The intakes are S-curved and RAM-coated. Magnetic RAM is also used on certain panels and conductive techniques bridge impedance gaps.



LOCKHEED MARTIN, DAN KATZ & COLIN THROM/AW&ST

The "Magic" Layer and the Future of RAM

The low-observable materials developed for the B-2 and F-22 kept RCS small, but their maintenance burdens proved heavy. Their durability disappointed, necessitating frequent replacements that ballooned support costs and time while restricting aircraft availability. RAM fillers tend to be spherical, a few to tens of micrometers in size and densely packed, which is good for absorptive qualities but bad for durability. Bonding them to aircraft surfaces also proved troublesome.

So, from the beginning of the F-35 program, Lockheed's goal was to achieve acceptable stealth while reducing maintenance needs. Use of several RAM techniques continued, including S-curved, RAM-lined ducts, edge treatments and what appear to be picture frames abutting many gaps. Early reports also indicated the number of parts making up the skin would be minimized and laser-alignment would fit pieces so precisely "that 99% of maintenance requires no restoration of low-observable surfaces," Lockheed says. The



goal was likely to make the intensive gap-bridging procedures unnecessary.

But during development, something happened. First, program officials began hinting the F-35 might be stealthier than the F-22; hard to believe, given its less-disciplined shape. Then officials started referring to a material secret, a “conductive layer . . . where the magic happens.” In May of 2010, Tom Burbage, then executive vice president for the F-35 program, disclosed the incorporation of “fiber mat” technology, describing it as the “biggest technical breakthrough we’ve had on this program.”

The fiber mat would replace many RAM appliques by being cured into the composite skin, making it durable. Burbage further specified the mat featured a “non-directional weave”— which would ensure EM properties do not vary with angle. Baked into the skin, this layer could vary in thickness as necessary. Lockheed declined to provide further details, citing classification. Without further evidence, fiber mat would imply use of fibers, rather than particles, which would make for stronger surfaces and the word “conductive” points to carbon-based RAM.

But only a month before Burbage’s disclosure, Lockheed filed a patent claiming the first method of producing a durable RAM panel. The patent details a method for growing carbon nanotubes (CNT) on any kind of fiber—glass, carbon, ceramic or metal—with unprecedented precision in control of length, density, number of walls, connectivity and even orientation. The CNT-infused fibers can absorb or reflect radar, and connectivity among the CNTs provides pathways for induced currents.

Significantly, the CNTs can be impregnated with iron or ferrite nanoparticles. Fibers can have differing CNT densities along their lengths and homogenous fibers can be layered or mixed. The embodiments described include front layers with impedance matching air, use of quarter-wavelength depths for cancellation, stepped or continuous CNT-density gradients and continuously varying densities at specific depths for broadband absorption. The fibers can be disposed with “random orientation” in materials including “a woven fabric, a non-woven fiber mat and a fiber ply.”

The patent claims composites with CNT-infused fibers are capable of absorbing EM waves from 0.1 MHz to 60 GHz, a bandwidth unheard of in commercial absorbers, with particular effectiveness in L- through K-band. The patent does not quantify the absorptivity, but does say the panels would be “nearly a black body across . . . various radar bands.” Also, interestingly, a layer can be composed so an attached computer can read the induced currents in the fibers, making the layer a radar receiver.

While the patent mentions stealth aircraft, it does not mention the F-35 specifically, and the manufacturing readiness level of the material at the time it was granted is not known. But the proximity in timing and technology of the filing to the “fiber mat” disclosure is hard to ignore. Asked to comment on whether CNT-infused fiber RAM is in use on the F-35 and whether it is the technology to which Burbage had referred, Lockheed Martin spokesman Mike Rein stated only, “We have nothing to add to what was outlined in the patent submittal.”

Even if CNT-infused fibers are not the F-35’s “magic” layer, they may represent the new state-of-the-art in RAM. And while this may be the biggest development in the technology, it is not the only one. New materials are being tested all the time. In particular, metamaterials which use sub-wavelength geometric structures to impart qualities that do not exist in nature have received particular attention for their stealth applications. The future of stealth may be inseparable from the future of RAM. 🌐





State Of Counterstealth Technology On Display At Airshow China

Dan Katz

This is the fourth article in a series. Even as the Shenyang J-20 fighter performed its first public display above November's Airshow China in Zhuhai, the tall arrays of low-frequency air surveillance radars standing over the crowds were evidence of Beijing's efforts not only to match but to counter the U.S. advantage in stealth.

Towering over the flight line at Zhuhai were three air-defense radars from China Electronics Technology Group Corp. (CETC) and its Nanjing Research Institute of Electronic Technology (NRIET). The low-frequency trio reveals a similar design philosophy comprising tall arrays of horizontally polarized dipoles, the VHF-band JY-27A with 400 elements, UHF-band YLC-8B with 1,800 and L-band SLC-7 with 2,900.

The approach taken by CETC and NRIET to detecting low-observable aircraft while overcoming the limitations of lower-frequency radars appears different than that taken by Russia's Nizhny Novgorod Research Institute of Radio Engineering (NNiRT), which has employed wider arrays and, more recently, vertically polarized elements. Early Russian VHF systems like NNiRT's P-12 and P-18 used two rows of horizontally polarized

The JY-50 is a 2-D VHF-band, passive radar with two rows of 12 inverted V elements backed by a reflective grating.

Yagi antennas. The P-12 had six elements in each row, the P-18 had eight. In 1982, NNiRT introduced the first VHF radar with 3-D capability—the ability to ascertain target elevation in addition to range and bearing—the 55Zh6 Nebo “Tall Rack.” This massive, semi-mobile system consisted of four arrays of horizontal dipole elements on top of each other, the bottom one consisting of six rows of 26. A few years later, the institute's 1L13 Nebo-SV “Box Spring” entered service with six rows of 14 Yagis, shorter than those on the P-12/-18 and with folded dipoles.

In the early 2000s, Russia revealed its first active, electronically scanned array (AESA) VHF radar, the 1L119 “Nebo-SVU,” which had six rows of 14 short Yagis with folded dipoles, now vertically polarized. This was the first mobile VHF band radar to achieve 3-D capability, but its accuracy was limited, particularly in elevation.

NNiRT addressed the problem by expanding the arrays while adding higher-frequency radars to the system. Later in the 2000s, the 55Zh6ME Nebo-M was introduced, consisting of three radars mounted on separate vehicles: VHF-, L- and S-band. The VHF radar had seven rows of 24 Yagi elements. A few years later, NNiRT introduced the 55Zh6UME, which mounted a VHF-band AESA (with six rows of 20 elements) along with a 36-row L-band antenna on a single trailer.

KB Radar of Belarus recently took a similar approach to add a height-finding capability to its series of VHF-band radars. This Vostok series, which uses a wide array of unique square elements, was previously restricted to two-dimensional operation. The new Vostok-3D incorporates an S-band array to add a height-finding capability.

L-band arrays also remain popular for stand-alone counterstealth radars of which at least one was on display here. In one of the halls, China Electronics Corp. (CEC) showed off its REL-4 radar, which has an array that bears a strong resemblance to NNiRT's late-1990s Protivnik-GE L-band radar. NRIET also produces



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an L-band system, the truck-mounted YLC-2A, and CEC also advertises a VHF-band radar, the JL3D-91, although neither appeared at the show.

Close but Not Engaging Yet

Data provided by manufacturers (see table), make it possible to characterize the state of low-frequency counterstealth radars. All of these systems can boast long detection ranges. The longest appears to belong to Russia's Nebo-M, which can detect a target with a radar cross-section (RCS) of 1 m² at 315 mi. (510 km) in a

Counterstealth Radars Performance

Radar	Country	Band	Detection Range		Accuracy		Resolu- tion	Set-up/ Breakdown Time
			Target RCS @ range (altitude)	Azimuth (deg.)	Elevation/Height	Range (m)		
Nebo-SVU	Russia	VHF	2.5 m ² @ 60 km (500 m alt.) 270 km (10 km alt.) 360 km (20 km alt.)	0.33	1.5 deg. for elev. > 5 deg.	100		25-30 min.
55Zh6ME	Russia	VHF, L, S	1 m ² @ 480 km (30 km alt., circle scan) 510 km (30 km alt., 90-deg. sector scan)	0.20	0.17 deg.	90	4	15 min
55Zh6UME	Russia	VHF, L	1 m ² @ 430 km (30 km alt.)	0.25	0.25 deg.; 600 m @ < 200 km, 800 m @ 200-300 km	80	5.4	5 hr.
Vostok-3D	Belarus	VHF, S	1 m ² @ 350 km (10 km alt.)	0.30	0.08-0.1 deg.	25	5.5	8-10 min.
YLC-8B	China	UHF	F-22 @ 350 km, JH-7 @ 550 km	0.40	1,000 m @ 300 km & elev. 2.6-25 deg. 1,500 m @ 300 km & elev. 0.5-2.6 deg.	100	6	30 min.
1L121E	Russia	UHF	1 m ² @ 18 km (90-deg. scan) fighter @ 50 km (60-deg. scan)	1.00	1.0 deg.	100	18	2 min.
Gamma-DE	Russia	UHF	1 m ² @ 400 km	0.17	0.25-0.30 deg.	60-100		
Protivnik-GE	Russia	L	1.5 m ² @ 100 km (1,000 m alt.) 240 km (5,000 m alt.) 340 km (12-80 km alt.)	0.20	0.17 deg.	100		15-40 min.
REL-4	China	L		0.35	400 m @ < 200 km, 700 m @ < 300 km	150	3.5	
YLC-2A	China	L	2 m ² @ 440-530 km	0.30	500 m @ < 200 km & elev. > 1.0 deg.	50	2.4	

1 m² = 10.8 ft²; 1 m = 3.3 ft.; 1 km = 0.62 mi.

Sources: Manufacturers

90-deg. search mode. But it achieves this with three radars. Also, RCS varies with frequency, so the signatures cited by each manufacturer are not necessarily equivalent targets.

While RCS figures for most stealth aircraft have not been disclosed, some radar manufacturers have claimed formidable detection ranges against specific aircraft. KB Radar boasts a detection range against the F-117 of 215 mi. for the Vostok-3D and its earlier versions. NRIET cites the same detection range for its YLC-8B against the F-22 and 340 mi. against a non-stealthy fighter like China's own JH-7.

No manufacturer has specified a detection range yet against the B-2 or F-35. The B-2's RCS should be far smaller than the F-22's at lower frequencies, due to its shape and deep radar-absorbing structures. As for the F-35, its shape would be as vulnerable to lower frequencies as the F-22's, if not more so; its stealthiness at lower bands would depend on whether its radar absorbing material (RAM) can absorb the frequencies.

But detecting and tracking an aircraft does not mean a radar can engage it. Pulse-compression techniques have overcome the limitations in range accuracy exhibited by early VHF radars, but current examples are still limited in bearing and elevation. Some can match modern S-band search radars but still seem unable to guide a missile to a target.

The most accurate system for which data are available is the tri-band Nebo-M, which has a root mean square error of 0.2 deg. in azimuth and 0.17 deg. in elevation. A missile using targeting data with this accuracy to engage



an aircraft 20 mi. away could be off laterally by 370 ft. and proportionally more for farther targets.

An adversary could attempt to use a low-frequency radar to guide a missile with active radar homing close enough for its onboard sensor to acquire the target, but missile radars have far smaller apertures, lower emitted power and less processing capacity. Most still use mechanically scanned antennas. Data are not available to determine if any current missile radar has the scan speed and acquisition range to reliably acquire a stealth aircraft before passing it. In addition, many anti-air missiles trigger their warheads with radio-frequency proximity fuses, which might exhibit reduced range against a stealthy aircraft, requiring them to pass closer than usual to detonate.

The VHF-band JY-27A has straight dipoles in horizontally aligned rows. The array scans electronically in azimuth and elevation.

Another barrier to engagement is resolution—how far apart two aircraft must be for the radar to recognize them as separate targets. The Nebo-M has an azimuth resolution of 4 deg., which at a range of 50 mi. translates to a lateral distance of 3.5 mi. If multiple aircraft fly closer than that, the radar will see a single target, at a centroid weighted by the strength of each return.

Russia's VHF radars may also have problems discerning aircraft returns from ground clutter at long distances. The impressive detection ranges of both the 55Zh6ME and 55Zh6UME are cited for targets with heights of 30,000 m (98,000 ft.), beyond the service ceiling of any fighter and at least twice the height of the radar horizon at those ranges. This could stem from the vertical polarization of its elements, which NNiRT may have chosen to improve detection of stealth aircraft.

Low-observable aircraft are vulnerable to lower frequencies largely because of surface-wave effects. When radar waves strike the airframe, they induce currents that then emit "surface waves" as they travel along the skin and encounter discontinuities. As a radar's wavelength grows closer to the size of a surface, these emissions increase, which causes RCS to rise.

But these surface currents depend on the polarization of the radar. An electromagnetic (EM) wave consists of perpendicular electric and magnetic fields. Surface currents are only induced by the portion of the electric field that is perpendicular to the surface. An electric field fully perpendicular to the surface—called a vertically polarized wave—induces the most surface currents. One parallel to the plane—a horizontally polarized EM wave—induces none.

The RCS for stealth aircraft may therefore be higher for vertically polarized radar, because they have more surface area parallel with the ground. But vertical polarization increases returns from ground clutter, hindering detection of aircraft at low elevations. This might raise the minimum altitude at which the radar can detect a target and effectively limit the detection range of the modern 55Zh6-series radars.

A final trade-off low-band radars encounter is mobility. True "shoot and scoot" surface-to-air missile (SAM) systems like the Russian S-300/-400 have set-up/breakdown times of 5 min., which contribute to survivability. The Vostok-3D has a breakdown time of 8-10 min. and the other radars in its class take at least 15. This gives anti-radar weapons more time to arrive before the system is on the move. NNiRT's UHF-band 1L121E is small enough to be moving 2 min. after shutdown but at great cost: a detection range against a 1-m² target of only 11 mi., accuracy of 1.0 deg. in azimuth and elevation and resolution in azimuth of 18 deg.



DAN KATZ/AW&ST



Weaponized Television

Literally overshadowed at Zuhai by CETC's three large-arrays was the company's JY-50, a passive VHF-band radar apparently making its trade show debut. The JY-50 mounts two rows of 12 inverted-V receiver antennas, backed by a reflective grating, atop a truck in an arrangement reminiscent of the P-12/-18 series.

Most radars are active, in the sense they look for returns from signals they themselves emitted. But radio waves are always in the air, from radio or TV stations and other sources. Passive radars are designed to detect these ambient radio waves when they reflect off an aircraft. Watchers of old TVs with V-antennas would periodically see a darkened band traverse their screens; this was the TV picking up a passing aircraft.

The JY-50 cannot determine elevation, and its accuracy in azimuth and range is probably limited, but it can exploit the advantages of VHF-band for early warning against stealthy aircraft. It should be more survivable due to its mobility and passive operation, which makes it impossible to detect by adversary electronic listening systems. But it is not invulnerable. Most modern fighters carry radars that can detect ground targets, and antennas make great radar reflectors even if they are not transmitting.

A 'Fence' in the Sky

Another more exotic counterstealth system promoted at Zhuhai, this one by Russia's Almaz-Antey, was NNiIRT's Barrier-E forward-scattering, multispan radar "fence." First revealed late last decade, Barrier-E is designed to provide early warning of incoming stealthy and conventional aircraft, as well as cruise missiles, flying at altitudes from 100-23,000 ft. (30 m to 7 km).

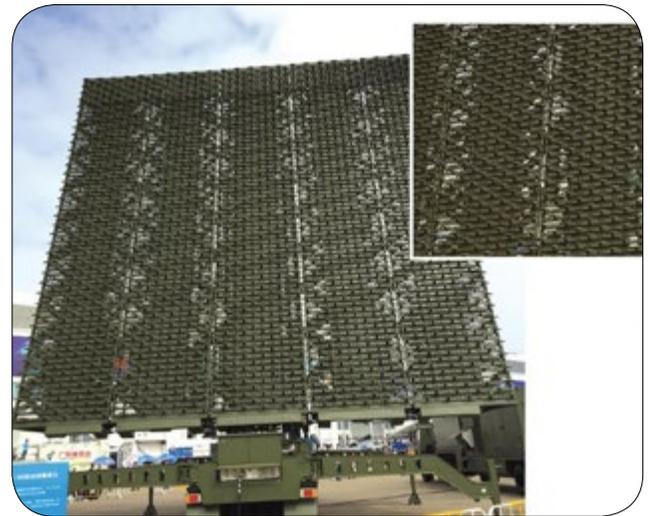
The tripwire is achieved by placing transmit/receive stations opposite each other, across "spans" of up to 30 mi. As many as 10 stations can function together in a single system. The towers create a fence 0.9-5-mi. wide that can detect aircraft with accuracy of 1,000-5,000 ft. along the fence and 260-660 ft. across the fence.

The L-band towers operate in a bistatic, forward-scattering fashion. Most radars are monostatic in that the receiver is collocated with the transmitter; in practice, they usually share an antenna. Therefore, stealth aircraft are designed to minimize energy reflected back in the direction from which it came. In a bistatic radar, the transmitter and receivers are located separately and, in the Barrier-E, they appear intended to catch aircraft between them so the receiver sees the energy transmitted by the opposite tower after it reflects off the target.

NNiIRT asserts that this approach increases target visibility by a factor of 1,000-10,000 compared to conventional radars. These figures may refer to how this setup can catch a specular reflection, the strongest of all radar returns, from the bottom of the aircraft as it traverses the fence, assuming it is low enough. It could also refer to the receiver's ability to catch returns at closer ranges than a collocated receiver.

In addition, NNiIRT asserts that detection performance is not affected by "antiradar coatings." This could simply mean the specular reflection is so strong and the ranges so short that stealth coatings, which are usually thin and designed primarily to attenuate surface waves, will not reduce reflection enough to prevent detection. Another possibility is that most magnetic and dielectric RAM cannot absorb L-band waves effectively without appreciable thickness. A third possible explanation is that a receiver in a forward scatter system would see stronger traveling waves than a monostatic radar because the traveling waves would be emitted in its direction before being

The UHF-band YLC-8B has swept dipoles, staggered horizontally. The array scans electronically in azimuth and elevation; it rotates 360-deg. mechanically.



DAN KATZ/AW&ST



attenuated by the surface and edge treatments.

Why Russia sees the Barrier-E as necessary, in spite of its many monostatic radars, is another question. One possibility is simply to catch all low-flying air vehicles where the horizon restricts radar detection ranges against any target. A second possibility might be a need to compensate for the difficulty Russia's VHF-band radars may have at detecting aircraft at medium altitudes at long distance.

Another rationale may be to provide additional protection against stealth aircraft at altitudes at which they are especially hard to detect. Stealth aircraft are often assumed to operate at high altitude—if radar cannot detect an aircraft, why risk visual, acoustic or infrared detection at lower altitude? But for radars, stealth aircraft are especially hard to detect close to the ground, because at lower frequencies they are masked by ground clutter and at higher frequencies they blend in with biological clutter. In the normal search and targeting bands, birds and swarms of insects have RCS in the same range as stealth aircraft, and the flapping of their wings can even create Doppler shifts in reflected radar waves that mimic those caused by an aircraft's velocity. This clutter does not exist at 20,000 ft., but at low altitudes it helps hide a stealth aircraft's signature. Barrier-E may be designed to mitigate this vulnerability.

The Great Hunt

What is clear from Zhuhai is the amount of effort Russia and China are putting into overcoming stealth. If there is any question about how much Beijing is investing in solving the problem, it may have been answered by another contractor at the show, the China Aerospace Science and Technology Corp. (CASC). The company's exhibit included a video of current and developmental UAVs, including one called the CH-805. The aircraft is shaped like a 1/13-scale B-2, and CASC says it will exhibit an RCS of less than 0.01 m². Asked why the aircraft is being developed, a company representative nodded toward the SAM system behind him. It is a target drone. 🚫





The Physics And Techniques Of Infrared Stealth

Dan Katz

This is the fifth article in a series. The advent of stealth aircraft has driven nations East and West to pursue a number of counterstealth technologies. One approach has been to go lower in the electromagnetic (EM) spectrum than conventional radar frequencies, to the L, UHF, VHF and even HF radar bands.

The other promising approach is to go higher, to the infrared (IR) band where passive sensors can detect the thermal radiation that is emitted by every object, particularly hot ones such as aircraft engines, exhaust plumes and friction-heated airframes. With increasingly capable IR-guided missiles and infrared search-and-track (IRST) systems being fielded, true low observability in the future will require stealth not just in the radar bands, but in IR as well.

Introduction to IR Stealth

The IR band technically stretches from the top of the extremely high frequency (EHF) radio band at 300 GHz to the visible band starting at 430 THz, a wavelength range from 1 mm down to 0.77 μm . The usable spectrum, however, is currently limited to 0.77-14 μm , which is further divided into three sub-bands: near-IR (NIR) at 0.7-1.5 μm ; mid-wavelength (MWIR) at 1.5-6.0 μm ; and long-wavelength (LWIR) at 6-14 μm . The exact boundaries vary and can include a short-wavelength infrared (SWIR) region in the 0.7-3.0- μm range. IRSTs function in both MWIR and LWIR. Early anti-aircraft missiles operated in NIR, but now almost all operate in MWIR, and the wavelengths of operation continue to rise.

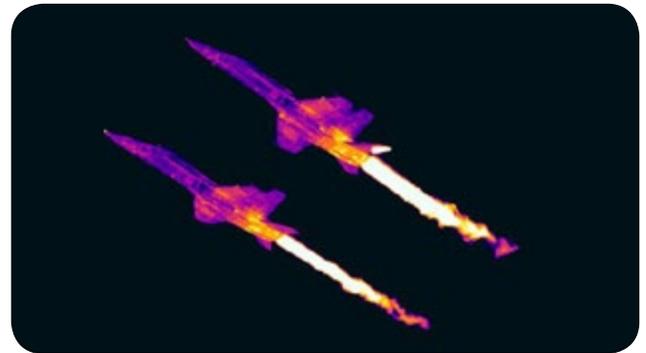
There are several different types of IR sensors that use materials sensitive to radiation at different wavelengths within the band. Uncooled lead sulfide (PbS) detectors operate at 2-3 μm . Cooled PbS or uncooled lead selenide (PbSe) detectors operate at 3-4 μm . Newer sensors with cooled PbSe, indium-antimony or mercury cadmium telluride (HgCdTe) detectors can operate at 4-5 μm . HgCdTe can also operate in LWIR along with microbolometers and quantum well IR photodetectors. In addition, detection ranges have benefited from the integration of focal plane arrays, with increasing numbers of detectors for higher resolution.

All objects with a temperature above absolute zero emit radiation in the IR band. As temperatures rise, total emissions increase with the fourth power of degrees Kelvin/Celsius, but they are spread across wavelengths and, with every degree increase, the emissions curve shifts to shorter wavelengths. An object at 20C (68F) radiates maximally at 9.9 μm , whereas one at 1,000C radiates maximally at 2.3 μm .

Emissions also depend on materials. A metric called “emissivity” expresses the ratio of a material’s radiation at a given temperature to that of a theoretically perfect emitter called a “blackbody” with an emissivity of one. Emissivity usually does not vary with wavelength, but materials can be designed so that they do.

Temperature and emissivity determine a material’s “radiance,” or emissions per unit area. However, an object’s “intensity”—signature strength with respect to a sensor—depends on its projected area at the sensor because a detector responds to “irradiance,” or the concentration of emissions striking it. Therefore, an object’s IR intensity depends on viewing angle and, because the sensor is looking out from the center of a

In this mid-wavelength infrared image of the U.S. Navy’s Blue Angel F/A-18s in a low-altitude pass, note the strength of the engine plume, its reflection off the stabilator of the upper aircraft and the heating of the rear fuselage.



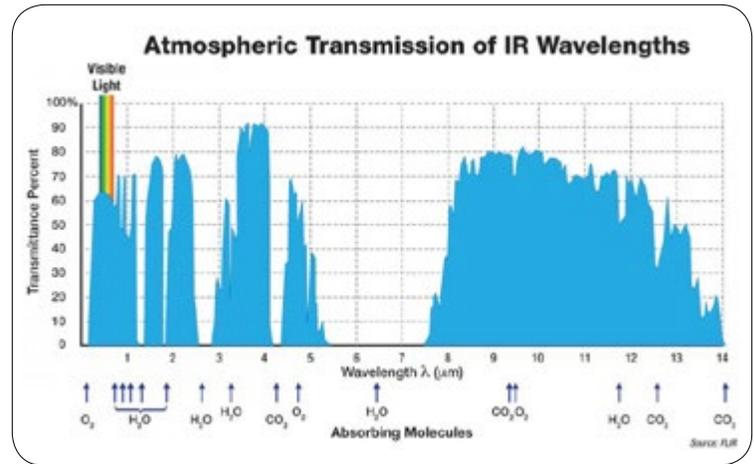
FLIR



sphere, irradiance always decreases with the square of distance.

In addition to emitting thermal radiation, aircraft can reflect emissions from the Sun, sky and ground, known as sunshine, skyshine and earthshine, respectively. Controlling IR signature requires considering both emitted and reflected radiation. Due to the law of conservation of energy, all incident radiation must be absorbed, transmitted or reflected. Emissivity always equals absorptivity, and materials are usually too thick to transmit. So if emissivity decreases, reflectivity must increase.

But radiation must arrive at a sensor to be detected. The atmosphere transmits some wavelengths less than others due to molecular absorption and specular scattering, principally by water vapor and carbon dioxide. Both become denser with pressure, and the denser the gas, the deeper and wider the “absorption band.” Water vapor density also varies with temperature but is so thin above 30,000 ft. it becomes insignificant. In practice, this absorption limits detection in MWIR and LWIR to “atmospheric windows” at 2-5 and 8-14 μm and means detection ranges are always worse at lower altitudes and angles.



Finally, targets must be distinguished against any background radiation or “path radiance” between the target and sensor. Ground radiance depends on vegetation and temperature and can have greater intensity than targets. The sky’s radiance increases toward the horizon and varies with time of year and latitude. A clear sky can be a difficult background against which to detect an aircraft, but clouds can both block IR radiation and reflect sunlight with intensity greater than targets. Below 3 μm , the dominant source of path radiance is sunlight scattered by aerosols, and above 3 μm , thermal emissions from the air increase to the end of the MWIR band.

A target’s total IR signature level (IRSL) is the sum of the signatures of all of its components. The signature of each component is determined by the contrast between its radiance and the background and path; its projected area on the sensor; the atmospheric attenuation of the emitted wavelengths—which, together with contrast and projected area, determine the component’s “contrast intensity”—and the sensor’s response to those wavelengths. Therefore, the primary contributors to an aircraft’s IRSL depend on viewing angle and sub-band.

In MWIR, an aircraft’s IRSL is largest from behind and smallest from the front. From the rear, the signature is dominated by engine “hot parts”—the nozzle centerbody, interior walls and aft face of the low-pressure turbine. The temperatures of these components are in the range of 450-700C, as are those of nozzle and exhaust plume. This is why almost all IR-guided anti-aircraft missiles operate in MWIR.

In the broader rear quarter, hot parts still contribute. So does the exhaust plume, but it is not as visible as one might think. Unlike solids, gas molecules oscillate freely, which causes them to emit and absorb energy at specific “spectral lines.” Since the main products of hydrocarbon combustion—water vapor and carbon dioxide—are also in the atmosphere, plume emissions are absorbed more than other signature components. However, the high pressure and temperature of the exhaust gases broadens their emissions around carbon dioxide’s absorption line at 4.2 μm , creating spikes in contrast intensity at 4.15 μm and 4.45 μm . But the atmosphere still attenuates these, particularly at lower altitudes, much faster than a smaller spike at 2.2 μm .



From the side, the plume's intensity is at maximum. It can extend more than 50 ft. behind the aircraft, but its radiance is concentrated in the first 4.5 ft. Side-on, the airframe also becomes a major contributor as its sensor-projected area increases. Nose-on, the leading edges of the wings and intakes are major signature contributors and the plume is still visible because it extends radially from the nozzle axis, although with rapidly decreasing temperature.

In LWIR, the greatest concern is the airframe, which can reach temperatures of 30-230C due to aerodynamic heating of the front and engine heating of the rear. While less radiant than the tailpipe, the projected area of the rear fuselage skin is 10 times larger. Reflected earthshine and skyshine are also significant in LWIR, particularly for low-emissivity surfaces and for aircraft viewed from above or below, with the earthshine's contribution growing with decreasing altitude. In NIR, reflected sunshine is the primary driver of IRSL from most angles. The plume contributes little in LWIR or NIR.

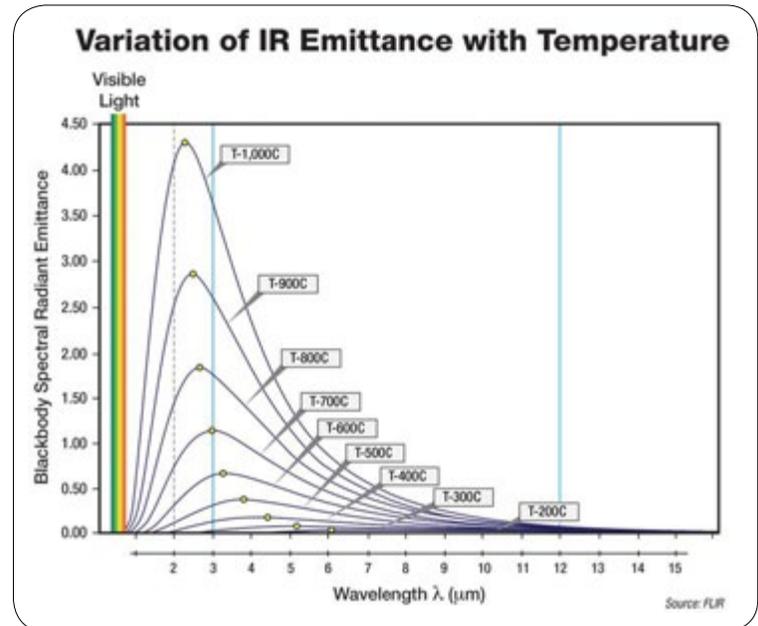
IRSL varies greatly with speed. With the engine in nonafterburning mode, the tailpipe and rear fuselage typically have larger signatures than the plume. When engaged, afterburners greatly expand the plume, double tailpipe temperatures and raise the rear fuselage temperature by about 70C. These effects can increase IRSL by almost 10 times.

The airframe, particularly its leading edges, also heats up at higher speeds. At 30,000 ft. and Mach 0.8, the skin temperature might be 11% above ambient, but at Mach 1.6 it could be 44% above ambient, which can more than double detection range. And as an aircraft goes supersonic it creates a "Mach cone" of compressed, heated air that can increase the area contrasting with the background by an order of magnitude and more than double detection range.

There is no publicly available data for IRSL of modern combat aircraft and, with all the factors, there is no simple metric of detectability like radar cross-section (RCS). For benchmarking purposes, Sukhoi contends the OLS-35 MWIRIRST on its Su-35 fighter can detect an Su-30-size target at 90 km (56 mi.) from behind and 35 km from the front. But the Su-30 is a large, twin-engine aircraft without significant IR signature suppression. Theoretical texts also state IR-guided surface-to-air missiles acquire targets around 10 km away from behind.

IR suppression for an aircraft usually starts with the engine. The signatures of hot parts are most easily suppressed by masking. The plume is shrunk primarily by enhancing the mixing of exhaust air with ambient air to reduce temperature and pressure more quickly. Common techniques include increasing engine bypass ratio and injecting cooler air, water vapor or carbon particles into the exhaust. Another method is to augment nozzles with chevrons, scallops or corrugated seals to promote radial spreading of the plume and mixing with ambient air. Chevrons along the nozzle trailing edge also create shed vortices, which accelerate mixing. These augmentations reduce sound emissions as well, which is why new airliner engines are fitted with chevron exhaust nozzles. Patents filed for these nozzles cite "substantial reduction in noise and IR signature."

Skin emissions can be reduced by using low-emissivity materials. Theoretical studies have suggested





In designing the nozzle of the F135 engine that powers the F-35 Joint Strike Fighter, Pratt & Whitney aimed to rival the F-22's wedge nozzles in signature while beating it on maintenance costs. The nozzle flaps incorporate minute holes to supply cooling air, like those on the F119, and overlap to create a sawtooth trailing edge, which introduces shed vortices to the exhaust and shrinks the plume. Their interior and exterior surfaces are likely composed of low-emissivity, radar-absorbent ceramics.

reducing skin emissivity from 1 to 0 can halve detection range. Layering materials with different indices of refraction can make surfaces reflective at certain wavelengths and emissive in others, such as those with greater atmospheric attenuation. Of course, surface coatings on stealth aircraft must also consider their radar effects.



PRATT & WHITNEY

Panther Piss and Platypuses

IR suppression has been part of U.S. low-observability initiatives for over a half century, often integrated with efforts to reduce rear RCS. The CIA's A-12, the first aircraft designed with signature control as a major criterion, was the first U.S. aircraft to suppress its rear RCS and reduce its vulnerability to IR-guided missiles. The aircraft's innate rear radar and IR signatures were large, due to the round, open titanium and steel nozzles and massive exhaust plumes. Lockheed compensated by adding "Panther Piss"—later revealed in declassified CIA documents to be cesium—to the fuel. This ionized the exhaust plume, reducing the aft-quadrant RCS, while also confounding IR-guided missiles of the time, possibly by radiating so intensely in NIR and MWIR that it saturated early sensors.

With the F-117, the first aircraft to use low observability as its primary means of survivability, Lockheed made IR suppression inherent to construction. The F-117's fuselage sloped aft from an apex above the cockpit to a broad, flat feature dubbed the "platypus." The engine exhaust flattened to thin slots 4-6 in. deep and 5 ft. wide, divided horizontally into a dozen or so channels. The lower fuselage terminated in a lip extending 8 in. past the exhaust at a slightly upward angle. This was covered in "heat-reflecting" tiles, similar to those used on the space shuttle, that were cooled by bypass air from the engines.

The platypus shielded the hot metal parts while the flattened plume reduced IR intensity from the side and accelerated mixing with ambient air. The extended lip masked the exhaust slot and first 8 in. of plume from below, while the low-emissivity tiles limited IR absorption and emission.

With the F-117, engineers were also introduced to the difficulty of balancing radar and IR signature suppression with the demands of extreme heat and pressure tolerance. The platypus was reportedly the hardest part of the design. Heat kept causing the structure to deform and lose its faceted outer shape. Ultimately, a structures expert designed a set of "shingled" panels that slid over each other to accommodate thermal expansion.

Northrop's B-2 stealth bomber kept many of the IR suppression techniques of the stealth fighter. Buried deep within the flying wing, the B-2's engines are prevented from heating the outer surface. Exhaust is cooled by bypass air, including from secondary air intakes, and flattened prior to exiting over "aft deck" trenches built of titanium and covered in low-emissivity ceramic tiles. Likely containing magnetic radar-absorbent material (RAM), these extend several feet behind the nozzles, blocking the plume's core from below and the side. Also, the engine fairings and aft deck both terminate in large chevrons, which introduce shed vortices.

This aft deck has proven one of the largest drivers of maintenance cost and time on the aircraft. By the late

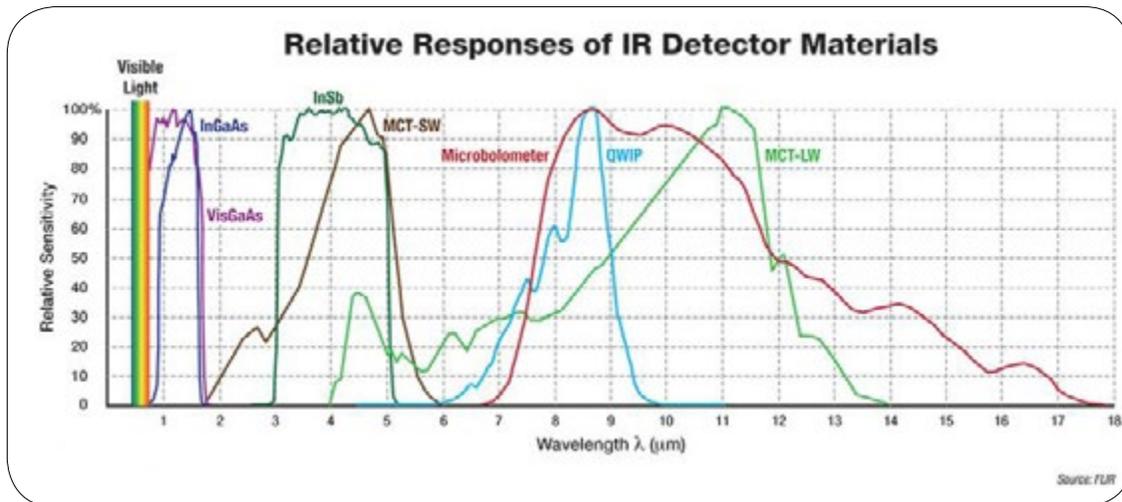


1990s, B-2s were experiencing exhaust lip blistering and erosion of the magnetic RAM faster than anticipated. New tiles were developed and new coatings added to the tailpipe, but cracking in the aft deck continued. By the mid-2000s, all 21 B-2s suffered from them. Interim fixes were fielded, including thermally protective covers for the tiles, while a long-term fix was developed which by 2010 was called the Third-Generation Aft Deck.

Turbine Shields and Topcoats

For Lockheed's F-22 and F-35, the need for afterburning engines, supersonic flight and fighter agility, as well as the desire for less maintenance, would require some new approaches. The U.S. stealth fighters use similar IR suppression techniques for internal engine parts, tail structures and airframe coatings. They diverge most noticeably in nozzle design.

The horizontal tails of both aircraft extend well beyond the nozzles, restricting the view of the exhausts and plume core in the azimuthal plane from the side and into the rear quadrant. The engines of both also have stealthy augmenters. Aft of the low-pressure turbine are thick, curved vanes that, when looking up the tailpipe, block any direct view of the hot, rotating turbine components. Fuel injectors are integrated into



these vanes, replacing the conventional afterburner spray bars and flame holders. The vanes mask the turbine and contain minute holes that introduce cooler air.

Both aircraft also feature IR-suppressive skin coatings. The final addition to the F-22's low-observable treatment is a polyurethane-based "IR topcoat" precisely sprayed by robots. Such IR topcoats have also been included in the F-16's Have Glass signature reduction program. The F-22 may also use fuel to cool its leading edges.

Despite the RAM fiber mats in the F-35's skin, Lockheed still finishes the aircraft with a polyurethane-based RAM coating applied by a newer robotic system. Program officials have stated this outmost layer possesses anti-friction properties; MWIR imagery of the F-35 suggests low emissivity as well. Both aircraft coatings still exhibit poor wear and temperature resistance and have needed time-intensive recoatings more frequently than desired. In 2015, the U.S. Air Force announced it was testing a new coating for the F-35 with better abrasion and temperature resistance.

The exact composition of the coatings is unknown, but polyurethane is often used as a matrix material due to its relatively high durability, adhesion and resistance to chemicals and weather. It has a natural emissivity of 0.9, but many fillers have been demonstrated to reduce the emissivity when used in composite materials. Levels as low as 0.07 have been achieved with bronze, although at the expense of higher conductivity



Pratt & Whitney's F119 engines use a number of techniques to shrink their plumes and limit the IR signature of the Lockheed Martin F-22 Raptor. Just visible in this photograph are the end of the curved vanes which block direct view of the low-pressure turbine and contain minute holes that inject cooler air to the exhaust. The "wedge" nozzles also flatten the exhaust, which shortens the plume by mixing it with ambient air as well as narrowing it from the side.

and therefore radar reflectivity. Multilayer glass microspheres of 5-500 μm diffused at 50-70% weight can achieve low emissivity at selected wavelengths and would probably be radar-neutral. Unoxidized iron also has emissivity in the 0.16-0.28 range, and its polyurethane-matrix composites have shown emissivity below 0.5.



U.S. AIR FORCE

Wedges and Tail Feathers

The F-22's "non-axisymmetric," or 2D, thrust-vectoring nozzles have upper and lower surfaces ending in wedges with blended central edges. These nozzles further mask the engine hot parts while flattening the exhaust plume and generating vortices. Minute holes are evident on their inner surfaces, likely providing bypass air for enhanced cooling.

The wedge nozzles are believed to be effective in signature reduction, but they are a major driver of the Raptor's maintenance cost and workload (nozzle internal flaps are one of the most often replaced parts even on conventional fighters). Thus, when designing the Joint Strike Fighter (JSF), engine and airframe manufacturers looked for a more cost-effective approach.

In late 1996, while the JSF competition was still ongoing, the two engine competitors tested axisymmetric designs aiming to rival the wedge nozzle's signature while beating it on cost. Pratt & Whitney tested the Low-Observable Asymmetric Nozzle (LOAN) on an F-16C, which demonstrated significant reductions in RCS and IRSL. The LOAN was known to incorporate shaping, special internal and external coatings and "an advanced cooling system" that was expected to more than double the life of the nozzle flaps.

In early 1997, GE tested a similar Low-Observable Axisymmetric (LO Axi) exhaust system on an F-16C, achieving its signature goals. GE stated LO Axi included overlapping diamond shapes, coatings and slot ejectors inside the nozzle to provide aircraft bay cooling air. The engine-maker said improvements in RCS design and material technology allowed axisymmetric nozzles to match the signatures of 2D exhausts while weighing half and costing 40% as much.

The nozzle on the Pratt F135s that power the F-35 descends from these approaches. It comprises two overlapping sets of 15 flaps, offset so outer flaps are centered on the gaps between the inner flaps. The inner flaps are thin, have metallic exteriors and straight sides and terminate in inverted "Vs." The sides create rectangular gaps between them with the nozzle fully diverged.

The outer flaps, which Pratt calls "tail feathers," are thicker and covered in tiles with blended facets. They terminate in chevrons that overlap the ends of the inner flaps to create a sawtooth edge. Toward the fuselage, the tiles end in four chevrons and are covered by additional tiles that terminate fore and aft in chevrons and interlock with adjacent tiles in sawtooth-fashion.

The F135 nozzle likely suppresses IR signature through multiple methods. The trailing-edge chevrons create shed vortices, shortening the plume, while their steeper axial angle likely directs cooler ambient air into the exhaust flowpath. The inner surfaces of both sets of flaps are white and incorporate minute holes similar to those on the F119, which might supply cooling air. Some reports suggest the presence of ejectors between the tail feathers and chevrons to provide even more cooling air. The tiles and inner flap surfaces are



likely composed of low emissivity, RAM composites. The trailing edge of the central fuselage also terminates in small chevrons, possibly further increasing airflow vorticity.

It is hard to quantify the success of these IR suppression efforts. Periodically, IR cameras will record stealth aircraft flying at air shows, but at ranges so close the images belie the suppressive effects of atmospheric absorption. Following the start of F-22 IR signature testing in 2000, Air Force officials stated the Raptor would exhibit a “low all-aspect IR signature under sustained supersonic conditions.” Some images captured by IR-sensor manufacturer FLIR of the F-35 at the Farnborough Airshow in 2016 suggest effective suppression of engine airframe heating and nozzle emissions. Undoubtedly, IR sensors are advancing, but they are also being met with initiatives to suppress IR signature. 🌐





Next Steps In Stealth: From Hopeless Diamonds To Cranked Kites

Dan Katz

This is the sixth article in a series. As more nations field combat aircraft with frontal stealth, which reduces detectability when engaging head-on, two factors are increasingly distinguishing low-observable (LO) designs. One is the degree to which radar cross-section (RCS) is reduced when viewed from the side and rear aspect. The other is “broadband stealth”—the degree to which signature stays small as radar frequencies reduce.

All-aspect and broadband stealth are growing in importance as aircraft are required to penetrate increasingly integrated air defense systems equipped with more accurate, lower-frequency counterstealth radars. To speculate how stealth could advance next, it is necessary to understand how the technology has progressed so far.

When rumors began swirling in the late 1970s about the U.S. developing radar-evading technology, most analysts thought the technology would center on rounding airframes to eliminate any radar-reflecting straight lines. Observers were stunned in 1988 when first the F-117 emerged with its strictly faceted surfaces and then the B-2 with its cross-section composed entirely of curves.

These appeared to be diametrically opposed shaping principles, but stealth designs developed since then have blended the techniques to different degrees.

The reason lies in the growing sophistication of RCS modeling, the differing missions of stealthy aircraft and the development of materials to compensate for certain shaping problems.

The tailless flying-wing B-2 was shaped by the need to minimize the RCS across more angles and frequencies.



U.S. AIR FORCE

Cracking the Code

As detailed in previous installments of Aviation Week’s State of Stealth series, radar reflections are governed by the four equations codified by James Maxwell in the early 1860s. These relate electric and magnetic fields to the electromagnetic properties and electrical currents of materials.

These reflections can be classified in five ways:

- “Specular” reflections bounce off surfaces at an angle equal and opposite to the angle of incidence.
- Edges “diffract” waves of parallel polarization into a cone of reflections with a half-angle equal to the angle between the incident wave and the edge. Tips diffract waves through 360 deg.

The perpendicular components of incident waves also generate currents in surfaces, which then emit three types of “surface waves”:

- “Traveling waves” are emitted by currents as they travel along surfaces and bounce off edges in a specular manner.
- “Creeping waves” are traveling waves that pass to the “shaded” side of the target and then back to the illuminated side.
- “Edge waves” are emitted by surface currents when they strike surface edges. These intensify and widen the main lobe of the specular return and create a fan of returns—sidelobes—around the specular reflection.

Solving Maxwell’s equations for a complex, 3D target from every viewing angle is incredibly difficult. Mathematical techniques have been developed, the most popular of which is the Method of Moments, but the computation required to generate complete RCS plots of electrically large targets (determined by their



dimensions in wavelengths) with complex features is so great it challenges even modern computers.

One of the greatest drivers of improving stealth technology has been more accurate methods for estimating RCS at relatively high frequencies—those at which the target's features are at least 5-10 wavelengths long. For such electrically large targets, electromagnetic interaction between constituent features is limited, allowing the total radar scattering effect to be approximated by breaking it down into discrete scattering centers and summing them.

The simplest estimation technique is called geometric optics, in which the rays of a wavefront are traced to determine their specular reflections. Physical optics attempts to approximate the fields generated on a surface by incident waves and resulting currents by making multiple approximations. Both have strengths, but also ways in which they fail to predict reflections accurately, particularly at low angles where diffraction becomes more important. A Geometric Theory of Diffraction made progress in this regard, but still encountered problems at important angles.

The breakthrough that made the Lockheed F-117 possible was achieved by Russian physicist Pyotr Ufimtsev, who in 1962 published a paper on a novel method for estimating edge diffraction, which became known as the Physical Theory of Diffraction. Ignored by Moscow, the paper in 1971 was translated by the U.S. Air Force Foreign Technology Division. In 1975, an electrical engineer at Lockheed's Skunk Works, Denys Overholser, incorporated Ufimtsev's approach in a computer program called "Echo 1." This broke targets down into thousands of flat triangular facets to estimate their individual RCS, then summed them to calculate the radar signature of the entire target. The limited computer capacity of the time meant the program could only calculate reflections from 2D shapes.

The F-117's shape was simplified to a series of facets to make computation of radar cross-section feasible.



U.S. AIR FORCE



U.S. AIR FORCE

By the time the B-2 was in development, a new generation of supercomputers enabled estimation of the RCS of curved

The DARPA/Lockheed Have Blue demonstrated faceted stealth as a precursor to the operational F-117.

surfaces. In the mid-1980s, McDonnell Douglas had set out to develop a more sophisticated RCS analysis

code. It had been discovered that facet-based codes, while they could run quickly, were less accurate than those using curved sections. Faceted models caused errors, termed "facet noise,"

that resulted in RCS predictions being too high—by up to 20 dB for LO designs at low-aspect angles. To approach the accuracy of curve-based models, targets had to be modeled with two facets per wavelength, requiring around 1 million facets for a fighter at X-band and greatly increasing the time to build the faceted model.

By 1987, McDonnell Douglas's new code included techniques to analyze precise curves defined by aircraft designers by modeling them not as facets, but as myriad standardized ribbons, each with its own geometry and angular considerations. This enabled high-fidelity predictions of double-curved shapes essential in the design of LO aircraft. The program typically modeled at eight samples per wavelength in each direction. For "bumps" such as sensor protrusions, 16 samples were used to accurately evaluate the impact.

The code also accounted for gaps, edge diffraction, multiple-bounce structures, transparencies, sur-



face-edge interaction, radar-absorbing material (RAM) and edge treatments. Computations took at least two orders of magnitude more time than facet-based techniques, but were more accurate, particularly for low-signature shapes with complex curves, and ultimately reduced overall design times.

There are a few general rules regarding the effect of curves on RCS. The RCS of a sphere increases with the square of its radius; that of a single curve surface increases with radius and with square of length; simple double-curved bodies are proportional to both radii. But what happens when radii continuously change, when a curve joins a flat surface, when the radii are electrically small, or when gaps or RAM are involved can only be determined by sophisticated, often proprietary, modeling codes. Design experience with the B-2 and F-22 in the 1990s showed contractors that even the most sophisticated modeling results must then be verified at full scale by an RCS testing facility.

Protecting the Six

A conventional fighter's radar signature when viewed from the rear is similar in magnitude to that from the front. Viewed from the side, RCS can be an order of magnitude larger. Signature is typically at minimum when viewed at a 45-



DARIN RUSSELL/LOCKHEED MARTIN

The F-35 shows angling of fuselage and tail sides but has many more bumps than previous stealth designs.

deg. angle, perhaps 5-10 db lower than fore and aft.

From behind, the RCS phenomenology is similar to the front. The dominant contribu-

tor is the engine exhaust. Radar waves entering from the jetpipe from behind will exit in that general direction, while those striking the nozzle-flap edges will send diffracted returns in the

same direction. Unswept trailing edges on the wing or tail also send diffracted waves in the same direction. Strong surface waves generated by the nozzle flaps also are likely to increase RCS across much of the rear aspect.

Side-on, conventional airframes have larger geometric cross-sections and often contain features that make good radar reflectors. Vertical surfaces generate "specular flashes" from the side. Right angles formed by vertical and horizontal tails generate strong specular returns to radars above the azimuthal plane, while those formed by the wing and fuselage or pylons do the same below the aircraft. Cylindrical shapes such as exhaust nozzles and engine nacelles also generate strong, consistent specular returns at all angles perpendicular to their surfaces.

But LO design must consider not just the signature, but also the sensor. Radar performance degrades at viewing angles where a target must be distinguished from background clutter. Most radar energy is transmitted and received via a main lobe aligned with the antenna's boresight, but smaller amounts enter through sidelobes that point in almost all directions. Clutter can enter the receiver via the sidelobes, and the processor has no way of knowing the return did not come from the main lobe. Such returns can mask that of the target.

Modern radars mitigate this phenomenon with Doppler processing. A pulse-Doppler radar records the time of arrival of a return and also compares its phase with that of the transmitted wave. The difference between the two reveals the target's radial velocity. The computer creates a 2D range/velocity matrix of all returns, which puts approaching targets in cells with no stationary ground clutter. This is why airborne radars exhibit their best detection ranges against approaching targets.

But if the target is being chased, its radial velocity will match some of the ground clutter, and it will be



harder to detect. For example, the Sukhoi Su-35's Irbis-E radar in high-power, narrow-beam search can detect a 3-m² (32-ft.²) target at 400 km (250 mi.) from the front but only 150 km from behind, and these ranges drop by half in normal search mode. The hardest airborne targets to see are those moving perpendicular to the radar, because their Doppler profile matches the ground directly below the aircraft.

In addition, all missiles have reduced kinematic range against fleeing targets. For example, the Russian R-27ER1 semi-active radar-guided air-to-air missile, equivalent to a later-version AIM-7 Sparrow, has a range of 93 km against approaching targets but only 26 km from the tail aspect.

For ground-based radars, the same

The original RCS programs could only handle facets, but by the 1980s codes could handle curved surfaces.

principles apply, but the antenna is stationary. Fleeing targets stand out as much as approaching aircraft. But ground-based radars are especially challenged in detecting targets moving perpendicularly, because their Doppler profile matches the stationary clutter all around. A tactic used by fighter pilots against ground radars, called “notching,” is to turn perpendicular to the radar, placing the aircraft in the “Doppler notch” in which the radar suffers significantly reduced range.

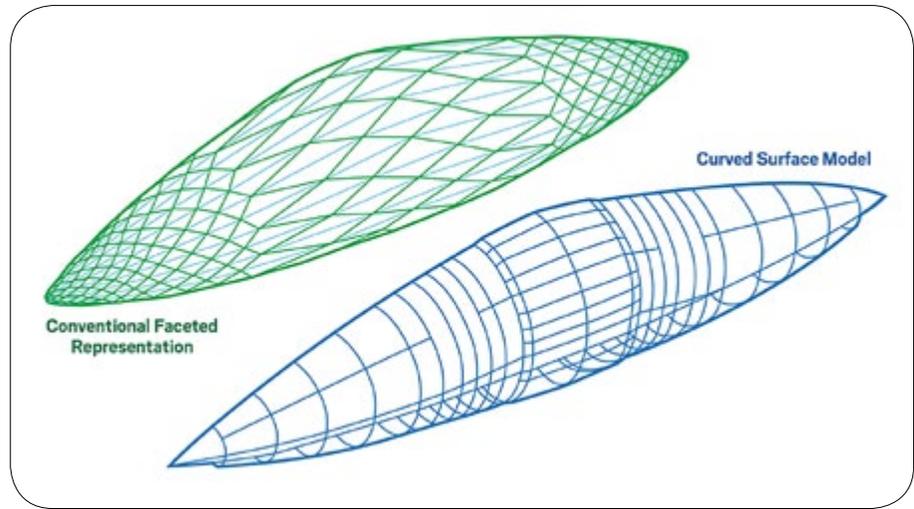
In addition, modern radars use phased-array antennas, which electronically point and scan the beam using phase differences between fixed modules. For these antennas, as the beam scans away from its physical boresight, its lobes widen with the cosine of the angle—by up to 50% at 60 deg., the limit of most phased arrays. This puts less energy on target and might reduce detection range up to 30%.

Hopeless Diamonds

Since the beginning of U.S. RCS reduction efforts, engineers have strived to minimize side and rear radar signatures. The breakthrough on the CIA's A-12 was the addition of a chine to the previously bullet-shaped fuselage. Nothing could be done at the time about the rounded shape of the aircraft's large nozzles, so a fuel additive was used to ionize in the exhaust plume, lowering the RCS. The A-12 was the first sign of how designing for LO would reshape combat aircraft.

The A-12 never had to penetrate the Warsaw Pact's air defenses, but the F-117 was designed precisely for that purpose. By the mid-1970s, Mach 3 was not fast enough to ensure survivability, and the Echo 1 program had determined the optimal shape for minimal RCS was a flat-bottomed diamond. Doubting it would ever fly, Lockheed's aerodynamicists dubbed this the “Hopeless Diamond.” But they persevered and cut out as few segments as they could to get the Hopeless Diamond—officially DARPA's Have Blue stealth demonstrator—into the air in 1977.

Faceting of the airframe directed all specular returns into a small number of angles. Edges were angled away from boresight as much as possible and aligned, along with trailing edges, with the specular returns. Where radar-return amplitudes spiked, they would plummet quickly as the aspect angle changed. The flat



MCDONNELL DOUGLAS



bottom prevented specular returns to radars not staring directly up at the aircraft, and the upper facets were all canted inward, to send specular returns and some of the sidelobes upward. Have Blue was designed with tails canted inward, aligned with the fuselage sides, but the crash of both prototypes highlighted its instability. The design was changed to outward cant for the production F-117.

From behind, the same platypus feature that reduced the F-117's infrared signature also kept its rear RCS low. With a narrow exhaust and a lip extending past it at a slightly upward angle, radars below the aircraft were prevented from seeing into the nozzles. Airborne search radars looking at the aircraft's rear would have been partially blocked by the exhaust's short height and narrow compartments, as radio waves cannot enter an aperture unless its smallest dimension is at least half a wavelength long.

The F-117 used a purely faceted shape because Echo 1 could not calculate the RCS of curved surfaces. By the time of the B-2, computers could and showed that curves and stealth were not incompatible but complementary. For the Advanced Tactical Fighter competition, won by the F-22, Lockheed actually began flying aircraft with curves before it knew how to model their signatures.

Better modeling and RCS testing demonstrated it was actually more effective to blend facets with curves of constantly changing radii. This broadened the specular return at the junction of the surfaces but did not increase total RCS at those angles, likely because it reduced the edge wave from the junction. At the same time, the curve reduced the traveling waves sent back to the wingtip, reducing RCS in the azimuthal plane by up to 10 db.

Unlike the F-117, the F-22's fuselage sides lie below the wing. But they are aligned with the vertical tails at angles so that specular reflections are returned only to distant ground-based radars. Edge treatments likely lessened the need for severe sweep of the leading edges, while a combination of modeling and testing likely proved the signature could tolerate small bumps to house actuators and landing gear.

The requirement for extreme maneuverability demanded thrust-vectoring nozzles, but the rectangular nozzles are composed of wedges that restrict specular reflections to high angles above and below the aircraft. A coating likely suppresses traveling waves while edge treatments suppress diffraction and edge waves. Finally, the tails extend past the nozzles, obscuring them along the azimuthal plane.

The smaller F-35 incorporates many of the F-22's stealth shaping techniques. More fairings with complex curves appear around the densely system-packed airframe, but modeling and testing may have shown these have small effect on RCS from angles of concerns. Advances in RCS modeling allowed Pratt & Whitney to produce an axisymmetric nozzle with a radar signature similar to the F-22's 2D wedges.

Broadband Stealth

The key change in radar reflection that occurs as frequencies reduce and wavelengths increase is that specular returns weaken and widen while non-specular mechanisms strengthen. Specular returns from flat plates decrease with the square of wavelength, but the width of the main lobe increases. Traveling-wave strength grows with the square of wavelength, and the angle of strongest return increases with the square root.

Diffraction from curved edges increases with wavelength and with its square for straight wedges. A 50-ft.-long, wedge-shaped leading edge swept at 45 deg. might measure -49 dBsm from the front in X-band, but a much higher -13 dBsm in VHF. Tip and vertex diffraction also increase with the square of wavelength. At 100 MHz (VHF), one acute-angled wingtip can measure more than -10 dBsm on its own, in every direction. Sidelobes generated by edge waves from flat plates increase with the square of wavelength, but double-curved surfaces create very weak edge waves because the currents smoothly taper at the edges.

As structure dimensions approach 5-10 wavelengths, these effects become significant and the target begins to exhibit "resonant" behavior in which RCS increases in an undulating fashion. The rise continues until



structures reach 0.5-1-wavelength long, when surface waves are maximized because they have to travel only one wavelength and then typically decrease with the fourth power of wavelength.

The first step in designing a broadband-stealth platform is eliminating surfaces that might exhibit this resonant behavior before the primary structure, which is why the B-2 lacks a tail. Tails increase RCS at many angles, due to traveling waves at grazing angles, edge waves, a widening specular reflection at higher angles and diffraction at many angles. This is also why two tail surfaces for fighters (as in the YF-23) are said to be stealthier than four (F-22 and F-35), at all wavelengths.

To control traveling waves and minimize azimuthal spikes in RCS, the B-2's edges are only in the horizontal plane and are strictly aligned with the leading edges. The bomber's large size also provides the coatings plenty of area over which to attenuate the surface currents even for long radar wavelengths. To minimize specular and edge-wave returns abeam, a flying-wing airframe offered a novel approach to sides: It did not have any.

In profile, the B-2 is composed of two curved surfaces joined at a narrow angle. The curves continuously change radii in multiple directions but are as gentle as possible while avoiding a prohibitively draggy cross-section and allowing the centerbody deep enough to accommodate engines, weapons bays, a cockpit with windows large enough to give pilots an adequate view and radar antennas under the nose at angles inclined to image ground targets 100 mi. ahead of the aircraft. There are few angles other than directly below or above the aircraft that can generate a strong specular return.

The gentleness of the B-2's curves limits the angles of specular reflections and minimizes reflection of surface currents. While not as severe at angled junctions, curves can still bounce currents, exacerbating surface waves, but curves at least 1 m in radius can generally be ignored.

To limit engine returns, the B-2 uses a serpentine duct and narrow exhaust that are coated with RAM but also hide the rotating fan and turbine from radar. The intakes and exhausts are located on the upper surface, their edges inset from the aircraft's leading and trailing edges. For a radar to see these features, it would have to be at a shallow angle to the aircraft, and therefore farther away.

This design feature is key to keeping the aircraft's RCS low across all radar bands. The basic approach to suppressing returns from engine inlets is to coat the intake with a thin layer of RAM and curve it so that any entering waves bounce off the walls so many times they are suppressed despite the thinness of the RAM. This works well for X-band, at which the wavelength is much smaller than the cavity formed by the intakes and thin RAM is adequate for suppression.

When the wavelength is small, the RAM-coated serpentine duct functions as designed, and the waves bounce around until they are attenuated. The intake is also not a concern if the radar wavelength is more than twice the minimum dimension of the inlet, because then the aperture reflects the signal like a solid surface. The danger is at wavelengths in between.

As wavelength grows past 1/5th of the cavity size, the intake's behavior changes from "free space" to "cavity resonance," and the inlet starts to act like a waveguide, strongly returning incoming waves. In addition, as the wavelength increases, the RAM attenuates less. Intake RCS reaches a maximum when incoming wavelength is 1-2 times the inlet's maximum dimension. This may explain why the F-35 has an extra thick coating of RAM on its intakes, but it is better just to deny radars a view of the feature.

The B-2 still has a perimeter that can generate diffraction and bounce surface currents that survive the journey to the aircraft's edges. The geometric RCS of the edge is believed to be minimized by using a convex "beak" shape with a minimum-angle tip. The majority of the perimeter is also covered in two types of RAM: magnetic RAM that can attenuate VHF radar waves by 20 dB and UHF by more than 10 dB with a thickness of less than 0.25 in.; and perhaps more than 1 ft. of conductive RAM, enough depth to reduce reflections by 20 dB from Ku to L or even UHF band.



The only official statement regarding the B-2's RCS comes from Senate testimony by the Air Force chief of staff in 1990. The service had submitted a brochure that listed the RCS of several birds and insects, the latter of which included examples at 0.001, 0.0001 and 0.000063 m². Asked where the B-2 fell in the chart, the chief answered, "in the insect category" but declined to specify further. Analysts have since assessed the B-2 in the 0.001-0.0001 (-30 to -40-dBsm) range. But by the late 1990s, program officials were hinting that RAM improvements had driven the RCS smaller, and the trend would continue.

So far, the tailless flying-wing or "cranked kite" approach to all-aspect, broadband stealth has only been seen on bombers and unmanned aircraft optimized for large payload and long endurance, and not on fighters with a need for agility. But Lockheed Martin's latest Next-Generation Air Dominance concept illustration, representative of the "sixth-generation" fighters being studied for the U.S. Air Force and Navy, shows a tailless, smoothly curved design. The shape of combat aircraft to come may be about to shift again. 🌀





The Future Of Survivability

Dan Katz

This is the final article in a seven-part series. The first artists' concepts of the Northrop Grumman B-21 Raider bomber and potential "sixth-generation" air-dominance fighters suggest how low-observable technology will continue to evolve and drive the shape of future combat aircraft. But as radars move to lower frequencies, become more agile and precise and are netted together with other, dissimilar sensors, can stealth survive?

When the only artist's concept to date of Northrop Grumman's B-21 Raider was released in February 2016, its similarity to the B-2 bomber was unmistakable (see images below). Many observers had expected something different, but if you want to design a shape that exhibits broadband stealth—and have it fly—the flying wing with a blended body and W-shaped training edge is likely the optimal solution.

Closer analysis of the image reveals refinements to the design that suggest the B-21's radar cross-section (RCS) will be lower than its predecessor's. The first difference is the trailing edge: a single-W compared to the B-2's double-W. That means two fewer vertices, which have significant RCSs at low frequencies. The B-2 was originally designed with a single-W. During development, concern arose that Soviet progress in building massive VHF radars might enable Russia to detect even the B-2. So it was decided that the aircraft had to be capable of flying low, exposing it to fewer radars and hiding it among the ground clutter, so the trailing edge was redesigned.

The B-21's inlet design is also changed. Gone are the B-2's serrated edges. Instead, the lips are straight and flush with the upper fuselage. The lower surface of the intake seems to flow smoothly from the leading edge, eliminating the radar-reflecting edges of the B-2's boundary-layer diverters. This may be similar to the F-35's diverterless intakes, which eliminate the gaps between inlet and fuselage seen on the F-22. In addition, the engine covers appear to protrude less, meaning fewer curves with small radii and less surface waves.

The biggest question raised by the initial B-21 image is the apparent lack of any exhaust. It would make sense to locate the exhaust on top of the aircraft, forward from the trailing edge, as on the B-2. This is likely a deliberate omission by the artist. The first, crude illustration of the B-2 released by the U.S. Air Force in 1988, drawn from almost the same perspective, also left out the exhausts. Knowledge of their shape is needed to accurately model an aircraft's RCS, so it makes sense to keep them hidden a while longer. The aft deck has proved one of the biggest problems of operating the B-2, so if engineers have found a solution, it would also pay to keep that information classified for as long as possible.

Even at the rollout of the B-2, Northrop and the Air Force tried to conceal the exhaust design by preventing any view of the aircraft from the rear. But they were defeated by Aviation Week editor Michael Dornheim, who flew over the event in a rented Cessna and photographed the B-2 from above, exclusively revealing its mysterious exhausts (AW&ST Nov. 28, 1988, p. 20). These and other elements of the B-21's broadband, all-aspect stealth advances will likely also become clearer with time.

Lockheed Martin's latest sixth-generation fighter concept is a tailless blended-wing design.



LOCKHEED MARTIN CONCEPT



How Low Can a Radar Go?

Techniques employed by the B-2 and B-21 are considered effective at reducing RCS down through at least the middle of the 30-300-MHz VHF band, past where almost all counterstealth radars operate. But there are already radars in the world operating in the 3-30-MHz high-frequency (HF) band. With HF wavelengths of 10-100 m, it seems impossible to design an aircraft that would be geometrically immune to resonant or Rayleigh scattering of electromagnetic waves. Radar-absorbent material (RAM) is also less effective at these frequencies. But several magnetic materials that exhibit attenuation of more than 20 dB at 30 MHz can maintain 10-dB reduction down to 3 MHz, and research is ongoing into better HF absorbers. These frequencies also allow radar signals to refract off the ionosphere, making them over-the-horizon (OTH) sensors with ranges of thousands of miles and the ability to detect low-flying targets.

The most famous of these OTH sensors is Australia's Jindalee Operational Radar Network (JORN), whose operators asserted they could detect the B-2 soon after it was revealed. China is known to have fielded similar radars along its coast, in its interior and possibly on a reclaimed island in the South China Sea. Russia has also developed models, such as the Sunflower system.

But these radars suffer from all the problems of low-frequency operation taken to the next level. They are large and inaccurate; the kilometer-long JORN arrays are said to exhibit errors on the order of a kilometer and cannot ascertain a target's altitude, making them at best early-warning sensors that can tell targeting sensors where to look. They also lack mobility. Most are fixed, and Russia's "semimobile" Sunflower takes 10 days to install. That makes such arrays especially vulnerable in wartime.

HF radars also do not scan like normal radars but instead dwell on "tiles" for extended periods, likely due to the slow cycling of HF waves. That means the radars often require external intelligence to know where to look and probably cannot track one target while searching for another. Because of their dependence on Doppler processing, HF radars cannot detect objects moving parallel to their arrays.

They also may have problems detecting small targets such as standoff weapons due to their small size compared to the radar wavelength; the Royal Australian Air Force (RAAF) says the JORN is only expected to detect targets the size of a BAE Systems Hawk jet trainer. HF radars' detection abilities also depend on target material, and the RAAF stresses that JORN is designed to detect metal objects and is unlikely to see small wooden boats, hot air balloons or wooden gliders. Wood is a notoriously poor radar reflector, and magnetic RAM may have the potential to cause similar difficulties for HF radars.

OTH operation is also notoriously tricky. The ionosphere varies with time of day, the 11-year solar cycle, solar disturbances, geomagnetic activity and weather patterns. HF radars work better in daytime, and any of the aforementioned factors can make detection of targets less likely. JORN still experiences all these difficulties, and Australia has been refining it for more than four decades.

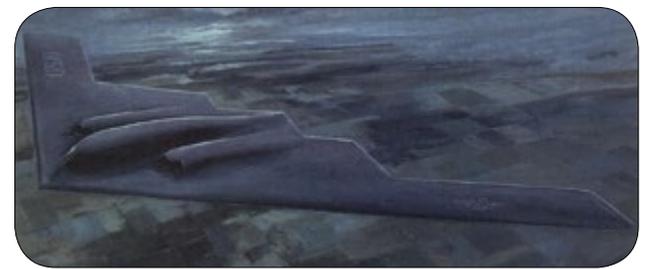
"Active Stealth"

HF radars are also likely more vulnerable to "active stealth." Better known as active cancellation, this

The only B-21 artist's concept omits details of the exhausts, as did the first artwork released of the B-2 (below).



AW&ST ARCHIVE



U.S. AIR FORCE



approach to evading detection is more of an electronic warfare (EW) technique. It works by recording an incoming radar signal and then emitting a matched signal half a wavelength out of phase, with the effect of zeroing out the return.

The technique is believed to be employed by European fighters, such as Dassault's Rafale, to limit detection range even at higher frequencies. At higher frequencies, however, active cancellation is a less robust approach to reducing detection range. An aircraft's radar cross-section is the sum of the RCS of all of its components, but the signatures of these components are always in different phases that interfere constructively or destructively with each other, depending on viewing angle. The higher the frequency, the shorter the wavelength and the faster total RCS changes with angle, forcing the active cancellation system to have more specific RCS knowledge and greater precision in matching the output. If the system gets it wrong, the signal would act as a beacon.

Newer radars that are faster and more agile in changing their waveforms will also challenge this technology. Many ground-based radars try to vary their signal enough that enemy aircraft do not detect them. If an aircraft does not detect a signal, it cannot cancel it. And even if the aircraft's EW system detects the enemy radar, there is an ongoing competition between radars trying to change waveforms faster than EW systems

can keep up with them. Finally, radars are beginning to learn

The need to combine fighter agility with broadband stealth could require advances such as fluidic thrust vectoring.

how to detect returns from specific features on an aircraft, which would require an active cancellation system to emit one signal per feature being

tracked, to achieve a null return.

But while active cancellation may be less robust at higher frequencies than passive stealth, it might be particularly effective

in the lower radar bands. The lower the frequency, the less quickly the radar signature changes with angle. When Rayleigh scattering is exhibited by a target, the geometric specifics of its shape cease to be important. With the slower wave cycling of lower frequencies, it is easier for EW systems to keep up with the radar to cancel or deceive it. It has long been rumored that the B-2 uses active cancellation selectively, but no confirming evidence has emerged.

The Future of Stealth

Perhaps the best evidence that stealth will remain relevant in military aircraft design for decades is the number of countries investing in the technology. In addition to the U.S., 11 nations are signed up to operate the F-35, and several more are interested. Russia has developed one stealthy fighter and China two. Both are also believed to be working on bombers with broadband stealth. Britain and France are collaborating on a stealthy unmanned combat air vehicle, while India, Japan, South Korea and Turkey are developing indigenous fighters, all of which feature stealthy airframes.

Over the coming decades, counterstealth technology will undoubtedly advance. Radar range, accuracy and resolution will increase with higher output power, lower-noise electronics, better antenna arrays, higher-capacity computers and advanced signal processing. Infrared sensors will also progress, with higher-resolution focal-plane arrays, detector materials that work at longer wavelengths and superior processing. Higher-bandwidth data links will permit fusion of data from multiple sensors of multiple types in multiple locations.

But stealth technology is not standing still. Radar cross-sections are getting smaller than the -30 to -40



NORTHROP GRUMMAN



dBsm estimated for the current generation of stealth aircraft. The F-22's RCS was equated to that of a marble (−40 dBsm) during development, but is rumored to have beaten this figure. The F-35's RCS was originally equated to that of a golf ball (−30 dBsm), but more recently insiders have hinted its RCS might have beaten the F-22 with its superior modeling, stealthier intakes and advanced materials.

The next generation of stealth aircraft will likely achieve even lower RCS. The B-21 will almost certainly be stealthier than the B-2. The U.S. sixth-generation combat aircraft are just starting to take shape, and almost all the artist conceptions released so far point to reductions to RCS. The designs are all tailless, blended airframes, some with intakes and exhausts above the wings and inboard from the edges, suggesting a trade of greater stealth for less maneuverability.

In addition to airframe shaping improvements, progress in multiple technologies will facilitate lower radar signatures. Advances in materials science will enable molecular-level control of a structure's electromagnetic (EM) properties. This could allow materials to be designed which hold the desired EM qualities to higher frequencies, from 30 MHz or even 3 MHz up to Ku-band, and absorb more energy with less thickness. Patents have also been filed on novel methods for producing carbon nanotubes and embedding them in structures so as to reduce radar signature. Work is also progressing on engineered metamaterials with subwavelength structures that scatter the EM waves to cancel out reflections.

Boeing's next-generation air dominance concept underlines the trend to tailless design with fewer discrete edges.



BOEING

To combine maneuverability with greater stealth, fluidic thrust-vectoring nozzles have been proposed with fixed external geometries and no moving parts. Instead, the exhaust is controlled by injecting bleed air into the nozzle to selectively block the flow. When activated symmetrically, these injectors constrict the exhaust like a convergent/divergent nozzle. When activated asymmetrically, they vector the exhaust toward the point of blockage. Such nozzles would allow the external geometry to be optimized for radar and infrared (IR) stealth. The lack of mechanical actuation systems means fewer parts and lower weight. And with thrust vectoring, external aerodynamic control surfaces can be made smaller and used less often, thereby improving stealth.

For better IR signature suppression, improving materials science will also likely yield materials with lower and more controllable emissivity at different wavelengths. The three-stream engines under development to improve fuel consumption will also supply more bypass air to cool exhausts faster and shrink plume signatures. Bypass air could be actively cooled before being ejected into the exhaust. If the technology of IR detection advances faster than that of IR suppression, directed infrared countermeasures may be fitted to stealth fighters.

Today, stealth remains an effective means of survivability. Many adversaries claim counterstealth capabilities, but stealth is relative, and U.S. combat aircraft appear to retain the advantage. One of the biggest benefits of stealth, although not the only one, is how it enables an aircraft to launch its weapons before it is detected by opposing fighters or air defense systems. This advantage is increasing with the growing range of weapons. The AIM-120C7 air-to-air missile has a range of 60-70 mi. and the GBU-39 small-diameter bomb at least 45 mi. The latest AIM-120D's range is reported at around 110 mi., and several glide bombs are being promoted with ranges of more than 60 mi.

There are certainly lower-band radars that might be able to detect stealth fighters at tactically useful distances, but this does not mean stealth is no longer relevant. None of these radars has the accuracy yet to re-



liably direct missiles all the way to their targets. And most of them cannot overcome the broadband-stealth characteristics of platforms such as the B-2 and B-21.

But stealth is a tool, not a panacea, and there are other approaches to survivability that work synergistically with stealth. Electronic warfare is often discussed as an alternative to stealth, but it is also a complement. The first stealth aircraft, the F-117, did not carry electronic-support measures, but every stealth aircraft since has carried radio-frequency receivers to detect enemy radars and chart a course through them that presents its angles of lowest RCS to the most threatening radars and minimizes chances of detection. Noise jamming reduces detection ranges against stealth aircraft, the same as for nonstealthy aircraft, enabling them to approach even closer to targets. Deception jamming tactics are also enhanced by stealth, because the signal needing to be canceled or made numerous is smaller. Jamming the communications among radars can also prevent them from sharing data or from allowing larger radars to cue smaller radars or guide missiles.

In the past, the concept of operations was that stealth aircraft would eliminate key air defense sites, making the airspace safe for conventional fighters. In the future, the operating concept might be that broadband stealth bombers, standoff weapons and electronic jamming would eliminate or suppress the low-band systems, making the airspace safe for stealthy fighters—while nonstealthy fighters are still barred by the presence of myriad high-power conventional radars with extreme waveform agility.

In the years ahead, the stealth-counterstealth competition will continue. Observers should be on the lookout for improvements in technology—but it is important to note that stealth is the science of reducing the chances that sensors will be able to detect, track and engage aircraft. All targets have signatures that change with angle, and all sensors have a range at which they detect signatures and at which they exhibit errors in locating those signals. Claims are easy to make, but data is what proves them. Stealth does not make targets invisible, nor does it have to. The question is whether the cost and design trade-offs of stealth are worth the benefits conferred in survivability and chances of victory for an entire force. ●

