F–35 Lightning II Joint Strike Fighter lacks high-altitude and supersonic cruise capabilities of F–22A Raptor and is not agile enough to evade modern surface-to-air missiles

U.S. Air Force (Julianne Showalter)

EVOLVING TECHNOLOGICAL STRATEGY IN ADVANCED AIR DEFENSE SYSTEMS

By CARLO KOPP

Since the end of the Cold War, America's conventional military might has been predicated on the ability to control the air. This style of warfare produced stunning results in Operation *Desert Storm* in 1991 and has been successful in subsequent military campaigns in 1999, 2001, and 2003. The ability of U.S. aircraft to penetrate hostile airspace and deny the use of friendly airspace to opposing air forces is now mostly assumed to be as immutable as a law of nature.

Central to U.S. dominance in modern airpower has been the exclusive possession of stealth technology, which has provided the U.S. Air Force with the ability to penetrate Cold War–era air defense systems with negligible and historically unprecedented low combat loss rates. The development of stealth during the 1970s and 1980s must be ranked as one of the most important technological outcomes of the Cold War arms race.

If one historical certainty can be extracted from the study of technological arms races over the last four millennia, it is that advances in military technology will elicit both symmetric and asymmetric responses. This cyclic evolutionary pattern of "measures versus countermeasures" is observed in military systems as it is observed in biological systems, and the notion that it will somehow cease to occur so as to accommodate the expectations of any nation is neither reasonable nor realistic.

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U.S. Air Force (Julianne Showalter)

Post–Cold War Evolution

The U.S. investment in stealth during the last decade of the Cold War did not elicit serious concern in the Soviet Union. The deployment of the advanced and highly mobile S–300V/SA–12 Giant-Gladiator and S–300PM/SA–10B Grumble surface-to-air missile systems,[1] and the advanced MiG–29 Fulcrum and Su–27 Flanker fighter,[2] all supported by a range of then-modern radar designs, convinced Soviet planners that the pendulum in the technological arms race was swinging in their favor. The collapse of Saddam Hussein's air defense system in January of 1991—under a deluge of U.S. high-speed antiradiation missiles (HARMs) and British air-launched antiradiation missiles, and airborne jamming by EF–111A Raven and EA–6B Prowler aircraft—was a major embarrassment for proponents of the Soviet model of dense, overlapping, and complex integrated air defense systems (IADS). Even more traumatic was the observation that stealthy F–117A Nighthawks were able to penetrate the strongest portions of the Iraqi air defense system with impunity night after night, with no losses suffered in combat.[3]

Stealth or very low observable technology, the large-scale use of precision-guided munitions (PGMs), and advanced intelligence, surveillance, and reconnaissance (ISR) technologies provide the United States with a pivotal advantage in the contest for control of the skies. The possession of these three key technologies has defined U.S. airpower and U.S. warfighting "style" in nation-state conflicts since the fall of the Soviet Union.

The end of the Cold War was a pivotal discontinuity for the expansive Soviet bloc defense industry, characterized then by central control, virtually unlimited access to taxpayer funding, and a secure long-term market comprising the Soviet armed services, their Warsaw Pact siblings, and a plethora of clients in the "nonaligned" and developing world. Within a matter of months, this secure environment collapsed, leaving this enormous military-industrial complex to fend for itself. Through the 1990s, the industry restructured around a model based on intensive technological and commercial competition, with a primary export market focus.

Large portions of the industry became joint stock companies, and many mergers occurred. Within the industry, a new generation of corporate managers emerged, mostly former engineers and technical professionals, rather than the loyal Communist Party cadres of the Soviet era. In many respects, Russia's defense industry now resembles that of the United States in the 1950s and 1960s—smart, competitive, lean, aggressive, and prepared to take calculated risks, both technologically and commercially, but funded through export sales. Surviving on market demand means catering to the interests and preferences of client nations. The success of U.S.-led air campaigns since 1991 produced a high demand for products capable of deterring U.S. military action.

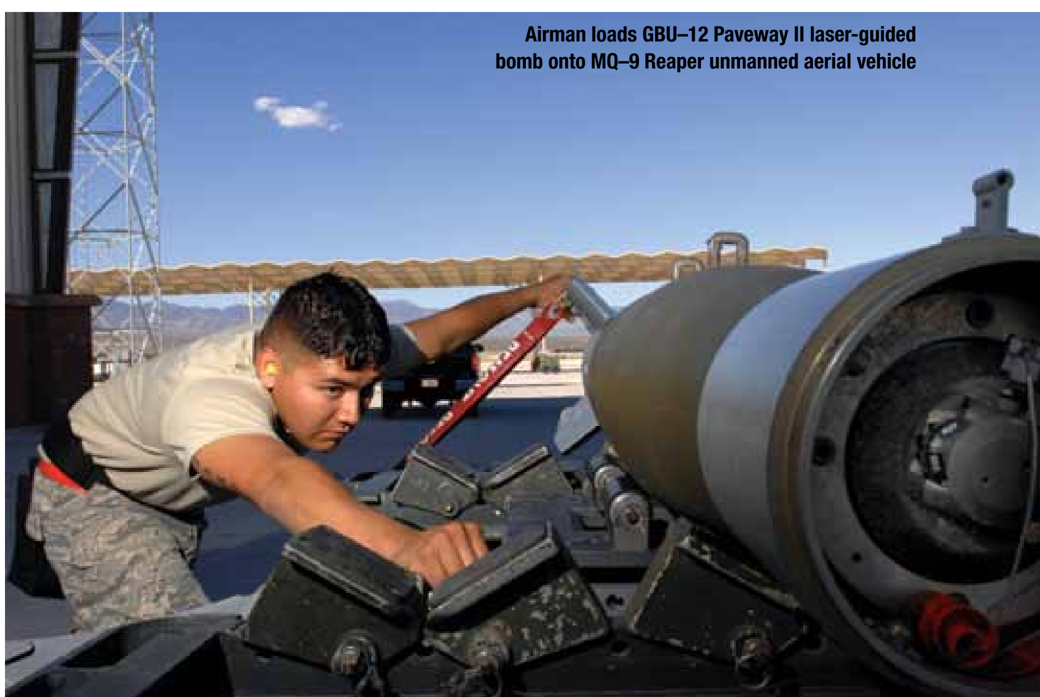
By the mid to late 1990s, technological strategists across the Russian industry defined the agenda for the next generation of products. The focus was placed in three areas, which were the defeat of U.S. PGMs, defeat of U.S. ISR capabilities, and most importantly, defeat of U.S. stealth technologies. Concurrently, symmetric responses to U.S. capabilities emerged, including the development of high-performance conventional fighters, such as the Su–35S and MiG–35, the MiG SKAT stealthy unmanned aerial vehicle and PAK–FA high-performance stealth fighter, a wide range of smart munitions that are direct analogues of U.S. designs, and many uniquely Russian supersonic weapons.

Russian industry took the lead in the drive to overcome key U.S. capabilities, but was soon followed by the Chinese and numerous former Soviet republics, including Belarus and Ukraine.

An important factor enabling the introduction of advanced high-technology capabilities, whether symmetric or asymmetric relative to U.S. capabilities, has been unhindered access to the globalized market for advanced basic technology, especially computer hardware and software, but also commercial Gallium arsenide[4] radio frequency components and many other technologies. Both Russian and Chinese industries can now match most of the basic technology used in contemporary U.S. weapons manufacture. The United States currently maintains a robust lead only in stealth technologies and just incremental leads across most other military technologies, the strongest in radar and electro-optical equipment.

the success of U.S.-led air campaigns since 1991 produced a high demand for products capable of deterring U.S. military action

The three-pronged technological strategy for the defeat of U.S. airpower is manifested in a wide range of programs, many of which are now well established, and is resulting in exported products. The approach adopted for the defeat of smart munitions is an application of three basic technologies. The first is point defense weapons specifically intended to kill smart weapons during the terminal endgame, as they near the target and become easily detected. The 9K332 Tor



Airman loads GBU–12 Paveway II laser-guided bomb onto MQ–9 Reaper unmanned aerial vehicle

U.S. Air Force (Larry E. Reid, Jr.)

M2E, evolved from the SA–15 Gauntlet,[5] and the 96K6 Pantsir S1/SA–22, are both digital weapons systems equipped with phased array engagement radars derived from fighter radar technology and are specifically designed to kill the HARM/advanced antiradiation guided missile, Small Diameter Bomb, Paveway, Joint Direct Attack Munition smart bombs, and U.S. cruise missiles.[6]

Comprehensive threat warning and countermeasures packages are now supplied for a range of air defense radars, including missile approach warning systems, coherent and incoherent radar decoys, chaff mortars, flare dispensers, smoke generators, and Global Positioning System jammers of varying capabilities.

Finally, there has been a comprehensive shift away from Soviet-era semimobile deployment of air defense weapons and sensors. Part of this shift has also involved rehosting many Soviet and post–Soviet-era radar, surface-to-air (SAM), and antiaircraft artillery systems from tracked vehicles to wheeled vehicles. The benchmark for current Russian air defense equipment is a 5-minute "shoot and scoot" capability. The late model S–300PMU2 Favorit/SA–20, S–400 Triumf/SA–21, 9K332 Tor M2E, and 96K6 Pantsir S1/SA–22 all meet this benchmark on wheeled chassis. Intended programs include the wheeled S–300VMK/SA–X–23, and the latest wheeled variant of the Buk M2/SA–17 Grizzly. All of these systems are fitted with digital phased array radars and all use digital radio networks to connect batteries and supporting systems.

during the 1990s the Russians developed a number of "counter-ISR" weapons, most of which are now in production

In the present and near future, U.S. aircraft will have to confront highly mobile air defenses operating under a sniper-like "hide, shoot, and scoot" doctrine and deal with the reality that only a fraction of smart munitions launched will survive terminal short-range missile, gun, and countermeasures defenses to actually impact their intended targets, including key air defense assets.

The intent to defeat U.S. ISR capabilities has produced a range of new technologies, but also further evolution of some late Soviet-era products, which remained in production. During the late Cold War, the Soviets maintained a large inventory of ground-based and airborne microwave-band high-power jammers, intended to defeat the North Atlantic Treaty Organization (NATO)/U.S. E–3 Airborne Warning and Control System (AWACS), U–2, and E–8 Joint Surveillance Target Attack Radar System (JSTARS). They also deployed a wide range of antiradiation missiles, mostly modeled on U.S. and European designs.

While the Soviet-era fleet of airborne jammers, comprising Yak–28PP Brewer E, Tu–16P Buket Badger J, and Tu–16PP Azaliya Badger L, respective analogues to the U.S. EF–111A Raven and EA–6B Prowler, collapsed during the early 1990s, ground-based jammers designed to disrupt U.S. airborne ISR radars not only remain in production, but also have been upgraded extensively with digital hardware and commercial off the shelf (COTS) computers. These include the Signal Topol E jammer built to defeat U.S. Navy E–2C variants, the Pelena 1 and 2 series built to defeat the E–3 AWACS radars, and the Kvant SPN–2/1RL248 series, which is sup-

Lockheed Martin representative demonstrates F–22 Raptor flight simulator

U.S. Air Force (Kristen Stanley)

plied in a range of X-band and K_u-band variants intended to blind U.S. high-resolution ground-mapping ISR radars carried by the E–8 JSTARS, U–2, RQ–4 Global Hawk, and various tactical fighters and smaller unmanned aerial vehicles (UAVs).

While Russian "soft kill" measures against U.S. ISR have seen evolutionary growth, "hard kill" measures have seen revolutionary growth. During the Cold War, the only hard kill weapon specifically built to deny ISR access was the S–200 Dubna-Vega/SA–5 Gammon SAM system, some variants of which could hit high-altitude targets at ranges as great as 160 nautical miles. The Russians retired their inventory of SA–5s during the late 1990s and sold off their warstocks to numerous nations, including Iran.

More importantly, during the 1990s the Russians developed a number of "counter-ISR" weapons, most of which are now in production. The Vympel R–37/AA–13 Arrow, intended to be carried by the MiG–31 Foxhound and Su–27M Flanker fighters, can kill an ISR aircraft, airborne jammer, or tanker from 160 nautical miles of range, outperforming the now retired U.S. Navy AIM–54C Phoenix. The larger Novator R–172, in development for the Su–35S Flanker, is built to kill targets at 215 nautical miles.

Much more important, however, has been the development of advanced long-range SAMs for this purpose, using modern guidance algorithms. Experiments performed by Almaz during the 1990s showed that SAMs could be flown much farther if they were steered along a ballistic midcourse trajectory, akin to a theater ballistic missile, rather than conventional "climb-cruise-home" trajectories. This technique had the added advantage of improving SAM endgame lethality as the missile picks up speed diving on its target. The late model SA–20 and SA–21 48N6E2/3 missile variants, using this technique, can hit targets at 108 to 135 nautical miles of range. The new SA–21 40N6 missile has a maximum range of 215 nautical miles, providing a genuine capability to deny ISR coverage.

The increased range performance of these missiles has seen commensurate increases in radar transmitter power levels, incrementally increasing useful ranges against stealth aircraft. While the primary stated use of these weapons is to kill ISR platforms or deter their use, Russian literature indicates another intended application, which is to kill or deter the use of high-power electronic warfare platforms such as the EA–6B Prowler, EA–18G Growler, and EC–130 Compass Call. The Chinese extended this model further and installed a wideband antiradiation seeker, analogous to that in the U.S. HARM, into the FT–2000 SAM, itself based on the FD–2000 airframe developed from the Russian SA–10 and SA–20. To date, the Russians have not announced any antiradiation seekers for SAMs, but could easily adapt the very precise Avtomatika L–112 series currently in production for Kh–31PD/AS–17 Krypton series antiradiation missiles.

Targeting of these weapons is performed using two means. Fire control or engagement radars for these SAMs have been equipped specifically with passive angle tracking hardware to target airborne jammers directly. Concurrently, a range of advanced passive detection systems have been developed and a number integrated with advanced SAM systems. These evolved in part from the well-known Cold War–era KTRP–81 Ramona or Soft Ball, and later KTRP–86/91 Tamara or Trash Can. These include the 85V6 Orion/Vega series, the 1L222 Avtobaza, and the Chinese YLC–20, the last borrowing in part from the Ukrainian Topaz Kolchuga M system.

These designs are capable of accurately identifying and geolocating emitting targets, tracking aircraft not only by high-power radar and electronic warfare equipment emissions, but also by lower power Joint Tactical Information Distribution System/Link-16 terminal and identification, friend or foe (IFF) transponder emissions. The recent U.S. Air Force decision to fit the directional Multifunction Advanced Data Link in preference to the Joint Tactical Radio System is primarily related to the proliferation of such systems.[7]

U.S. Air Force (Aaron D. Allmon II)

Air Force F–117A Nighthawk stealth fighter penetrated best-defended portions of Iraqi air defense systems with no losses during Operation *Desert Storm*

in any near future conflict, U.S. forces will have to confront a complex spectrum of air defense systems

Russia's technological effort to deny the use of U.S. ISR and smart weapons capabilities is directly related to its effort to defeat stealth technologies. Prior to the advent of stealth, the principal strategy for penetrating air defenses involved the use of ISR capabilities to map opposing air defenses, which were then subjected to a barrage of high-power jamming by airborne electronic warfare platforms and a deluge of smart munitions targeting the enemy's radars and SAM sites. By putting ISR platforms at serious risk, and by attriting smart munitions during the terminal phase of flight, this technological strategy blunts, if not wholly defeats, U.S. legacy techniques for breaking opposing air defense systems, increasing U.S. strategic dependency on stealth.

Counterstealth Systems

When surveying and assessing counterstealth systems, it is necessary to place them into context. While they can be deployed as "add on accessories" to a legacy Soviet-era air defense system to increase its potency, many of these systems are being explicitly designed around the doctrine of high mobility and integration through radio networking with modern digital air defense weapons.

In any near future conflict, U.S. forces will have to confront a complex spectrum of air defense systems, ranging from legacy Soviet systems to newly built Russian and Chinese systems, with various hybrid mixes of Cold War and new systems possible and likely. Digital and solid-state radar upgrades to legacy Soviet-era S–125 Neva/SA–3 Goa, S–200 Vega/SA–5 Gammon, 2K12 Kvadrat/SA–6 Gainful, 9K33 Osa/SA–8 Gecko, 9K35/SA–13 Gopher, and 9K37 Buk/SA–11 Gadfly have proven popular in the market. Mobility upgrades using new self-propelled configurations for the S–125 Neva/SA–3 Goa and 9K33 Osa/SA–8 Gecko have proven especially popular. Russian and Belarus manufacturers have also reengineered all of their Cold War–era mobile IADS and battery command posts, and developed new derivatives, using modern digital COTS technology.

The Russians suffered the loss of several combat aircraft, including a Tupolev Tu–22M3 Backfire heavy bomber, to Georgian SAM defenses during their recent adventure. Covertly upgraded by Ukrainian contractors, the Georgian systems were not effectively countered by the electronic warfare self-protection systems on Russian aircraft.[8]

The mainstays of Russian counterstealth technology are VHF-band radars. This focus is for good engineering reasons. Stealth designs, such as Electronic Warfare Self Protection equipment, are characteristically built to defeat specific classes and categories of radar equipment. Two strategies have been used to date. Aircraft intended to penetrate complex and deep air defenses are designed with "wideband" stealth, intended to defeat as wide a range of radar types as possible. Aircraft intended to defeat shallow defenses or scattered battlefield air defenses are built with "narrow band" stealth, designed to "break the kill chain" by defeating fire control or engagement radars only.

Stealth designers have two principal technologies available for reducing the radar signature of an aircraft. These are shaping of airframe features and materials technology applied in coatings or absorbent structures.[9] Typically, the first 100- to 1,000-fold reduction in signature is produced by shaping, with further 10- to 30-fold reductions produced by materials. The smart application of these techniques reduces the signature of a B–52-sized B–2A Spirit down to that of a small bird, from key aspects.

The effectiveness of both shaping and materials technologies varies strongly with the wavelength or frequency of the threat radar in question. Shaping features must be physically larger than the wavelength of the radar to be truly effective. A shaping feature with a negligible signature in the centimeter X-band or K_u-band may have a signature that is 10-fold or greater in the much lower decimeter and meter radar bands.[10]

Russian effort to provide counterstealth capabilities is not confined to conventional VHF-band radar

Materials are also characteristically less effective as radar wavelength is increased, due not only to the physics of energy loss, but also to the "skin effect" whereby the electromagnetic waves impinging on the surface of an aircraft penetrate into or through the coating materials. A material that is highly effective in the centimeter X-band or K_u-band may have a 10-fold or less useful effect in the lower decimeter and meter radar bands.[11]

Russian counterstealth radar designers have publicly reiterated that their focus on VHF-band radars is based on the much reduced effectiveness of shaping and materials designed to defeat upper band radars, when confronting VHF-band radars. In the West, VHF-band search radar was largely abandoned during the 1950s in favor of magnetron and traveling wave tube–based radars operating in the higher L-band and S-band. The Soviets persisted with this technology until the end of the Cold War, primarily as VHF-band radars were much cheaper to manufacture, using antenna and transmitter technology similar to that used in television transmitters. The best known Soviet VHF-band radars were the P–8/P–10 Delfin or Knife Rest, and later the P–12/P–18 Spoon Rest, built by the thousands and exported as search and acquisition radars for the S–75 or SA–2 Guideline SAM system. Less common was the much larger P–14 Tall King, used most often as a search radar for S–200/SA–5 Gammon batteries. These cumbersome designs were slow to deploy and stow, were very inaccurate in measuring target positions, lacked height-finding capability, and performed poorly against low-flying targets and jamming. In the West, Russian VHF radar is typically identified with the Spoon Rest and Tall King generation of technology.

Post–Cold War VHF-band radars are fundamentally different in design and make use of the latest solid-state radar techniques and advanced COTS computing and software technologies. At least two are active electronically steered array (AESA) designs, with agile beam-steering capabilities within a sector comparable to the U.S. Navy SPY–1 Aegis radar, and miniaturized solid-state transmitters and receivers in each antenna element. Advanced clutter suppression technologies, such as Space Time Adaptive Processing[12] recently introduced into the U.S. Navy E–2C/D, are a known feature of at least two recent Russian VHF-band designs.

Advanced processing aside, the use of AESA technology is a critical advance in these radars, as it not only provides for fast and accurate target angle measurement using monopulse techniques, but also permits the use of powerful nulling techniques for suppressing hostile jamming. The cited accuracy of some new VHF-band radars is similar to that of established Russian L-band and S-band radars used for SAM targeting.

Unlike Cold War–era designs, many of the current VHF-band designs are highly mobile self-propelled systems, and two qualify as genuine "shoot and scoot" designs. The largest and longest ranging VHF-band radar now in production is the NNIIRT 55Zh6 Nebo U or Tall Rack, which has been integrated with the SA–21 and is now being deployed around Moscow. The sheer size of this radar denies it mobility. It has a characteristic inverted T antenna system and provides very accurate height finding capability.

Comparable in performance is the VHF-band Rezonans N/NE, which is explicitly marketed as "Stealth Air Target Early Warning Radar." Like the Nebo U/UE series, it takes 24 hours to deploy and is intended for static long-range air defense applications. Production quantities remain unknown at this time. Unlike the Nebo U/UE, it uses electronic beam steering techniques. Much more interesting are the newer NNIIRT-designed 1L119 Nebo SVU and Nebo M RLM–M radars, which are self-propelled and designed from the outset to support SAM batteries in the field.

The earlier Nebo SVU is a modern AESA design carried by semitrailer and capable of stowing and deploying in 20 minutes, significantly less time than observed with legacy Soviet air defense radars. The 84-element folding AESA combines mechanical steering in azimuth and tilt, like a conventional radar, and provides electronic beam steering. This is used during conventional circular sweeps to provide highly accurate angle measurement, with errors claimed by NNIIRT to be similar to the S-band 64N6E Big Bird series phased array used for SA–20 target acquisition. In sector search mode, the Nebo SVU is mechanically rotated to point at the threat sector, and then performs agile electronic beam steering through a claimed ~50° arc, not unlike the Patriot's MPQ–53 phased array radar. The primary cited application for the Nebo SVU is target acquisition for SAM batteries.

Russia's development of counterstealth radars will reshape, over the coming decade, the character of the air defense systems the United States will confront in future expeditionary operations

The Nebo M RLM–M is the much more powerful and accurate self-propelled offspring of the Nebo SVU. Using a similar but much larger hydraulically deployed and stowed AESA design with 168 active elements, this system is carried on the same 8×8 all-terrain BAZ–690915 chassis as SA–21 SAM system launchers. It provides around 40 percent more range and much more accurate angle measurement than the Nebo SVU, retaining the electronic beam steering agility of its predecessor.

The RLM–M is a formidable modern radar in its own right. It is intended for use as part of the Nebo M multiband counterstealth radar system, which employs the VHF-band RLM–M, the L-band RLM–D, and the S-band RLM-S AESA radars, all networked together via the RLM–KU command post. What is not stated in the Russian-language PowerPoint slides is that by default, this system must incorporate a radar track fusion capability similar to that in the recently introduced U.S. Navy Cooperative Engagement Capability (CEC) system.[13] Proper deployment of the Nebo M would see the VHF-band radar painting incoming stealth aircraft head on and the flanking L-band and S-band components painting the target from the often less stealthy sides. Also unstated is that with an operational networked "CEC-like" track fusion system resident in the RLM–KU command post, other more potent configurations with multiple radars are feasible—for instance, networking and fusing tracks from several RLM–M or RLM–D systems.


U.S. F–22 Raptor stealth fighter

U.S. Air Force (Michael B. Keller)

Another interesting recent development is the Belarus-designed KBR Vostok E VHF-band solid-state radar, capable of hydraulic stow and deploy in a mere 6 minutes, approaching the "shoot and scoot" capability of the SAM batteries it is designed to support. Intended to replace the Spoon Rest, KBR recently claimed their first export to an undisclosed client. First displayed in 2007, this design uses an entirely new and much more compact antenna element scheme. KBR claims this radar will track an F–117A Nighthawk class stealth target at 40 nautical miles of range.

The Russian effort to provide counterstealth capabilities is not confined to conventional VHF-band radar. The NNIIRT 52E6MU Struna-1MU/Barrier E is a multistatic, low-power tripwire system, using a passive coherent location (PCL) technology similar to the U.S. LM Silent Sentry design.[14] Like the Silent Sentry, the Barrier E is limited in effect to low- and medium-altitude targets. What is often unstated about PCL systems is that the "transmitters of opportunity" such designs rely upon (for example, VHF- and UHF-band television and radio stations) use antenna designs specifically built to transmit almost all of their power near the ground—power transmitted upward is considered wasted in such applications. The result is that the effectiveness of such systems is very limited at high altitudes.

While VHF-band is the focal area for Russian counterstealth development, high-power L-band radars at 24 to 30 centimeters are an area of active development because stealth designs strongly optimized for the centimeter bands suffer appreciable radar signature increases in the L-band, even if not as pronounced as in the VHF-band.

The VNIIRT 67N6E Gamma DE is a good example of such, as it is a high-power mobile L-band AESA design intended for air defense and ballistic missile defense applications. Like the Nebo SVU and Nebo M RLM–D radars, it can be mechanically rotated, or locked to a sector to perform Aegis-like electronic beam steering sector searches. Similar advanced digital processing is employed. VNIIRT claims the ability to acquire and track a 0.01-square-meter target at 70 nautical miles range.

The shift to lower band operation has not been confined to ground-based radar. The new Chinese KJ–2000 and KJ–200 AWACS aircraft appear to be L-band AESA designs, in part because the solid-state transmitters are easier to build for L-band compared to the S-band used by the U.S. APY–1 and –2 AWACS radars. The Chinese KJ–2000 is modeled on the Israeli Phalcon, the sale of which to China was blocked by the Clinton administration.

An important development is Tikhomirov NIIP's new L-band AESA intended for installation in the leading edges of the wings of fighter aircraft, with the demonstrator sized for the Russian Flanker fighter. With considerable growth potential in power and antenna size, this radar has the potential to be effective against stealth designs, which have been strongly optimized against centimeter band threats. This author performed extensive performance modeling on this design. Growth configurations will be capable of tracking a 0.01-square-meter L-band target at 20 nautical miles, a tactically useful distance.

the survivability of the F–35 depends wholly on its stealth performance

In summary, Russia's technological effort in the development of counterstealth radars is broad and deep and will reshape, over the coming decade, the character of the air defense systems the United States will confront in future expeditionary operations. The common argument of "Why should new Russian SAMs perform any better than in 1991?" overlooks the fundamental reality that all of the pivotal technological limitations exploited in 1991 have been engineered out of current technology SAM systems, many of which now approach, match, or exceed the sophistication of U.S. and European Union designs.

Stealth Aircraft versus Counterstealth Systems

The idea that stealth is an expired technology, no longer worth investing in, has become quite popular, yet it is also fundamentally wrong. The lethality and survivability of the new generation of air defense systems now appearing in the market are so high that conventional defense penetration techniques predating stealth will be almost completely ineffective. Very-long-range "ballistic" SAMs will make life interesting—and often short—for crews flying ISR and standoff jamming missions.

As extensive as the Russian investment in the development of VHF-band counterstealth systems may be, these will be almost completely ineffective against the B–2A Spirit, as its physical size yields effective shaping in the VHF-band, and the depth of its leading-edge absorbent structures is sufficient to remain effective in the meter wavelength bands. The same would also be true of the New Generation Bomber, should it eventually be developed.

Russian VHF-band counterstealth radars will become a major operational issue for the future U.S. fighter fleet as the size of these aircraft precludes effective shaping in the VHF-band. Many VHF radars will be able to track stealthy fighters at tactically useful distances, albeit much smaller compared to legacy fighters. A fighter's ability to survive is then determined by its ability to deny launch opportunities through speed and altitude, evade any launched SAMs through high turn rate maneuvering, and compromise terminal SAM seeker guidance by stealth and electronic countermeasures.

The F–22A Raptor is in a strong position because its high penetration altitude and supersonic cruise capability place it out of reach of all but the best long-range SAMs. Its stealth is effective from all key aspects, and its shaping is well designed to defeat threat radars from the K_u-band down to the L-band, negating all but the VHF-band radars. The aircraft's high supersonic turn rate maneuver capability will provide it with an excellent ability to spoil SAM endgame maneuvers. The aircraft is large enough to accommodate internal electronic countermeasures equipment for endgame self-defense.

The same cannot be said of the F–35 Joint Strike Fighter, intended to equip Air Force, Navy, and Marine Corps squadrons over the coming decade. Lacking the high altitude and supersonic cruise capabilities of the F–22A Raptor, the F–35 operates well inside the kinematic engagement envelopes of most modern medium- and long-range SAM systems. This aircraft is therefore wholly dependent on stealth and supporting electronic countermeasures to survive, in a more challenging portion of the flight envelope, where it is within reach of a much larger number of SAM types, and where SAM endgame maneuver performance is better due to higher air density. The F–35 will not deliver the agility required to effectively evade modern SAMs by maneuver.

Proponents of the F–35 have argued that the aircraft's stealth performance, and the intended capability of its Northrop Grumman APG–81 AESA radar to jam X-band and some S-band threat radars, will be sufficient to permit the F–35 to penetrate deep into air defense systems equipped with modern SAMs, with the superceded SA–20 often cited as an example. Unfortunately, such air defense systems will use passive angle tracking facilities on fire control radars, and emitter locating systems, to exploit any AESA jamming emissions to target and guide SAM shots. The use of the AESA as an electronic warfare self-protection device presents risks that may often exceed its utility in this role. Moreover, the use of the AESA as a directed energy weapon to disable the electronics of inbound missiles is an equally questionable tactic, as measures to harden missiles against this mode of attack are cheap and easy to implement.

The survivability of the F–35 thus depends wholly on its stealth performance. The stated X-band radar cross section of 0.001 square meters for this design[15] in its forward sector is respectable but degrades with increasing threat radar wavelength. Some design choices in the shaping of the F–35, such as the sculpted lower fuselage and axi-symmetric exhaust nozzle, are simply not compatible with the deep penetration of advanced air defense systems where high-power threat radars in the L-band through to the X-band may illuminate the aircraft from any aspect, and some at steep elevation angles. This is why these design "features" were not used on the F–117A Nighthawk, B–2A Spirit, cancelled A–12A Avenger II, and F–22A Raptor.

The reasoning behind the compromises in the stealth design of the F–35 was that the threat systems that could put it at risk would be preemptively destroyed by the F–22A Raptor force in the opening phase of an air campaign, using the Small Diameter Bomb and the potent internal ALR–94 Emitter Locating System. This was feasible for the type of air defense threats seen a decade ago, but is not true for the highly mobile, networked modern systems we now see, designed around a "hide, shoot, and scoot" doctrine. The defeat of such air defense systems will inevitably be a slow process of grinding attrition. It is worth observing that the "hide, shoot, and scoot" doctrine presented a genuine challenge during the 1999 Operation *Allied Force* air campaign—and most of the obsolescent SA–6 Gainful batteries deployed actually survived the conflict.[16]

U.S. Options

High-power standoff jamming of VHF-band radars is technically feasible, but the advent of very long range "ballistic" SAMs will present survivability problems for jamming platforms, be they crewed or robotic. Fighter-sized aircraft and UAVs intended to survive advanced air defenses need to be built around either of two design strategies. One is the "stealth + speed + altitude + agility" model employed in the F–22A Raptor, and the other is the "very wide band stealth shaping" model employed in the cancelled A–12A Avenger II and the proposed X–47 unmanned combat aerial vehicle.

The strategic challenge the United States now faces is that neither of the viable technological strategies capable of defeating modern counterstealth systems are politically compatible with the absolute commitment that has been made to manufacturing large numbers of F–35 Joint Strike Fighters. **JFQ**

NOTES

[1] David K. Barton, "Design of the S–300P and S–300V Surface-to-Air Missile Systems," excerpted from *Microwave Journal*, May 1994, available at <www.ausairpower.net/APA-Russian-SAM-Radars-DKB.html>.

[2] "Su-27SK: Single Seat Fighter," KnAAPO, available at <www.knaapo.ru/eng/products/military/su-27sk.wbp>.

[3] Ben R. Rich and Leo Janos, *Skunk Works: A Personal Memoir of My Years of Lockheed* (New York: Back Bay Publishing, 1994).

[4] Gallium arsenide is a compound of the elements gallium and arsenic. It is an important III/V semiconductor, and is used in the manufacture of devices such as microwave frequency integrated circuits (for example, monolithic microwave integrated circuits, infrared light-emitting diodes, laser diodes, solar cells, and optical windows).

[5] Iosif Drize and Alexandr Luzan, "TOR–M1 SAM System: Protecting Ground Installations against High-Precision Weapons," available at <www.aviation.ru/PVO/Tor-M1/>.

[6] See "Pantsir-S1 Air Defense Missile/Gun System," available at <www.kbptula.ru/eng/zencom/panz.htm>.

[7] Stephen Trimble, "USAF selects datalink to bridge communications gap between F–22 and F–35," *Flight International*, April 15, 2009, available at <www.flightglobal.com/articles/2009/04/15/325156/usaf-selects-datalink-to-bridge-communications-gap-between-f-22-and.html>.

[8] David A. Fulghum and Douglas Barrie, "Georgia Strikes Back with Air Defenses," *Aviation Week*, August 11, 2008, available at <www.military.com/features/0,15240,173602,00.html>.

[9] Eugene F. Knott, John F. Schaeffer, and Michael T. Tuley, *Radar Cross Section*, 1st ed. (London: Artech House, 1986), chapter 1; and Eugene F. Knott, John F. Schaeffer, and Michael T. Tuley, *Radar Cross Section*, 2d ed. (London: Artech House, 1993).

[10] Ibid., 2E, table 14.1.

[11] Ibid., 2E, chapter 8 contains numerous examples.

[12] Yuri I. Abramovich, ed., *Military Application of Space-Time Adaptive Processing*, RTO–EN–027 (Ottawa: Research and Technology Organisation/North Atlantic Treaty Organization, April 2003), available at <www.rta.nato.int/Pubs/RDP.asp?RDP=RTO-EN-027>.

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[14] Miroslav Gyűrösi, "NNIIRT 52E6MU Struna-1MU/Barrier E Bistatic Radar," Technical Report APA–TR–2009–1101, available at <www.ausairpower.net/APA-52E6MU-Struna.html >; and Lockheed-Martin, "Silent Sentry," available at <www.lockheedmartin.com/products/silent-sentry/index.html>.

[15] David A. Fulghum, "F–22 Design Shows More Than Expected," *Aviation Week & Space Technology*, February 8, 2009, available at <www.aviationweek.com/aw/generic/story_generic.jsp?channel=awst&id=news/aw020909p2.xml>.

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