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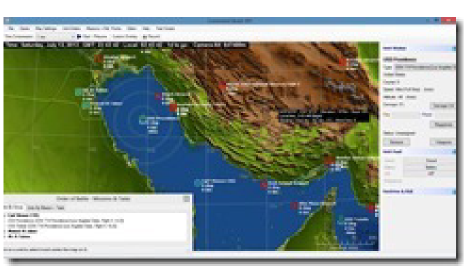
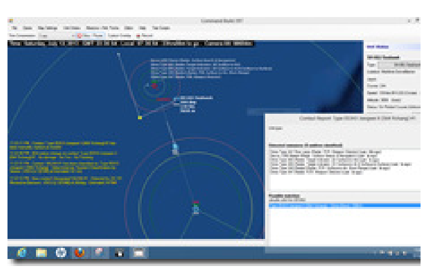
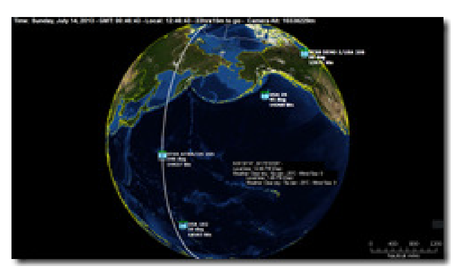






AIRBORNE STEALTH IN A NUTSHELL – PART I

By **Dimitris V. Dranidis**

"Stealth", a buzzword common in defence circles since the early 80s, only became a mainstream reference in the nineties, after the second Persian Gulf War in 1991. Night-enhanced images of the otherworldly-shaped F-117s taking off in the night and striking high-value targets with scarcely believable precision and seeming invulnerability to thick air defences were widely televised and etched in the memories of TV viewers worldwide. The subsequent exposure of stealth aircraft and their participation in numerous air operations in the 90s, in combination with the loss of at least one F-117 in Kosovo, has peeled off some of the mythical cloak surrounding stealth. However, a lot of misconceptions about the abilities and limitations of this technology still remain, even amongst people in posts of high professional responsibility. It is therefore useful to take a broad look at how stealth works, what it can and what it cannot do. This article will examine strictly the application of stealth in air assets. Different technologies and strategies for stealth are the province of land, naval and underwater forces.

First of all, although it is common to discuss the principles of stealth technology (also referred to as VLO or Very Low Observables technology) only as relevant to a narrow band of the electromagnetic spectrum (radar emissions), stealth as a design practice applies a wide range of signatures. Ben Rich, the leader of the Lockheed team that designed the F-117, has stated: "A stealth aircraft has to be stealthy in six disciplines: radar, infrared, visual, acoustic, smoke and contrail. If you don't do that, you flunk the course."

That said, not all disciplines are equally important when discussing any given platform category. Underwater warfare will naturally hand dominance to the acoustic spectrum (though non-acoustic sensors can and do exist). Land combat will emphasize visual, infra-red and acoustic signatures. Radar and (to a lesser extent) infrared bands dominate the scene of airspace surveillance, and so they have to be given higher priority when thinking the applications in air warfare.

Before discussing the various techniques of reducing the radar and infrared signature, it is useful to understand the principles of radar reflectivity and how they can be exploited when one starts thinking about aiming for stealth in earnest.

Radar Reflectivity 101

All radar systems, from an AWACS to a police speed radar, work in the same principle: A certain amount of electromagnetic energy is transmitted through a directional antenna, which focuses it into a conical beam. When a reflective target (in radar engineering terms, anything observed by radar is a potential target) blocks part of the beam, that part of the beam is reflected in many different directions, or "scattered." If the scattering is fairly random, as is usually the case, some energy will be reflected in the direction of the radar antenna. Most radars transmit this energy in pulses, thousands of them every second. In the gaps between the pulse transmission, the radar becomes a receiver, and the gaps are carefully chosen to be just long enough for the signal to make its way to the target and back at the speed of light[1].

The time interval between the transmission and reception of the pulse gives the range from the radar to the target. The radar antenna moves at a pre-determined regular rate, so the time at which the target moves in and out of the beam can be tied to the position of the antenna, giving the target's bearing from the location of the radar.

[1] This is why, if one knows the pulse-repetition frequency (PRF) of a given radar set, it is quite easy to deduce the maximum theoretical range of the radar.

This process has been considerably developed and refined in the 6+ decades since the first workable radars were deployed. However, it is still true that radar does not "see" things in the way that the human eye does. Humans see in a world which is saturated with visible light, so that almost every square inch of it reflects some light toward us at all times; the radar only "sees" the energy that is reflected toward it. The radar can detect a target ONLY when its antenna captures enough energy to rise above the electronic noise that is invariably present in the receiver. (Typically, there is a definite signal-to-noise threshold associated with a positive detection). All the variables in the transmission-scattering-reflection sequence affect the maximum range at which this can happen. These variables include:

- The strength of the outgoing signal
- The width of the beam
- The size of the antenna
- The reflectivity, or RCS, of the target.

The radar beam, it is important to remember, is a cone. The greater the range, the greater the area illuminated by the radar, and the smaller the proportion of the energy which will be scattered by a target with a given RCS. The same effect results in the scattered energy returning to the radar. Therefore, at a longer range, the already-reduced energy hitting the target is scattered over a wider area and less of it will be captured by the antenna. The eventual amount of energy received back by the antenna, even at the best of circumstances, is a very small fraction of the original outgoing pulse.

Increasing the power of the radar will increase its range (a long-time Soviet/Russian favourite), but the benefits are limited by the fact that much of the extra radiated energy is simply wasted on empty space. Greater power can also mean more noise in the system. An antenna of larger aperture is helpful, because it can produce a narrower, more intense outgoing beam and intercepts more returned energy. The limit is the physical size of the antenna, which is important on any mobile or transportable radar and critical on an airborne system.

One of the developmental F/A-18E/F airframes demonstrates how certain VLO techniques can be applied to a design that is anything but stealthy to begin with: all major apertures are aligned with the wing leading and trailing edges, and the fuselage sides and air intakes are canted at the same angle as the fins. Antennae and vents are aligned with the main wing planform. The main undercarriage and engine bay doors have serrated edges. Because the air intake ducts do not provide line-of-sight blockage to the engines, they house a radar absorbent baffle which reduces intake efficiency but also decreases a major source of radar return. Photo McDonnell Douglas

RCS and why it matters

RCS is the one single variable that is out of the radar designer's control. The relationship of RCS to the detection range is not in direct proportion, because of the aforementioned conical beam and radial scattering effects. Detection range is in proportion to the ***fourth*** root of RCS. For example, if a given radar has a range of 100 miles against a target with an RCS of 10 square meters, its range will be eighty-five miles against a target of half the reflectivity (5 square meters). A $1m^2$ RCS translates into a fifty-five-mile detection range. Thus, a ninety percent reduction in reflectivity equals a forty-five percent reduction in detection range; hardly a very inspiring feature. A very large reduction in RCS, not 1/10 but 1/1000, is essential to have a tactically significant effect (e.g. an 82% range reduction at 1/1000).

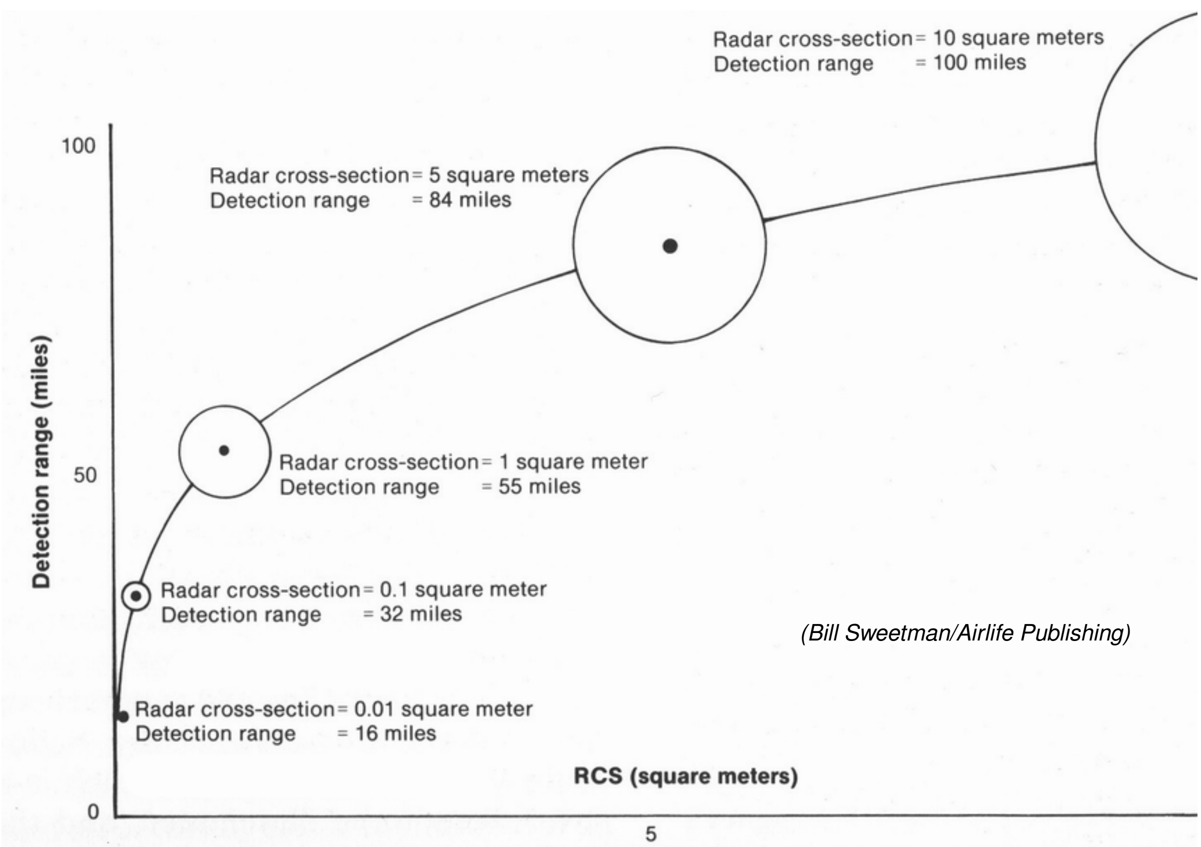
What makes stealth possible and worth the effort is that such tremendous reductions in target RCS (entire orders of magnitude) are achievable, and the reason that they are achievable is that conventional non-stealthy aircraft are almost ideal radar targets.

Searching for an aircraft with radar can be compared to searching with a flashlight for a tiny model airplane suspended somewhere in a pitch-black concert hall, hung with matte-black drapes. How hard it will be to find the model depends on many things other than its size. If the model aircraft is white in color, it may be picked out easily. If it is highly polished, it will glint; the observer will see patches of light on its surface that seem almost as bright as the flashlight. The glints will be particularly strong if the model has flat surfaces which are angled at ninety degrees to the source of the light. Other targets may have completely different characteristics. A flat mirror might seem likely to be highly visible, but unless its surface makes two right angles to the beam (that is to say, it is "normal" to the beam), it will reflect all the light away from an observer. A bowling ball does the opposite; it always reflects the same amount of light, regardless of its attitude.

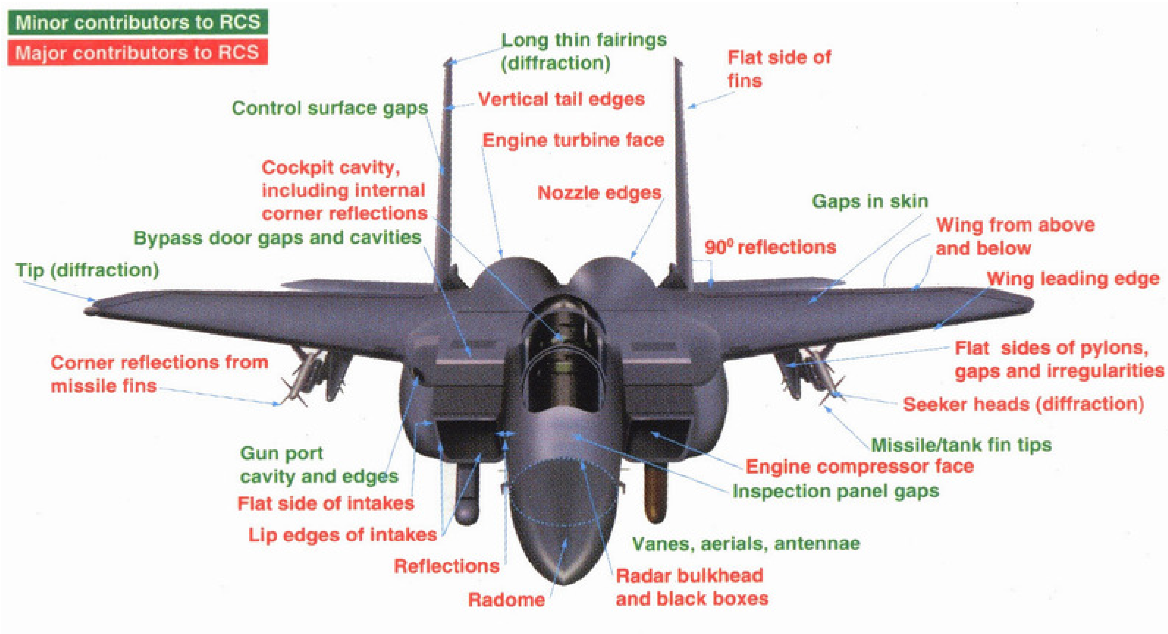
To the radar wave, most synthetic surfaces, like the skin of an aircraft, are mirror-like. A conventional aircraft has a complex external shape, full of curves, flat panels and edges. While its shape agrees with the laws of aerodynamics and the principles of engineering, it is entirely random in terms of the way it scatters radar energy. As the airplane moves (rapidly, relative to a radar which is pulsing energy toward it), it throws off a constantly changing, scintillating pattern of concentrated reflections.

The measurement called RCS was originally developed by radar engineers, as they tried to measure the performance of their creations against a common reference point. RCS is determined by first measuring, or calculating, the amount of radar energy reflected from a target toward an observer. RCS is based on the size of a *reflective sphere* (the optical equivalent would be a spherical mirror) that would return the same amount of energy. The projected area of the sphere, or the area of a disk of the same diameter, is the RCS number itself.

The most important point to be made about RCS is that a small, efficient reflector (such as a flat plate, normal to the radar beam) can reflect as much energy as a very large sphere, and will have a very large RCS. A 10x10cm square plate, for example, has an actual physical area of 0.01 square meter. Its RCS however, when it is normal to the radar beam, is 1 square meter, or 100 times as large as its physical area.



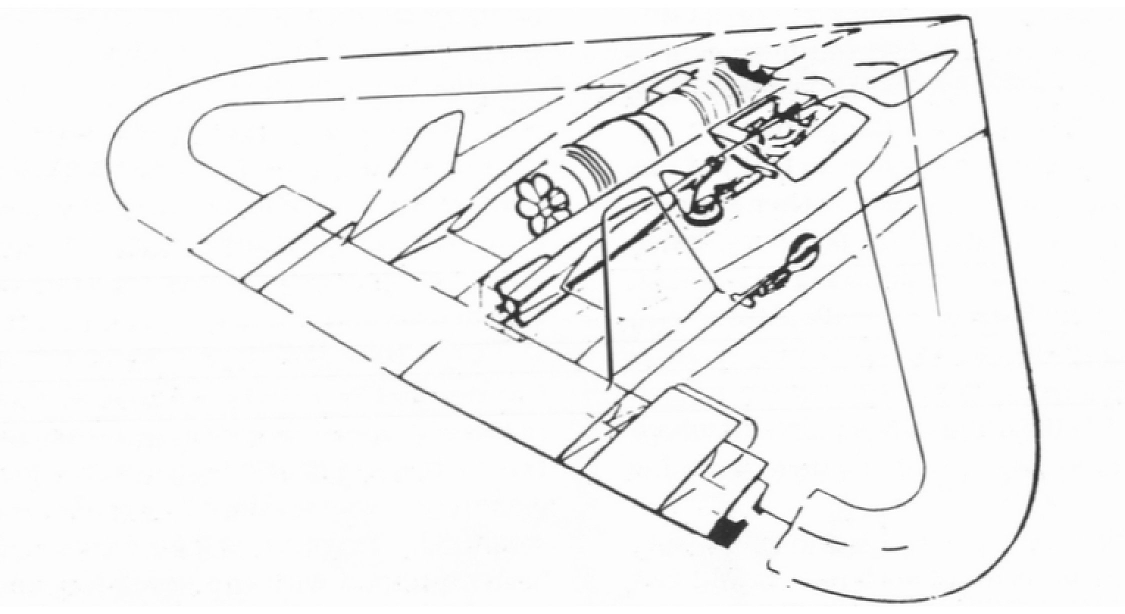
(Bill Sweetman/Airlife Publishing)



Composite or complex shapes can be even worse. Reflective surfaces at ninety degrees to one another (as, for example, the tail-mounted horizontal and vertical stabilizers of numerous aircraft) can turn a radar signal through two right angles and fire it back to the receiver in full intensity. Many modern aircraft are full of such reflectors, and the resulting RCS figures are almost staggering. Viewed from the side, a typical fighter, such as the F-15, may have a projected area of 25 square meters. Because of the aircraft's design, however, the broadside RCS may be sixteen times as large, at 400 square meters, or the size of a very large house. Typical frontal-aspect RCS figures for modern aircraft run around 3-10 square meters for fighters, and up to 1,000 square meters for a bomber such as the B-52 or a transport aircraft like the Boeing 747.

Minimizing RCS

There are two broad aspects of RCS minimization techniques. One falls under the effort to shape the airframe, and covers the geometric design considerations that are taken into account when aiming for a low RCS. The other principle is referred to as “radar-absorbent materials” and is concerned with the materials that help to reduce the reflectivity of the airframe, as well as the structures that will support these materials and integrate them into the



This study for a Tactical High Altitude Penetrator (THAP) aircraft was prepared by the USAF's Aeronautical Systems Division, and was released in 1980. It is a flying triangle with two buried turbofan engines and a deep layer of RAM (comprising non-conducting skins and foam cores) extending around its entire perimeter. The canted vertical fins provide pitch, roll and yaw control in cruising flight. It is interesting to note the similarity of the design with the so-called TR-3 Black Manta, a supposedly advanced stealthy tactical/operational reconnaissance aircraft. USAF via Interavia airframe (often referred to as “Radar-absorbent structures”. These two axes are of course not taken in isolation during the design; trade-offs often have to be made between them.

Shaping for Stealth

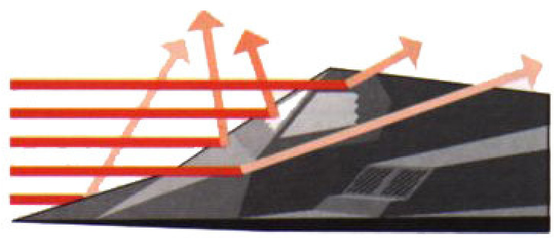
The stealth designer's mission starts with the same words as the physician's Hippocratic oath: "First, do no harm." There are certain popular design features that are incompatible with low RCS:

- Engines in external pods or hung on pylons, such as those of the B-52, provide many excellent retro-reflectors. Their first-stage compressor blades are also prime reflectors on their own[2].
- Vertical stabilizers and slab-sided bodies (particularly when combined with the unavoidable horizontal wings) are ruled out.
- External stores are a strong no-no, as they create multiple hard-to-control reflections on their own.

The designers can, however, take advantage of the fact that the most threatening radar beams will illuminate his aircraft from a point that is much more distant horizontally than vertically. Most radar waves will impinge on the target from a narrow range of shallow angles. If as much as possible of the surface of the aircraft is highly oblique to those angles, the RCS will be low because most of the energy will be scattered. This can be accomplished by blending the airplane's bulky body into the wing.

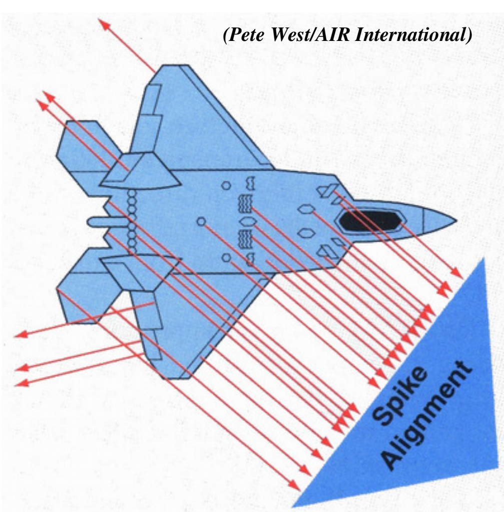
Aircraft shaping is useful over a wide range of radar frequencies but over a limited range of aspect angles. The forward cone is of greatest interest and hence, large returns can be shifted out of this sector into the broadside directions.

Engines produce strong radar reflections and have to be concealed in some way, while permitting air to reach the engine efficiently. This tends to demand a long, complex inlet system, which takes up a great deal of internal space. The prohibition on external stores puts further pressure on internal volume.



There are a number of basic methods of using geometry to control the way the airframe will reflect and scatters a radar wave. One is to make the shape flat or rectilinear and at the same time oblique to the incoming waves, as already mentioned, so that reflection will never go toward the likely location of a receiver. This is the principle behind the "faceted" F-117A.

Another trick, similar but antipodal to the first one in principle, is to shape the airframe in such a way that, instead of having the reflected energy scatter in all directions (and thus a portion of it being always picked-up by the enemy radar), it will bounce back on a very limited number of directions, maybe only one or two. This means that an enemy radar will get only one strong reflection (a spike) when the spatial geometry is “just perfect”, but virtually no reflection at all in any other instance. Unless the radar beam makes two ninety-degree angles to one of the surfaces (which is unlikely, except at extreme look-down angles), the aircraft may remain undetectable. A good example is the frontal wing surface of the B-2. A radar which illuminates the B-2 from anywhere in the front quadrant would produce only two strong "glint" reflections, one from each wing, and these two spikes are impossible to generate concurrently. This method is extensively used in numerous stealthy and semi-stealthy aircraft in order to minimize RCS. It does have the drawback that, in order to make a useful difference, pretty much every straight line on the entire airframe has to be aligned in the direction of the few selected spikes, thus posing extra headaches for the design of everything from landing gear doors to access panels to stabilizers to fasteners etc. etc.

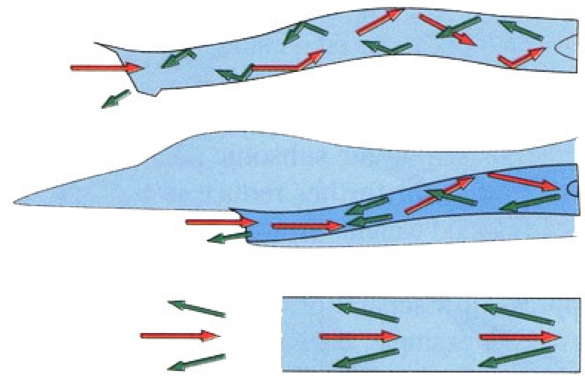


(Pete West/AIR International)

Another method is to use a compact, smoothly blended external geometry to achieve a continuously varying curvature. Most conventional aircraft have constant-radius curves for simplifying the design and manufacturing processes. However, a constant curve is an isotropic scatterer: It reflects energy equally in all directions, an effect which has been likened to the rear window of a Volkswagen Beetle car, gleaming in the sun regardless of the

[2] *It is far from coincidental that many current NCTR techniques are, to a large extend, based on the processing of strong radar returns from the first-stage engine compressor blades to determine the identity of the illuminated target.*

incoming angle. A varying curvature is similar to a sea-shell helix: The curves have an ever-changing circle radius, as though they are sections of a spiral rather than arcs of a circle, and thus do not reflect energy in the usual predictable way. Rather, they tend to absorb the energy as it scatters towards the interior of the curve itself (in a fashion similar to the manner in which hi-fi sound speakers absorb superfluous sound in their internal helix structures). This careful shaping technique can be observed in the overwing engine nacelles of the B-2, as well as the basic fuselage cross-section of the Rafale. This method, however, requires far greater predictive ability and enormously increased computational capacity over the much simpler faceting. It is thus barely surprising that the F-117, an aircraft almost completely based on faceting, has been operational since the early 80s while more complex designs were significantly later in the pipeline.



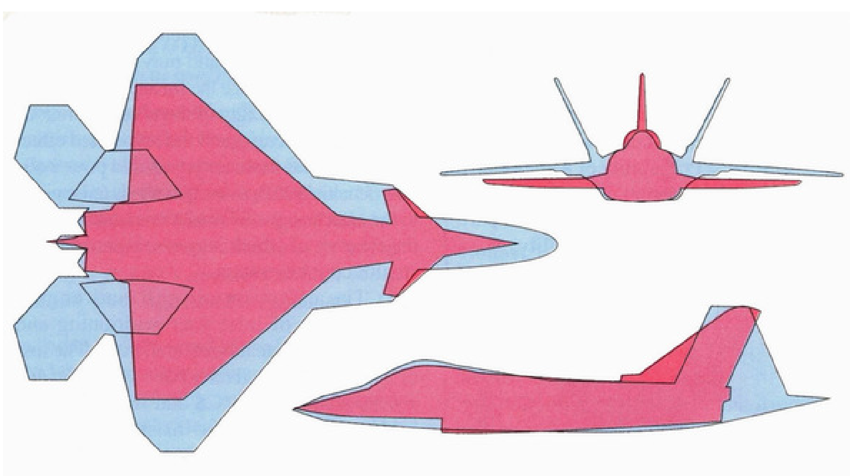
Use of a 'double-S' shaped air intake duct on the Eurofighter. The vertical off set from the inlet almost achieves 100% line-of-sight blockage to engine compressor face. With RAM lining of the duct, the combination greatly reduces the frontal RCS due to backscattering. The duct is reminiscent of that used on the F-16 but the latter is a simple single-S shape and exposes about 60% of the compressor face. A straight duct has the largest RCS by far. (Pete West/AIR International)

Eliminating the radar reflections of the cockpit also results in a useful RCS reduction. Techniques here usually include the application of several absorbent layers on the canopy/windshield walls. This is applicable both on stealthy airframes and conventional assets like the F-16.

The amount of precision engineering necessary for exploiting VLO geometry is often overlooked or under-appreciated. During the F-117's full-scale development phase, one of the prototypes was suddenly found to have a much higher RCS than expected. After an inch-by-inch examination of the airframe, it was discovered that a single screw had not been tightened 100% into the fuselage and it was the culprit for the increased radar reflection.

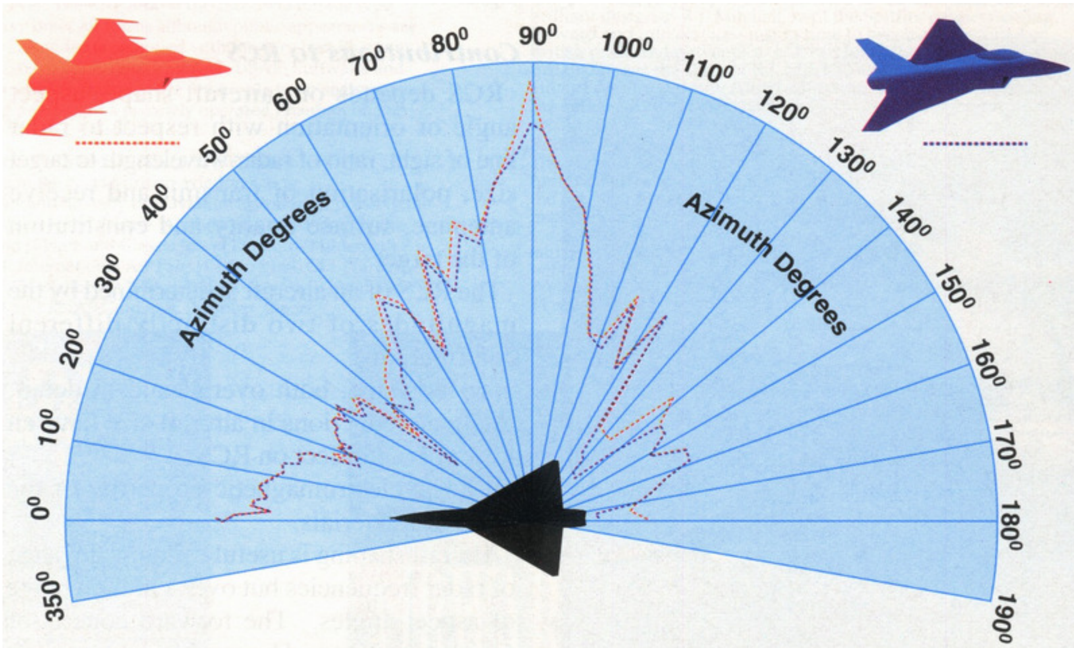
Following is a summary list of shaping laws for VLO designs:

- Avoid flat or re-entrant surfaces likely to be vertical to the incoming radiation. This is one of the primary reasons for the highly-angled stabilizers on both the F-22 and the JSF.
- Bury the engines, with air intakes and exhausts located over the upper surface of the airframe, to mask the cavity from the major illuminating radar threat. Use a screen over the air intake, together with gauzes, vanes and deflectors within the diffuser duct. This is aptly demonstrated by general placement of the engines on the F-117, and in particular their grill-type covers.
- Give the inlet duct an 'S' shape to hide the compressor face and to force m ultiple reflections on the RAM-lined duct. The Eurofighter Typhoon follows this rule with its single inlet shape.
- Avoid variable geometry intakes to minimise reflections from the gaps and steps of the compression ramps and eliminate bypass doors by finding other methods to control intake airflow. The Rafale has deliberately a fixed (though anything but simple) inlet system, and the EF-Typhoon also includes small moving "lips" on the inlet leading edge in order to deal with excess airflow without the need for bypass doors.
- Carefully shape the inlet lips (including sharpness) and nozzles by sweeping to align with major surfaces. Various



Size and configuration comparison between EF2000 and F/A-22. Small physical size is no advantage for RCS, though it delays visual acquisition. Both EF2000 and Rafale are considerably smaller than the F/A-22 with 35% less wing area and with their delta wings, the European designs offer good fuel volume for their size. With the new crop of fighters costing $2,500-$3,000/lb empty weight, smaller and lighter aircraft are less expensive. (Pete West/AIR International) modern designs follow this paradigm including the B-2, F-22, JSF, F/A-18E, Rafale etc.

- Design and manufacture any internal structure within radar-transparent skins to reduce reflections in given directions. The cumulative effect of the interior reflections could easily exceed the radar return from a metallic skin.
- Use RAM wherever appropriate (e.g. leading edges, bulkhead and black boxes within radar cavity, on the interior of the inlet and on metallic structure under radar-transparent skins).
- Use a very high quality of manufacture to avoid gaps, holes, etc., since attention to detail is vital.
- Cover gun port, inlet and exhaust of auxiliary power unit (APU) when not in use. The covert gun port is probably going be a feature of both the F-22 and the Rafale.



Predicted signature of an armed and unarmed generic fighter illuminated by a 3cm wavelength radar, as it sweeps from nose-on to tail-on. This example includes surface reflections and edge diffractions but excludes corners, tips and double reflections. From the front (and even to 30° azimuth) the box-type air intakes totally dominate the signature since their straight lips cause strong diffractions at their sharp and unswept edges. More than 60% of the RCS at 64° is due to the wing's leading edge. Addition of the weapons and their pylons can be seen be very large at 39 ° and 139°. (Pete West/AIR International)

Long wavelengths are less affected by the small details of shape and absorbent structures. Though current stealth technology may frustrate modern air defence radars the same is not true of older long wavelength (lower frequency) radars that have been kept operational worldwide. Some countries were prompted to do this not because of low RCS aircraft but to avoid over-reliance on one type of radar and to overlap many different types to make their air defence system more difficult to jam.

However, all airborne targets detected by long range surveillance radars must eventually be passed over to fighters or SAM sites. These are equipped with high frequency tracking and targeting radars that can be defeated by proper shaping and RAM. How effectively surveillance radar systems could hand over to shorter wavelength sensors is questionable and is one of the main arguments for investing in stealthy designs.

RAM and RAS

Okay, so we've got the perfect VLO design down cold, right to the last screw. Yet the aircraft still keeps reflecting enough energy to be picked-up at a tactically dangerous range. What now? The next step is to use certain special materials to further attenuate radar waves. The term "Radar-absorbent materials" (RAM) applies to a whole class of materials in different forms which are designed specifically to do this. Radar-absorbing structure (RAS) involves building these materials into practical load-bearing structures and shapes for the target vessel (in this case, aircraft).

All RAM and RAS work on the same basic principle. Radar signals are electromagnetic waves, and thus bounce efficiently off any conductive object. However, the electromagnetic characteristics of different objects and materials are not the same. One of the best demonstrations of this principle is the domestic microwave oven.

The microwave oven is based on a magnetron tube, a radar-wave generator which was invented during World War II and which made British and American radars decisively superior to their German counterparts. It is hardly a

Typical radar threat characteristics

Radar System	Frequency (GHz)	Wavelength (cm)
Early warning	0.15-0.2	150-200
	3-4	7.5-10
Ground control intercept	2-3	7.5-15
Height finders	2-7	4-15
Aircraft	8-20	1.5-4
Air-to-air missiles	10-20	1.5-3
SAM **(transportable)**		
Acquisition	0.15-3	10-200
Tracking	5-10	3-6
SAM (mobile)		
Acquisition	2-6	5-16
Tracking	5-13	2.3-6
Radar guided AAA	14-16	1.8-2

(Ray Whitford/Air International)

coincidence that one of the major US brands of microwave ovens is made by a division of Raytheon, a well-known manufacturer of radars and radar-related systems. The device was originally invented by radar engineers who had observed its effects.

While some substances reflect radar waves efficiently, others do not. The difference lies in their molecular structure. Some materials, including many organic substances (such as food), include "free electrons" in their molecular chains. Electrical engineers call them "lossy." Radars, like radios and televisions, operate on a given wavelength; in the case of most radars, the wavelength is measured in gigahertz (GHz), or billions of cycles per second. When a radar transmitter illuminates an object with such characteristics, the free electrons are forced to oscillate back and forth at the frequency of the radar wave. But these particles have friction and inertia, however tiny, and the process is not one hundred percent efficient. The radar's energy is transformed into heat, and the chicken is cooked or (depending what modern folk myth is being repeated) the poodle explodes or your underwear catches fire. These substances are "lossy dielectrics" because they are non-conductive.

RAM has been available for years in many forms, and many of them are not even classified. Most such material consists of an active ingredient—a dielectric, such as carbon, or magnetic ferrites—which is molded into a non-lossy dielectric matrix, usually a plastic of some kind. Lockheed developed a lossy plastic material for the A-12/SR-71, as well as the hypersonic D-21 drone. Loral has long provided a material that resembles a ferrite-loaded neoprene, which is used in the inlet ducts of the B-l. A ferrite-based paint known as "iron ball" is used on the U-2 and SR-71.

Some basic limitations apply in some degree to all kinds of RAM:

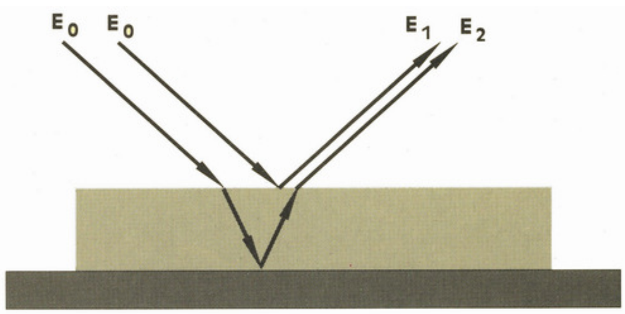
- All of them absorb only a portion of the radar energy and reflect the rest.
- A given type of RAM is also most effective at a certain frequency and less so at others. Therefore, comprehensive spectrum coverage demands a combination of different materials, often bulky.
- The effectiveness of RAM varies with the angle of the incident radar wave.
- Generally, the thickness and weight of RAM increases with its effectiveness. This means that a large aircraft is generally easier to be fitted with a broad-coverage RAM collection than a smaller aircraft. This is one of the reasons that the B-2 is far stealthier than the F-117.
- Many types of RAM are sensitive to adverse weather condition. This was of particular headache to early B-2 airframes, which were deemed unsuitable for operations from foreign bases partially because of the material's sensitivity to rain. Reportedly a new type of material has been installed more recently and the problem has been rectified.

RAS is more complicated, more recent in origin and more classified. However, the essential principle seems to be a "defense in depth" against radar waves, to achieve a high degree of absorption over a wide bandwidth. Except in a case of dire need, nobody is going to cover an airplane with a thick, solid skin. One alternative means of providing the necessary depth is to use "honeycomb" structure.

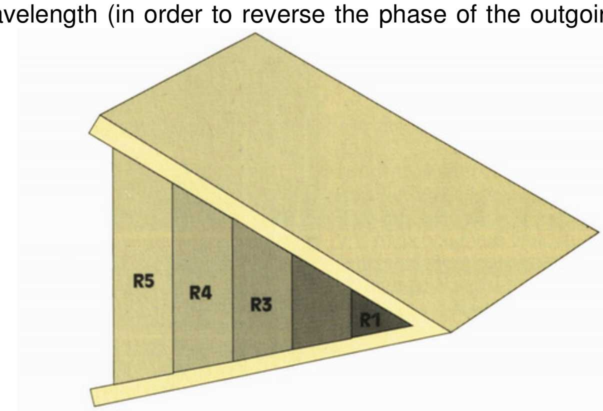
Honeycomb is so called because it looks like the natural honeycomb. Its core is made of a light fiber material, such as Du Pont's Nomex, bonded together in such a way that it forms a flexible slab with hexagonal passages from front to back. Load-bearing skins, which can be relatively light and flexible, are then bonded to the front and back of the slab. The result is a panel across which you can drive a truck without breaking it, and an aircraft skin which needs no stiffeners or stringers.

From the viewpoint of RAS, the advantage of honeycomb is depth without proportionate weight. A honeycomb RAS might consist of an outer skin of Kevlar/epoxy composite, which is transparent to radar, and an inner skin of reflective graphite/epoxy. The Nomex core, between them, would be treated with an absorbent agent, increasing in density from front to rear of the honeycomb.

The front-face reflection of such an RAS would be minimal. As the radar wave encounters the thinly spread absorber on the outer edges of the core, a small part of its energy is absorbed and a small part scattered. As the wave proceeds through the core, it encounters more densely loaded core material which both absorbs and reflects more energy. But before the reflected energy can reach free space again, the outermost layer of absorber once more attenuates it. It is an electromagnetic Roach Motel; radar waves check in, but they don't check out.



A properly configured RAS layer can also reduce the radar reflection by passive cancellation. The way this works is that the external skin may reflect back part of the energy pulse (E1), but the rest will be redirected through refraction into the internal of the airframe and then bounced back out again at the exactly opposite phase (E2). Thus hopefully the two radar returns will cancel each other out. The problem with this method is that, in order to work, the distance that the internally-refracted radiation will travel (i.e. the depth of the under-skin layer) must be very precisely tuned to match the one-half of the radiation's wavelength (in order to reverse the phase of the outgoing signal). This of course means that the method will work only against a very narrow frequency spectrum, and that it will be impractical against a low-frequency (large wavelength) radar.



Another popular structure that follows the gradual absorption principle is extensively used on the leading and trailing edges of stealthy airframes. The idea is that the external skin is composed of a high-frequency ferrite absorber, while the interior begins with a low-absorption layer and thickens back into gradually deeper and more absorbent layers. This has an effect similar to the honeycomb structure, in trapping and successively absorbing an ever-growing amount of the energy.

Active Cancellation

A method of passive cancellation of the reflected radar signal was already discussed, together with its shortcomings. A far more flexible but also more complex approach is to actively replicate the incoming signal and reverse its phase in order to achieve the same effect. Since it involves active emissions, this technique is more appropriately classified as part of the active jamming effort, but is nevertheless noteworthy with regards to stealth because its net effect is the reduction (or even complete elimination) of the amplitude of the reflected signal, and thus the reduction of the targeted object's apparent RCS.

Just how complicated it is to cancel a reflected radar signal can be reasoned from the fact that the original incoming signal from the radar will be reflected from many spots on the aircraft's body. Each spot will produce an individual reflection with its own unique amplitude and phase. The amplitude of the reflection would depend on many factors, such as incidence angle, particular type of material, geometrical form of a certain location on the aircraft's body that produced the reflection and some other factors. The phase shift will be dictated by the wavelength of the radar signal and the location (and geometrical form) of the particular spot that produced the reflection in question. The enemy radar does not, however, receive all of the reflected variations of the original signal as separate entities. It either selects the strongest return signal, or averages several strongest reflections. This simplification can be used to the advantage of the aircraft, since it will only need two antennas to transmit a simulated return signal averaged over the length of the aircraft. The return signal, picked up by the radar, would look somewhat chaotic, consisting of background noise and the main return spikes. These spikes are, presumably, the main targets of active cancellation (here again we see the importance of first shaping the aircraft to minimize and actively control the formed spikes). It is important to understand, however, that in case of a real-world effective system we are dealing with an immensely complicated issue. Something that can be popularly explained with a single wave sinusoidal signal will become progressively more complex in real-life situations.

Active cancellation as a working method places strong emphasis on several things to happen "just right":

- The aircraft has to have a system capable of analyzing the incoming signal in real-time and replicating its characteristics faithfully enough to disguise itself as the "true" signal, before its phase is reversed. Analyzing the signal on first contact is not enough; the enemy is likely to shift the emission characteristics of the radar equipment within its physical limits (PRF, signal frequency etc.) throughout the duration of the detection/tracking attempt. Likewise therefore, the analysis process has to be repeatedly performed as long as the aircraft remains within the detection envelope of the emitter.

- The phase-reversed signal must be transmitted with just enough power to match the "real" signal reflected back at the receiver. Careful power management is crucial here; a clever software algorithm in a modern radar system may try to check the signal strength difference between incoming spikes and reject those that seem a bit "too powerful" for the given situation. The purpose here is deception, not to flood the other guy's scope with white-noise static.

- The bearing of the incoming signal must be determined accurately so that the "fake" reflection will be reflected at the original transmitter and nowhere else. This also implies a very accurate laying of the onboard beam-transmitter for the fake signal, as well as rapid beam-steering for circumstances where the airframe's attitude and velocity vector is rapidly changing (e.g. while maneuvering to avoid enemy fire). This is easier said than done: it is hard enough to precisely locate (in both azimuth and elevation) the emitter in order to point the fake signal only there and nowhere else; let alone keeping the beam on-target while the aircraft is performing anything from routine subtle navigation course adjustments to gut-wrenching missile-avoidance maneuvers. For this reason, only an electronic-scan array is practically suitable for emitting the fake signal.

Despite this tall order of requirements, active cancellation offers several advantages compared to more conventional jamming techniques. Both barrage and deception jamming cannot avoid tipping-off the enemy on "something" going-on; here, however, the element of surprise is fully retained for exploitation. A significantly less amount of transmission power is required, only enough to replicate the weak energy reflection back to the enemy emitter; thus the overall system can be light and compact enough to be fitted to aircraft hitherto unable to benefit from the existence of heavyweight jammers. This also means that other onboard avionics are significantly less hampered by RF-interference while active cancellation is in progress (those who recall the EW-avionics interference troubles of aircraft such as the B-1, the EF-111, the Su-27 or the EA-6 will certainly appreciate this).

The Spectra integrated EW suite on the Rafale fighter is a prime example of active cancellation. All the elements described above are in place: sensitive and precise interferometers for passive detection & localization, powerful signal processors as part of the overall avionics suite, and conformal electronic-scan arrays dedicated to the transmission of EW signals. Combining a semi-stealthy airframe structure (treated with RAM in significant quantities) with various traditional forms of jamming plus active cancellation can result in an airborne weapons platform of vastly lower RCS than one would expect from an otherwise "ordinary-looking" canard-delta aircraft.

There have been speculations that the Russians may be using this technique on their S-37 Berkut and possibly MiG 1.42 prototype fighters. It is also believed that the ZSR-63 defensive aids equipment installed on B-2 bombers may be using this technique.

It is not clear whether the F-22 and F-35 are going to employ active cancellation in their EW arsenal. Certainly the pieces are in place hardware-wise: An added bonus of the AESA radars fitted on both aircraft is that the operation of multiple RF beams in parallel (as opposed to the single beam of mechanical-scan and passive electronic-scan systems) enables the radar to scan, track *and* jam at the same time. It is however unknown if the relevant software is going to be in place to exploit this capability. Certainly the F-22 is more than capable of performing this function with its ultra-sensitive ALR-94 receivers and ample onboard processing power, in addition to the large AESA set. Whether the significantly smaller and thus volume/weight-challenged F-35 will be able to perform the function on its own hardware remains to be seen.

Plasma Devices

A more recent approach to the art of VLO is the employment of plasma fields. Plasma physics as a potential aerospace technological branch has been long under research, mainly for the purposes of spaceborne propulsion and thermal heating for endo/exo-atmospheric spacecraft[3]. The effect of plasma as an RF-signal inhibitor is well known for decades now, as the communications black-out that a space vehicle encounters during re-entry is caused by the shielding effects of plasma. This builds naturally in front of the spacecraft as it hits the Earth's atmosphere and compresses the air to high temperatures.

According to JED, Russia is working to develop plasma-cloud-generation technology for stealth applications and achieved highly promising results, reportedly reducing the RCS of an aircraft by a factor of 100.

Russian research into plasma generation is spearheaded by a team of scientists led by Anatoliy Korotoyev, director of Keldysh Research Center. The institute has developed a plasma generator weighing only 100 kg, which could easily fit onboard a tactical aircraft. For the system to work, there has to be an energy source on the aircraft that ionizes the surrounding air, probably at the leading surfaces. Since the resulting ions are in the boundary layer of the aircraft, they follow the airflow around the plane. But the system is not without drawbacks. First, the amount of power required is quite high, so it will likely only be activated when an enemy radar is detected. The other is that the plasma also blocks the radar of the aircraft being protected, necessitating holes in the plasma field to look through it.

The plasma generator was tested first on flying models and then on actual aircraft. The new Su-27IB/Su-34 strike aircraft (known in export - certainly without the plasma generator - as the Su-32FN) utilizes the system and is likely the first production combat aircraft with this critical technology.

Work on plasma generation is not the purview of Russia alone, though. In the US, for example, research in this field is being conducted by Accurate Automation Corporation (Chattanooga, TN) and Old Dominion University (Norfolk, VA). French companies Dassault (Saint-Cloud, France) and Thales (Paris, France) are jointly working in the same area as well. – *(Michal Fiszer and Jerzy Gruszczynski)*

The US Navy has been experimenting (through third-party development) with a plasma stealth antenna developed for use on VLO vessels & aircraft. The system employs arrays of multiple U-shaped glass tubes filled with low-pressure gas (somewhat equivalent to fluorescent tubes). This antenna is energized and acts as a highly-directional, electronically steered transmitter/receiver in pretty much the same principles as an AESA system. When de-energized, the antenna is virtually transparent to hostile electromagnetic signals. One of the problems with such a system is its vulnerability to resonant signals at the tubes' self-frequency. A summary description of the system (among other sources) can be found here: http://www.aeronautics.ru/plasmaantenna.htm

Infrared Stealth

Passive IR detection devices rely on the fact that every atom of matter, including clouds and rain, continuously sends out electromagnetic radiation at an IR wavelength which corresponds to its temperature. It is necessary to think in terms of absolute (Kelvin) temperature. Even though a certain object may be regarded as cold, a snowflake for example at 0°C, on the absolute temperature scale it is at 273K. For aircraft detection, IR seekers look for contrasts between hot parts on the airframe such as jetpipes and surfaces subject to kinetic heating, and the background radiation. In designing IR detectors several things have to be considered: the range of wavelengths emitted by the target, the likely wavelength of the most intense radiation, the ways these wavelengths are affected by the atmosphere; and because the maximum contrast is desired, the character of the likely background radiation. Many IR devices operate in the 8-13 micron band since this is the most IR-transparent band in the atmosphere. In engine exhausts, carbon dioxide produces most of the IR signature at 4.2 microns, so modern IR sensors can 'see' at two different wavelengths, (medium: 3-5 microns and long: 8-14 microns) to provide good target discrimination.

The engine exhausts are the primary battlefield in the war against infrared detection. There are many types of infrared sensor in service, and their different capabilities are sometimes confused. The basic fact is that the atmosphere absorbs infrared energy. At a range of a few miles, a small infrared sensor can receive enough energy to produce a TV-type image of the scene; at greater ranges, this capability is much diminished. Most medium-to-long-range systems do not detect the infrared emissions from the aircraft itself, but the radiation from the hot air and water vapor emitted by its engines.

[3] *Research on plasma physics has been an area of intense Soviet & Russian scientific activity, which resulted in a number of breakthroughs in theory as well as practical applications of plasma. Perhaps one of the most interesting and promising applications of plasma is the so-called ion thruster, used to propel spacecraft. This technology was first developed in Russia (mainly by Keldysh Research Center) and recently successfully used on the US "Deep Space 1" satellite. The system uses xenon gas as fuel and can achieve exhaust velocities of up to 30 km/sec (ten times that of an average rocket engine.)*

The radiated IR energy is proportional to the fourth power of absolute temperature. With engine turbine entry temperatures (TETs) currently at around 1,900K and rising, the back end of a military aircraft is the greatest source of IR radiation. With afterburner on, it becomes more so. Moderate stagnation temperatures are inevitable on leading edges of a fighter's airframe due to kinetic heating at high Mach numbers. As the stealthiness of fighters increases so their missiles' exhaust plumes play a greater role in early detection. Lower visibility plumes will minimise detection of both launch platform and missile.

The key to degrading the performance of IRST systems is to ensure that the exhaust dissipates as quickly as possible after leaving the aircraft. Or example, the engines can be fitted with flow mixers to blend the cold bypass air with the hot air that passes through the combustor and the turbine. The exhausts geometry can be adapted to a wide and flat shape rather than the traditional round, increasing the mixing rate (but probably reducing thrust efficiency). Furthermore, the interaction between the exhaust stream and the airflow over the aircraft can be engineered to create an additional vortex which further promotes mixing.

There are several other methods to reduce the IR signature:

- Have the ability to supercruise (cruise at supersonic speeds without afterburning) to restrict the temperature of the nozzle. Moreover, supercruising allows the pilot to engage on his terms, increases weapons' envelopes, minimises exposure to SAM threats and not only stretches combat radius but forces an adversary to expend his own fuel in order to get his aircraft to an energy state where he can engage it.
- Use a high bypass ratio (BPR) engine to mix in cold air to reduce exhaust temperature. That said, a bypass ratio greater than about 0.4 conflicts with the requirement of the high dry thrust to achieve supercruise.
- Use a curved jet pipe to mask the hot turbine stages.
- Use two-dimensional nozzles (which increase the surface area of the exhaust plume) or ejector nozzles (which mix in ambient air) to increase the rate of cooling.
- Increase cooling of the outer skin of the engine bay or insulation to reduce temperature of the airframe skin.
- Use a curved air intake to mask, to some extent, forward emissions from the engine.
- Limit maximum supersonic speed to reduce IR signature due to kinetic heating.

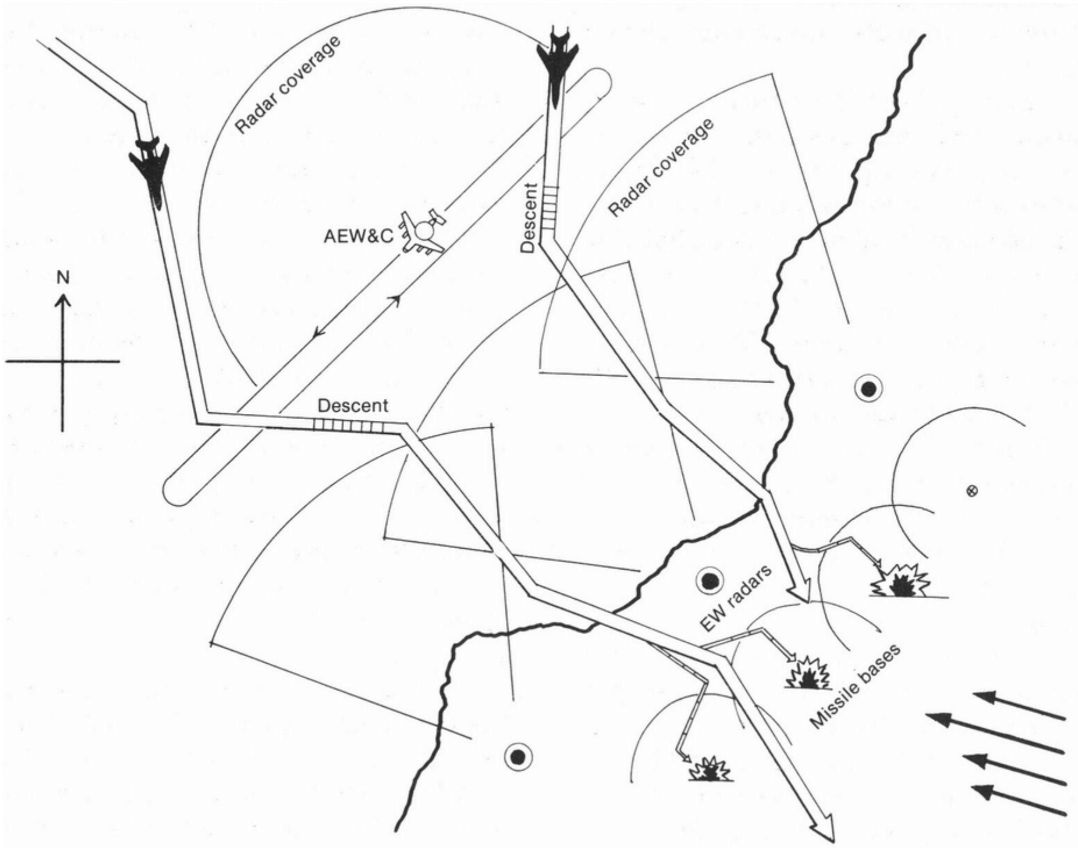
Stealth in Harpoon – Effect & Tactics

A serious simulation of air & naval operations like Harpoon could hardly ignore the effect of stealth in combat operations. The current (H4.1) rules of the board version treat stealthy targets as having 1/10 of the detection range of a very large target (in RCS/IR-signature terms). Thus, for instance, a given radar may detect a B-52 at 200nm but will detect an F-117 only at 20nm. The abstraction and simplification necessary for the table rules dictate that all stealthy units are treated equal in terms of their signature strength; there is no discrimination between the 1st-gen VLO technology of the F-117 and the much more advanced measures in B-2, for example. The Harpoon Classic/HC97/H2002 closely follows the table rules and thus adopts the same model.

In Harpoon 2 & 3, the fundamentally different sensor & cross-section model allows a more discrete application of signature values to each unit in the database. Each air & surface unit has its own distinct RCS, IR and visual signature that determines its detection range against a sensor of given sensitivity. The following table is an example of the detection range of certain radar types against various potential targets. The data is true for the DB2000 v6.4.2 dataset. All figures are in nautical miles (nm) for head-on detection.

Target	Radar Type					
	Big Bird (SA-10C)	N-001 (Su-27 / 1985)	APG-63 (v1980)	APY-2 RSIP (E-3C RSIP)	Schmel-2 (A-50 / 1989)	Schmel (A-50 / 1984)
B-52H (1982)	150	120	125	600	300	250
Tu-22M-3 (1983)	141,1	112,8	125	600	300	250
Su-30MKI (2001)	104,0	83,1	97,1	600	300	250
F-15C (1997)	99,9	79,8	93,2	600	300	250
F/A-18C (1994)	94,9	75,8	88,5	600	300	250
F/A-18E (2003)	40,2	32,1	37,6	268,9	148,8	123,7
RGM-109B (1990s)	22,8	18,2	21,2	152,1	84,1	70,0
F/A-22A (2005)	8,5	6,8	7,9	56,8	31,4	26,2
F-117A (2002)	7,3	5,8	6,8	48,9	27,1	22,5
AGM-129 (1991)	7,2	5,8	6,8	48,4	26,8	22,3
B-2A Blk30 (2005)	2,2	1,8	2,1	14,7	8,1	6,8

It is interesting to observe the effect of RCS-reduction measures taken even on aircraft whose design was not particularly stealthy to begin with; a good example is the F/A-18E compared to its predecessor variant. The F-117 has a comfortable edge against radars of its era but is beginning show some vulnerability against more modern systems. The F/A-22A has just enough stealth to easily engage both fighters and SAMs with appropriate stand-off weaponry (of course this aircraft has other virtues as well that help immensely; supercruise for example plays hell with the no-escape zones of enemy missile systems). The B-2 is virtually undetectable against 1980s/90s hardware (indeed, under favorable weather conditions, visual & IR acquisition is far more likely than radar detection) and still an extremely elusive target even for current & near-future sophisticated systems such as the E-3C RSIP.



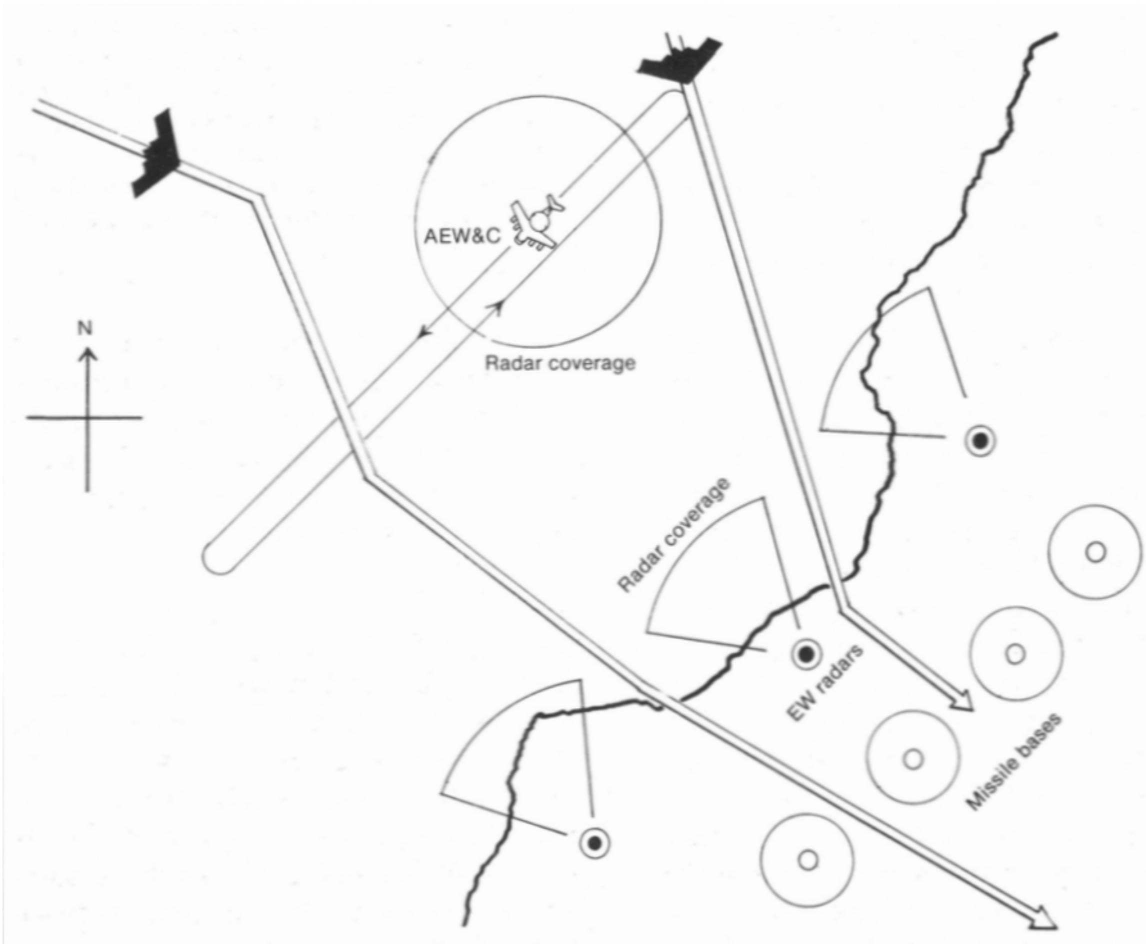
A typical bomber penetration scenario: Two B-1B bombers approaching from the northwest are likely to be detected by AEW&C aircraft and/or an overlapping chain of ground-based EW/GCI radars. By changing course and dropping to low altitude, they can delay detection, but by now enemy defences have been alerted for good. While the SAM sites behind the radar fence can be attacked with SRAMs or cruise missiles, the fighters approaching from the southeast cannot be so readily countered, and some of the bombers will probably be lost. *(Bill Sweetman)*

The application of the stealth advantage in air/naval operations can be broadly separated in two levels: strictly tactical and tactical/operational. The strictly tactical advantage is pretty straightforward: A defensive network of normally overlapping sensors is constructed with a certain target RCS in mind. Against a VLO target, the sensor coverage (in both horizontal range and altitude) shrinks dramatically with gaps opening between individual units, gaps through which the stealth forces can roam undetected. This allows targets under the coverage of heavy anti-air defenses to be successfully engaged and destroyed.

Stealth also favors its employer in the one-on-one engagement sequence against the affected enemy weapon systems themselves. Because the net effect of reduced sensor signature is the drastically reduced engagement envelope of enemy weapons, friendly stealthy assets can now engage enemy forces with weapons and tactics that would previously be suicidal. An F-16 dropping an LGB on a SA-11 battery at 20000ft is asking for trouble; the same bombing run can be accomplished by an F-117 with a high probability of survival and success.

The tactical/operational aspect of stealth employment is less straightforward and sometimes overlooked. A long-standing axiom of strategy is that appropriately arraying the forces at hand is half the victory. If that arrangement can be done covertly, frustrating enemy surveillance & reconnaissance attempts, the chances of success in the forthcoming battle are even higher, as surprise and the initiative are gained. In air warfare, the post-WW2 dominance of long-range surveillance radars seemed to pretty much eliminate any possibilities for the covert deployment &

transfer of aerial assets across the battlefield (as is often common with ground forces and of course the norm with submarine forces), as long as the adversary was equipped with adequate surveillance systems[4]. Stealth however makes it again possible to perform secret maneuvers across the aerial battlefield even at the first day of combat, in order to surprise the enemy and gain advantageous positions. Critical to this endeavor is the ample existence of various support forces such as aerial tankers, friendly AWACS aircraft and extensive EW forces, cooperating to both support the friendly maneuvers and also hinder enemy reconnaissance efforts, while at the same time keeping track of enemy forces so that the maneuvers and force dispositions can be suitably adjusted. While this is also feasible with conventional non-stealthy assets (particularly under the coverage of strong jamming and deception measures, as is standard in Soviet/Russian doctrine), the existence of stealthy assets makes the employment of such tactics significantly more feasible as the result of reduced delectability to enemy sensors.



Same scenario as before, but with B-2As this time: A sharp cut in radar detection range makes the AEW&C aircraft much easier to evade, and opens up gaps in the coverage of the EW/GCI radars, even at high altitude. With no early warning, and with targets at their maximum effective range, SAMs are unable to engage the bombers effectively. The fighters are too late to arrive (if an alarm is raised at all) and will have their own problems in locating the bombers. *(Bill Sweetman)*

[4] *This was one of the primary reasons that both NATO and the Warsaw Pact had each other's radar networks in the Central Front high on their target lists. For either side, to lose air surveillance over Europe would mean the loss of the initiative in air operations – with catastrophic consequences in the progress of both air and ground operations for the duration of any potential conflict.*

The benefits of stealth apply not only to platforms but to a lot of weapons as well. Anti-surface munitions like the JSOW, JASSM, Apache/SCALP/Storm Shadow, Taurus/KEPD and many others are specifically shaped and treated to minimize their radar and IR signatures. This has two useful payoffs: On the one hand, the weapon itself becomes less vulnerable to enemy defensive systems, which means that fewer of the weapons launched will be shot down before reaching their target(s). This in turn means that fewer weapons and their parent platforms need to be allocated to any given mission, and finally the end result is that a greater number of targets can be confidently engaged with a given force.

The other benefit is the advantage of surprise and its effect in cases where shrinking the enemy's available reaction time is of the essence. A good example of such a situation is a typical OCA strike against an airfield. If non-stealthy strike aircraft or stand-off weapons are used, it is quite likely that they will be detected far enough out that the enemy will have some time available (even just 4-5 mins will do) to get as many of his ready-to-fly aircraft in the air and fly them somewhere else to preserve them. If the aircraft being flushed include armed hot-pad alert fighters (a common protective measure) these can immediately and actively contribute to the base's defense against the incoming attack. Contrast this with a situation where, as a result of using stealthy weapons and/or platforms, the base is caught

Boeing's "Bird of Prey", a recently declassified stealth technology demonstrator

virtually napping and the attack is detected so perilously close that the enemy has no time to get anything in the air but instead can only rely on his ground-based terminal defences. This can mean the difference between the base suffering little or no damage and being virtually obliterated.

In Part-II we will examine some of the limitations of stealth technology and techniques, how these can be exploited and what systems and tactics exist that can reduce the decisive edge offered by this technology.

Partial Selected Sources:
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