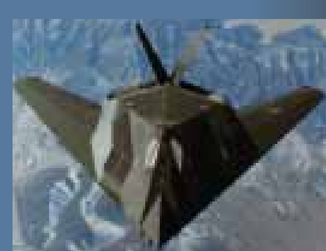
UNDERSTANDING STEALTH



John Shaeffer

What does stealth mean to you? When several non-technical people were asked this question, their responses included "making invisible," "spooky stuff – secret military stuff," "stronger and mightier than others," "sneaky, unseen, secretive," "strong, destructive, powerful," "sleek," and "unable to be detected."

It is no accident that stealth is so misunderstood. In the late 1980s, the media aroused interest by revealing that a significant part of the national defense budget was directed toward "stealth." But just what was it? The media portrayed stealth vehicles as aircraft that were magically invisible to enemy air defense radars which had been developed to detect earlier generations of aircraft. In reality there is no magic involved. Stealth does not mean being invisible.

This paper explains the subject of stealth to the layman. Questions that will be answered are: 1) What is stealth? 2) What are the principles behind aircraft stealth design? and 3) Why is stealth difficult to defeat?

Webster defines ***stealth*** as "the act of going furtively or as a secret procedure or action." ***Stealthy*** is defined as "accomplished secretly or furtively or as acting clandestinely, furtive, or sly." In a military operation, the ability to be secret or furtive means a great deal. First, it means that the "good guys" can perform their mission without interference from the enemy. Second, it means that a mission can be performed with fewer resources since attrition and loss are no longer issues. Third, it means reduced costs for performing a military mission. Fourth, it means that our armed service personnel are much safer and much more likely to come home. Fifth, it means that previously undoable missions, such as special operations rescues, can now be accomplished. More importantly, in military language, stealth means greater probability of mission success and greater survivability.

Since 1975, stealth design principles have been incorporated into many weapon systems including satellites, missiles, aircraft, unmanned piloted vehicles, helicopters, ships, tanks, ground vehicles, submarine snorkels and even buildings. Most of this effort has occurred within special secret "black" programs. A number of stealth systems, however, are now being publicly acknowledged, such as the F-117 stealth fighter, the B-2 intercontinental bomber, the Sea Shadow naval vessel, the canceled A-12 Navy aircraft, the F-22 advanced tactical fighter, the new Joint Strike Fighter (JSF), the Army's new Comanche helicopter, the X36 scaled supersonic test bed aircraft and the Dark Star remotely piloted reconnaissance aircraft. In addition, several naval ships have partial stealth designs: the Arleigh Burke DG-51 and the new LPD-17 amphibious-assault ship. As a nation, we have invested considerable resources in these systems.

Stealth design has and will continue to play a major role in the development of our military assets. Stealth considerations, while no longer new, are still shrouded in mystery due to several factors: 1) Stealth was initially developed by the Department of Defense in "black" programs which prevented dissemination of knowledge; 2) Stealth design concepts are not yet a part of standard academic engineering curriculums; 3) Stealth concepts are often presented by physicists and electrical engineers who use mathematical detail such that others often have difficulty understanding the basics.

Now that the system acquisition process has moved out of the "black," non-technical decision makers need to understand stealth. And individuals need to make judgments regarding the viability of stealth. They need to appreciate the importance of our investment in stealth and to understand that stealth is very difficult to defeat, making investment in these systems a good procurement decision.

This paper presents stealth from an aircraft viewpoint. Many of the concepts, however, are the same for other systems, such as ships and land vehicles.

KEY CONCEPTS TO UNDERSTAND STEALTH

In order to be stealthy, an aircraft must be undetectable to the enemy. How does the enemy detect our aircraft? They can use any number of characteristics. They can visually see us with their eyes. They can see engine heat sources using infrared detectors. They can hear us using their ears or special microphones. They can use radio receivers to listen to our radio transmissions. Or they can use radar to see us.

The military/technical description of these characteristics is "system observables" or "signatures." To avoid detection and be survivable, we minimize our visual signature, infrared heat signature, acoustic signature, radio transmission signature and radar echo signature.

Stealth design minimizes all of these signatures. While the term stealth is synonymous with being clandestine or invisible, we cannot in reality be invisible. What we strive to do is to be less visible, which means that we can get much closer to an enemy before he can detect us. Our goal is to be undetected for as long as possible so that if and when detected, it is too late for the enemy to do anything about it.

Typically, the most important signature is radar echo because it has the greatest range – up to 400 miles. Visual, infrared, acoustic, and radio emissions are short-range signatures. That is, they can only be used by the enemy when we get very close.

Why is detection range or the distance at which the enemy can see us important? Simply put, the closer we can get to the enemy before detection, the less time he has to do something about us, such as aim and fire a missile to shoot us down. We work very hard to reduce radar echo signature because it potentially presents the enemy with the greatest response time to do us harm.

Radar is used to find or acquire potential targets, track targets, aim a weapon and finally fuse the weapon. By designing radar stealth, we reduce the enemy's chances of successfully performing each of these operations, thus improving our survivability.

Submarines, camouflage covering, low contrast visual paint schemes, and uniforms are examples of stealth which have existed for many years; however, the concept of radar stealth is relatively new. Until the 1970s, no serious attention was paid to reducing the radar echo. The 1973 Yom Kippur War aircraft losses to radar guided missiles were so high that the entire issue of air power superiority came into question. This led the Defense Advanced Research Projects Agency (DARPA) to initiate the HAVE BLUE program in 1975 to design a stealth aircraft. This effort was extremely successful and has become ***the most significant advance in military aviation since jet engines. Stealth rendered null and void the enormous 300-billion-ruble investment the Soviets had made in missile and radar defenses over the years***[1]. The radar echo signature was reduced by more than a factor of 1000[1]. This significantly reduced radar's detection range and thus reduced the enemy response time available. The success of the HAVE BLUE program led to the F-117 and B-2 programs and to many other classified systems.

Radar echo reduction of this magnitude requires a "clean sheet" of paper design. It cannot be retrofitted or added later. Aircraft shape is most critical. This shape must bounce energy away rather than back toward the illuminating radar.

The goal of stealth design is to be less visible to radar threats. This does not mean being invisible as the popular press would have us believe. The basic goal is for the aircraft to blend in with the background, much like a chameleon. To accomplish this, aircraft echoes must be no larger than false targets that radars also see, such as birds and insects. By being less visible, stealth aircraft can only be detected when they get much closer to a radar site. This minimizes the response time of an adversary, thus increasing survivability.

Avoiding detection by a radar system is conceptually simple. Systems or potential targets are designed to minimize reflected radar energy back toward the illuminating radar. To understand how this is done, we need an understanding of how radar systems work; of how radar electromagnetic energy travels and reflects; of how radars view potential targets (threat sectors); and finally, of how we reduce reflection back towards the radar site by reflecting this energy into other directions in space where there is no receiver (ear) to detect us and by using electromagnetic absorbing material treatments.

Radar echo strength is a measurable quantity much as automobile speed is measured in terms of miles per hour. Radars use this echo for detection. Target echo is called **R**adar **C**ross **S**ection, or RCS for short. The smaller or fainter the radar echo, the smaller the target radar cross section or RCS. RCS or target echo strength is a measure of how hard it is for a radar to see a target. Target echo strength is a property of the target and is different for each radar/target view angle. RCS is measured in terms of "capture area." Targets with high capture area have loud echoes. Targets with small capture area have faint echoes. The goal of stealth design is to make the target echo RCS capture area as small as possible at the radar view angles.

Radar target echo is a measure of how much of the transmitted radar beam is reflected back to the radar. If we had a rapid fire billiard cue stick shooting 100 balls per second, targets with large echo RCS would bounce more of the billiard balls directly back to the cue stick than targets with small echo RCS. The billiard balls which bounced in other directions (not back) cannot be used for detection.

Aircraft radar echo reduction is accomplished by recognizing that:

- Radars locate targets in angle and distance. They transmit fan or pencil beams of energy, like a flashlight, to locate angle position. They determine distance from the radar by measuring the time required for the target echo to return from each transmitted pulse. Receiving consistent echoes at the same angle and range indicates that a target is detected.

- Radars have a minimum sensitivity limiting how far away they can locate targets.

- Electromagnetic waves travel in straight lines and reflect like bouncing billiard balls, i.e., the outgoing bounce angle is the same as the incoming angle.

- Radars view potential targets only from limited positions in space. This defines the threat sector of the radar transmitter/receiver relative to the target, i.e., where we must minimize our echo.

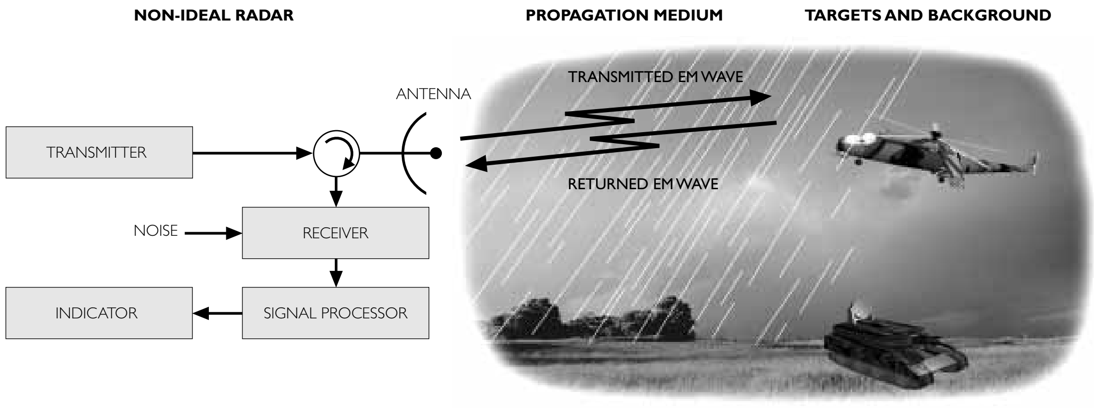


FIGURE 1: BASIC RADAR SYSTEM: TRANSMITTER, ANTENNA, RECEIVER, SIGNAL PROCESSOR

- Aircraft design for stealth seeks to minimize reflections in the threat sector – usually the front. This is accomplished by making the aircraft shape reflect energy away rather than back toward the radar, by designing the engine inlets to absorb electromagnetic energy, by applying electromagnetic absorbing material on selected portions of the vehicle, such as perimeter edges, and by having very smooth surfaces.

Let us now look at each of these topics in more detail.

HOW RADARS WORK

RADAR stands for **RA**dio **D**etection **A**nd **R**anging. It was significantly advanced by England and the United States in WWII, and was of great help to the British during the Blitz. The fundamental information obtained by present day radars is target angular position and distance (range) relative to the radar transmitter/receiver. The component elements of a radar as seen in Figure 1 are: the transmitter which produces a repetitious series of pulses, a transmitting antenna which collimates this energy into a fan or pencil beam much like a flashlight reflector projects light into a narrow beam, a receiving antenna (much like the transmitter antenna – often the same) which only receives energy from defined regions in space like a TV satellite receiver dish, and a receiver/signal processor which must listen for echoes received relative to the time the transmitter pulse was broadcast. Since the speed of propagation of the radar wave is known, i.e., the speed of light, the echo electronic time measurement tells us the distance or range to the target. The radar receiver must then try to recognize the received signals as being different from the inherent background electronic noise and false target echoes. A target detection is made when consistent echoes are identified from the same direction and range in space.

The transmitted radar energy is an electromagnetic wave similar to light in every respect except wavelength (the distance between crest peaks). Radar wavelengths range from about six feet to less than one half an inch. Since these radar wavelengths are smaller than target sizes of interest, such as aircraft or ships, the basic notions of light reflectivity hold for radar. The transmitted wave behaves very much like a billiard ball, i.e., the beam travels in straight lines and bounces off a target with the out angle being the same as the in angle.

A radar can only detect a target when its antenna is pointed at the target, Figure 2. Usually the same antenna is used for transmit and receive. If not, they are located very close to each other. The radar antenna must search out volumes in space. The transmitted beam is usually narrow in one or two directions. A fan beam extends up and down and is narrow in azimuth (left to right) and a pencil beam is narrow in two directions. Therefore, in order to search volumes of space, the antenna must rotate and search by consecutively pointing into different spatial directions, i.e., scan a volume.

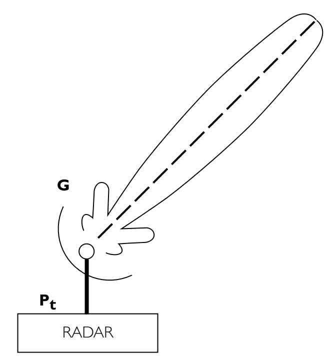


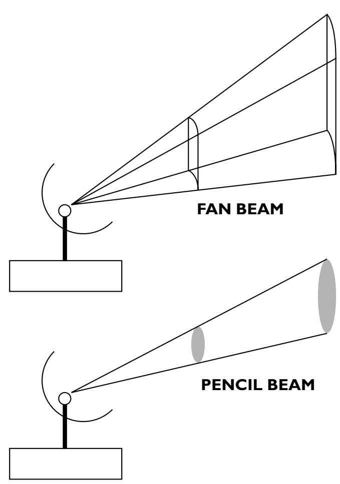
FIGURE 2: RADAR ANTENNAS FOCUS ENERGY INTO BEAMS (LIKE A CHEERLEADER MEGAPHONE) WHICH MUST SCAN A VOLUME OF SPACE TO FIND TARGETS

The antenna gain for transmit and receive can be likened to high power optical binoculars. The higher the magnification (gain), the more narrow the field of view. The antenna is similar to a cheerleader megaphone for transmitting. To receive, the small end is placed at the ear to collect sound coming from the direction of the large end.

Picture radar transmitter/receiving antennas as a pair of eyes which are arranged to always point in the same direction. One eye is the transmitter which sends out pulses of energy (billiard balls) in the direction of view. The other eye, the receiver, points in the same direction and only receives echoes from that direction of view. To detect a target, we must move the eyes across the region of space where we expect to see a target.

Alternately, we could think of the radar transmitter as a flashlight attached to our head and our eyes as the receiver. We can only see a target when the eyes point in the same direction as the flashlight. Close in the flashlight beam is narrow and bright and targets in the beam are easy to see. Far away the flashlight beam is broad and dim and targets are more difficult to see.

When radar energy is broadcast, it starts to spread out in space and lose intensity, Figure 3. This is very much like throwing a stone into still water and watching the waves radiate out and decay from the disturbance. Electromagnetic waves also decay as they radiate from an antenna. When we double the distance from the radar, the transmitted intensity decreases by a factor of four. This concept is referred to as the natural geometric spreading of energy. The total transmitted energy has not changed, but the intensity is smaller since a greater area is illuminated.



- SAME AMOUNT OF ENERGY ACROSS EACH AREA
- INTENSITY, ENERGY PER UNIT AREA GETS SMALLER AS WE MOVE AWAY
- INTENSITY GET SMALLER BY FOUR WHEN DISTANCE IS DOUBLED

FIGURE 3: RADAR ENERGY SPREADS AS BEAM PROPAGATES AWAY FROM TRANSMITTING ANTENNA. INTENSITY GETS SMALLER BY FOUR WHEN DISTANCE IS DOUBLED

When this decaying transmitted wave hits and reflects from a target, a similar process occurs, Figure 4. The energy that "hits" a target is reflected into many directions of space including back toward the transmitter/receiver. As this reflected energy travels away from the target it too decays by a factor of four for every doubling of distance.

The echo signal at the receiver decays by sixteen every time the distance to the target doubles. This results from the factor of four decay from the transmitter, times another factor of four decay back from the target. The echo back at the radar is faint compared to the transmitted pulse. The further away the target, the weaker the returned echo.

The goal of a radar system is to detect targets. The parameters available to a radar designer to do this are:

- Transmitter power (loudness of the initial yell)
- Transmitter antenna gain which collimates energy into narrow beams (megaphone to direct the energy). Similar to satellite dishes, the larger the antenna, the narrower the beam
- Receiver antenna gain, similar to the transmit antenna (megaphone in reverse collects energy for listening)
- Receiver sensitivity (straining the ear to listen for faint echo)

Signal processing to detect the faint echoes as different from noise and natural background targets (separating out the return echo from other natural noise sources such as waterfalls, birds, etc.)

The echo strength of a potential target is a function of how far away the target is and how much energy this potential target reflects back toward the receiver transmitter. The amount of energy reflected back is characterized as the target radar cross section. Stealth design reduces the target radar cross section in order to avoid detection.

It is important to note that the designer of the radar system has absolutely no control over how much energy is reflected back toward the radar receiver.

Targets with small echoes (radar cross section) can only be detected when they get closer to the radar site. With reduced radar cross section (RCS), the question which naturally arises is: If I reduce my echo RCS by x amount, how much closer can I come toward the radar site before being detected? We can answer this question by using the previous example which says that every time the distance doubles, the echo strength changes by sixteen. Table 1 is a chart showing this relationship. Assume the initial target echo RCS is one and is detected at a distance of 100 miles. If the target echo RCS is reduced by a factor 10, 100, 1000, and 10,000, the detection range is reduced to 56, 32, 18, and 10 miles, respectively.

ECHO STRENGTH (RADAR CROSS SECTION)	DETECTION DISTANCE (MILES)
1.0	100.
0.1	56.
0.01	32.
0.001	18.
0.0001	10.

TABLE 1: HOW DETECTION RANGE BECOMES SMALLER WHEN RADAR ECHO GETS SMALLER

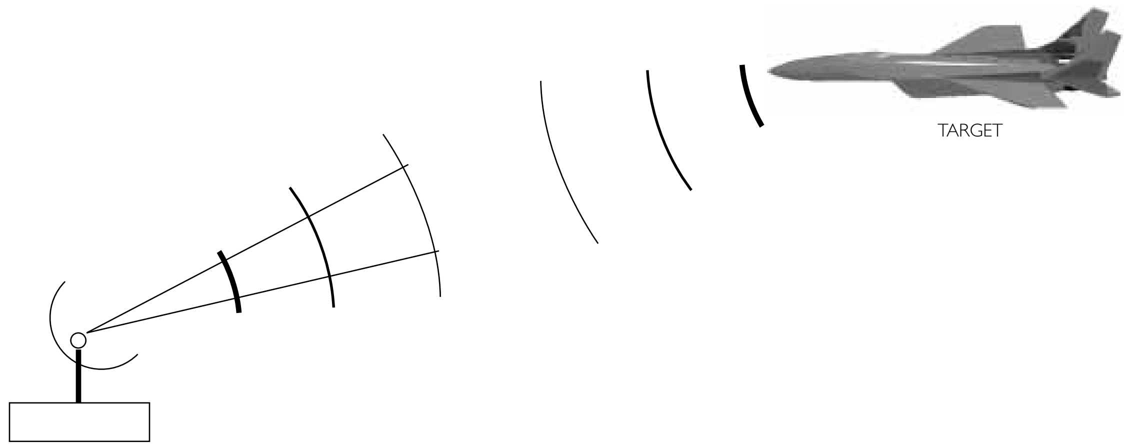


FIGURE 4: ECHO INTENSITY GETS SMALLER BY SIXTEEN WHEN RADAR TO TARGET DISTANCE DOUBLES

The echo must be reduced by a significant amount to appreciably decrease detection range and thus enemy reaction time. As demonstrated by the HAVE BLUE program[1], such drastic RCS reductions are in fact obtainable. ***This was accomplished by choosing an aircraft shape which bounced the incident radar energy away rather than back to the radar site.***

HOW ELECTROMAGNETIC WAVES REFLECT

In order to understand stealth design, we need to understand how the radar transmitted electromagnetic waves travel and reflect from surfaces. This reflection characteristic is most important in our stealth designs.

Electromagnetic waves are the same as light waves, except for wavelength. These waves, once launched from a source, travel in straight lines similar to optical rays from the sun or a billiard ball struck by a cue stick (assuming no spin on the ball).

When this radar electromagnetic wave strikes a target, as in a billiard ball hitting a rail, the outward bounce angle is the same as the incoming angle, Figure 5a.

In Figure 5b, we see that the transmitted rays bounce away from the radar when hitting a tilted flat plate. From a sphere, the upper and lower surfaces bounce the incident ray away, while the center surface bounces the ray directly back to the radar.

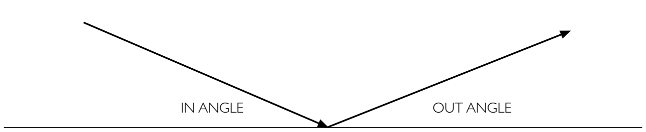


FIGURE 5A: RADAR WAVE BOUNCES LIKE A BILLIARD BALL: (IN ANGLE) = (OUT ANGLE)

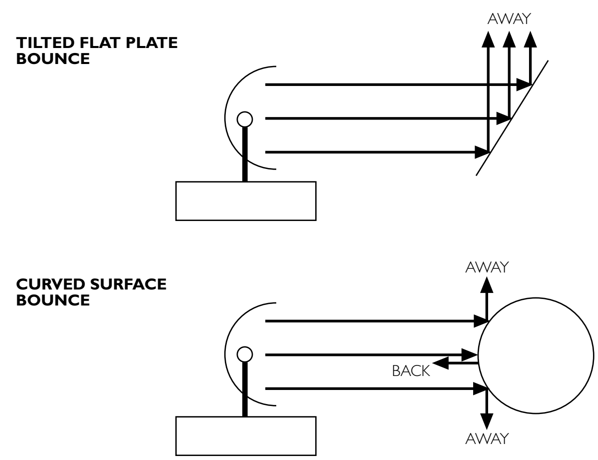


FIGURE 5B: ENERGY REFLECTS LIKE A BILLIARD BALL

In Figure 6, we show the bounce angles for six different incoming radar pulses or billiard balls. In each case the bounce angle is the same as the incidence angle, i.e., out = in. This is called specular reflection and is the simple notion we all learn in high school physics (or at the pool hall).

An examination of Figures 6 and 7 shows that the billiard ball is bounced ***back*** toward the radar ***only*** when the local surface points or faces the radar. The billiard ball bounces ***away*** when the local surface does not face the radar.

We immediately see how to design stealthy shapes: Avoid aircraft surfaces pointing back toward the radar. Always bounce the billiard ball away from the radar.

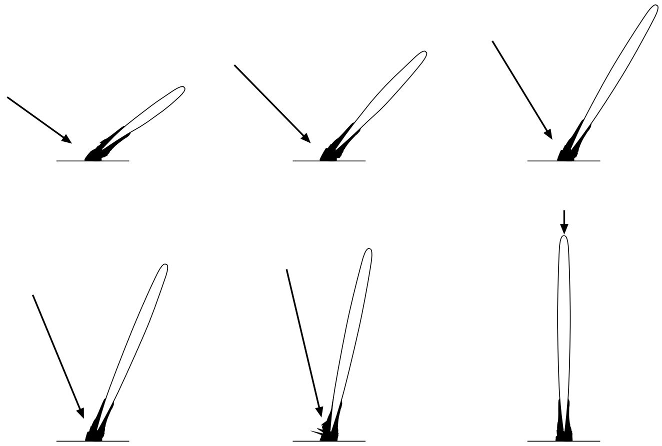


FIGURE 6: ENERGY REFLECTS LIKE A BILLIARD BALL

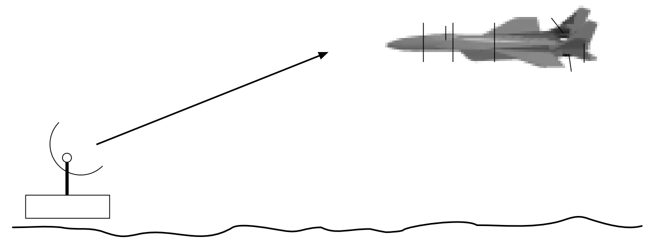


FIGURE 8: THREAT RADARS TYPICALLY VIEW AIRCRAFT TARGETS FROM AIRCRAFT FRONT SECTOR

THREAT SECTORS

Stealth aircraft can never be made to have low radar cross section from all viewing angles since surfaces and edges must point somewhere in space. There will always be regions where the surfaces and edges have significant echo reflection.

Threat radars will not view an aircraft from all possible directions. Radars will not view aircraft from the top or bottom and there is only a low probability of viewing from the side. Typically, the most important view angle is from the front of the aircraft as the aircraft flies toward a potential target defended by a radar site, Figure 8. Rear sector is not as important as the front sector because a tail attack is more difficult.

In military/technical terms, the region surrounding an aircraft where there is a very high probability of being viewed by a threat radar is called a threat sector. ***From these viewing directions (threat sectors) we desire very low echo radar cross section.*** This is summarized in Figure 9 for an aircraft.

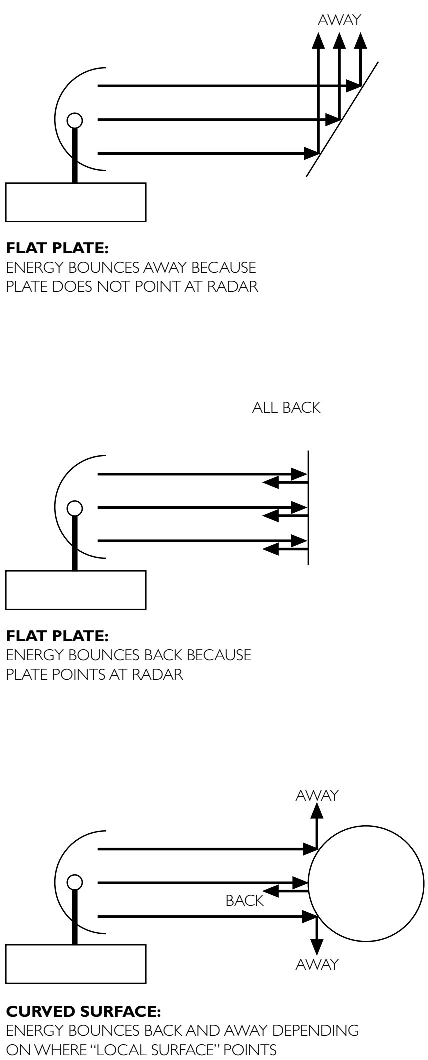


FIGURE 7: ENERGY BOUNCES BACK ONLY WHEN "LOCAL SURFACE" FACES TOWARD RADAR

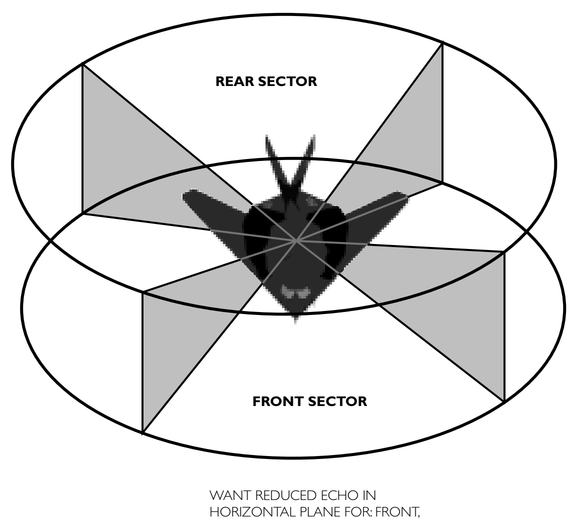


FIGURE 9: AIRCRAFT RADAR THREATS ARE IN THE FRONT SECTOR AND HORIZONTAL PLANE

OVERALL CONSIDERATIONS

Aircraft are designed for specific missions, such as tactical, strategic, observation/reconnaissance, air superiority, or covert. Survivability in performing these missions can be accomplished in a number of ways: by choosing the mission profile for altitude and speed to minimize engagement with enemy radars; by mission planning to avoid threats; by using electronic jamming countermeasures; or by designing a stealthy vehicle. Of these, stealth design is optimal since it allows the greatest latitude for vehicle/mission operation. For the stealth option, a balanced approach is then adapted for reducing the major observables features: radar signature, infrared heat signature, visible signature, and telltale electronic emissions signatures.

GOAL OF STEALTH DESIGNS

The major goal of stealth design is to blend in with the background, i.e., minimize the target contrast with respect to the background, much like a chameleon. This applies to all of the observables: visual, acoustic, infrared (heat), and radar. Visual camouflage has been utilized for many years by choosing paint schemes which cause a target to blend in with its background. For radar cross section of aircraft, we normally think of free space as the background with insects and birds as the contrasting radar cross section targets.

The road map for reducing the radar signature is shown in Figure 10. The vehicle mission defines the types of threats likely to be encountered. Our intelligence community then helps us choose the specific design parameters for stealth: frequency ranges; echo RCS levels (how faint the echo can be and still be survivable); and viewing angles from which the aircraft will be seen. Once the stealth specifications are set, the design begins by choosing the aircraft shape followed by close attention to the ancillary items shown in Figure 10.

The goal of aircraft stealth is simple: Do not allow energy to be reflected back toward the threat sectors where potential radar sites are located.

There are two ways we can accomplish this:

1) Reflect the incident radar into any direction other than back to the radar site

2) Utilize radar absorbing material to turn the radar illumination energy into heat.

Of these, ***shaping to reflect energy away is the most important.***

Absorbing materials, at best, reduce reflected energy by factors of ten to one hundred. Since we need echo reductions of 1,000 to 10,000 to significantly reduce detection range, shape becomes the primary approach. After shaping, absorbing materials are utilized to further reduce residual reflections.

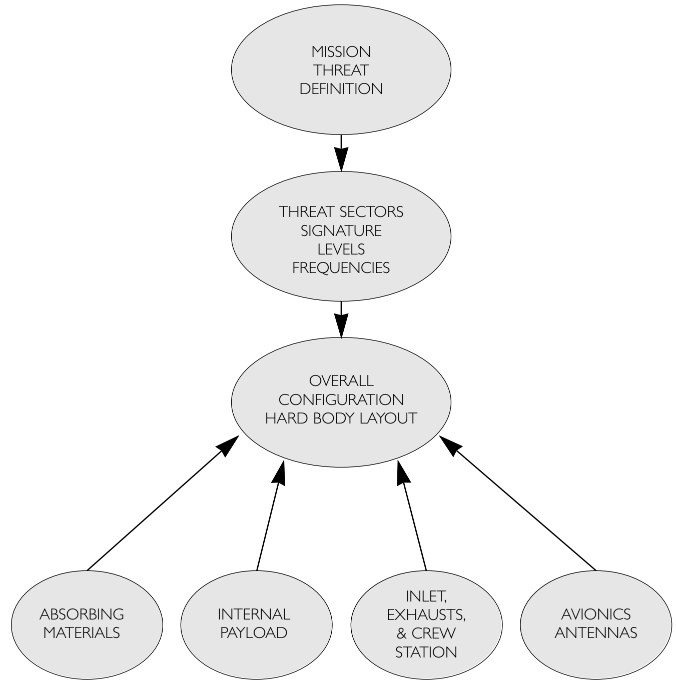


FIGURE 10: SHAPING ROADMAP FOR STEALTH DESIGN

The overall approach for reducing aircraft echo RCS includes:

- Aircraft shaping to bounce energy away from the front sector
- Designing engine inlet cavities to have a minimum echo. Cavity returns are similar to shouting into a closed hollow box. All of the energy going in comes back out (toward the threat sector). By creating multiple bounce geometries coupled with walls lined with absorbing materials, the inlet cavity echo can be made much smaller.
- Minimizing surface roughness, i.e., have very smooth surfaces, to reduce echo RCS for higher frequency radars when surfaces are viewed near grazing angles
- Designing onboard antennas and sensors so they do not contribute to echo RCS in the threat sectors
- Designing of the pilot crew station to prevent energy from penetrating the canopy transparency, bouncing around, and reflecting back into the threat region

The net aircraft RCS signature is the sum of all these reflection mechanisms. Of these, the aircraft shape is the most important, with engine inlets a close second.

HARD BODY SHAPING

Aircraft shape, called the hard body shape, is designed to bounce the incident radar energy ***away*** from the radar site. This is accomplished by not having surfaces point into those regions that need to appear stealthy. For aircraft we want a low echo radar cross section all the way around the vehicle azimuth plane. We particularly want very low echo cross section when viewed from the front. Hence, stealth aircraft tend to look flat with major surfaces pointing up or down rather than horizontal. By having nearly horizontal surfaces, an incoming horizontal billiard ball will not bounce directly back.

Controlling the surface direction is only part of the solution. Surfaces must be joined by edges which form the major lines of the body. These edges reflect billiard balls in the same manner as surfaces. Again think of aiming a billiard ball perpendicular to the pool table rail. The ball bounces directly backward. In stealthy design we pay very close attention to the direction of the major body lines relative to the threat sectors, i.e., we do not want to have these major body lines (edges) point into the front stealthy region.

Lines which define the flat surfaces, however, must point somewhere in the horizontal plane. That is, as we go around the aircraft, we must sometimes become perpendicular to the lines defining the body surfaces. At this point, the billiard ball will bounce directly backward. We call these high reflection regions "spike echoes" because they are of high amplitude and of narrow angular width.

So what do we do about these unavoidable spikes? First, we try to design the hard body shape so that these spikes are located away from the front threat sector. Second, we design the hard body with as few major body lines as possible, minimizing the number of spikes. Third, we make sure that other unavoidable surfaces or edges which have bright spikes line up with the major body spikes.

We design the aircraft hard body to have a minimum of echo spikes. These spikes point away from threat sectors. Regions in between these spikes are designed to have very low cross section.

This poses the question of whether these spikes can be used by a threat radar for detection. Fundamentally, no. These spikes are very bright reflections but are very narrow in angle. This means that as an aircraft flies toward or past a radar site, the viewing aspect angle is always changing. The bright spikes do not point at a radar site for a long enough time to provide a repeated track detection.

The primary threat sector is the front while secondary threat sectors are to the rear and sides. These sectors are in the horizontal plane. The optimum shapes for the hard body tend to have flat upward and downward pointing surfaces. Examples of these shapes are the saucer, the triangle, and the diamond. The saucer shape has edge returns (normals) which point all the way around the disk making it unsuitable for an aircraft. The triangle has three edges and the diamond four edges, which have a bright spike-like reflection when viewed perpendicular to the edge, Figure 11. These shapes are more suitable for starting a design.

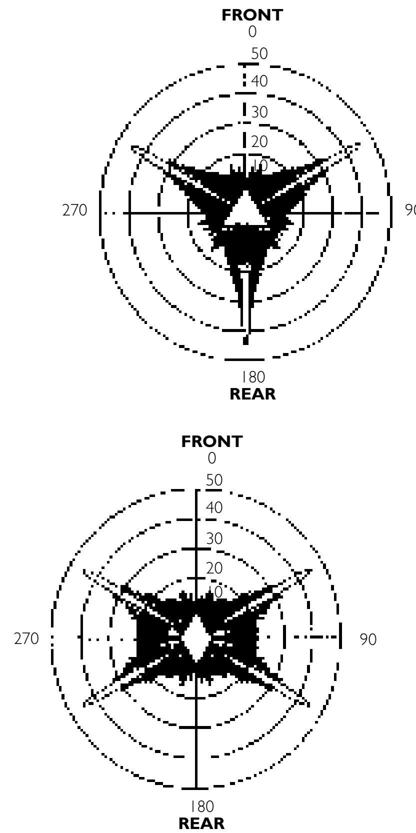


FIGURE 11: ECHO RCS PATTERN FOR TRIANGLE AND DIAMOND SHAPES

When viewed from above, any shape will have edge normals pointing somewhere. We deal with this fact by making sure these edge normals point away from the primary front threat region and by having as few major planform edges as possible, thereby minimizing the total number of bright spike reflections.

The primary characteristic of stealth aircraft is that their surfaces point in the up and down directions and that they have a minimum number of spike reflections in their planform shape. This requirement leads to bodies which tend to be flat or squat with few major body lines. These aircraft tend to be very clean, simple shapes. Missing are vertical tails, vertical edges of any sort and external pylon weapons carriage.

The goals for hard body configurations can be summarized as follows:

- Minimize the number of spikes resulting from major body lines.
  - Sweep spikes away from front threat sector.
  - View surfaces joining the major body lines from a shallow or grazing angle.
- Integrate engine and exhaust smoothly into the airframe.
  - Edges of inlet and exhaust should be parallel major body lines.

- Blend pilot crew station canopy into airframe with a conductive coating.
- Utilize internal weapon bays to avoid external pylons which act as corner reflectors.
- Eliminate vertical surfaces and edges.

ENGINE INLET DESIGN

After the hard body shape has been designed, we must quiet the echo from the engine inlets. Inlets are a major problem because all of the electromagnetic energy which goes into the cavity opening comes back out after reflecting from the walls and engine front face.

The F-117 aircraft reduced the engine inlet return by covering the inlet opening with a screen grid which reflected the incident electromagnetic energy away from the threat sector while still letting air in for engine operation. This design prevented energy from ever going into the inlet. This grid design, while suitable for first generation stealth design, is only for subsonic operation and does cause some penalties on engine performance. Succeeding generation stealth engine inlet designs must fully address suppression of the inlet echo.

Inlet echo suppression is accomplished by using electromagnetic absorbing materials coupled with shaping of the duct and engine front face. The duct is shaped to force the incident energy (billiard balls) to bounce from wall to wall rather than straight in and straight out. The walls are then coated with absorbing materials so that the bouncing energy is absorbed.

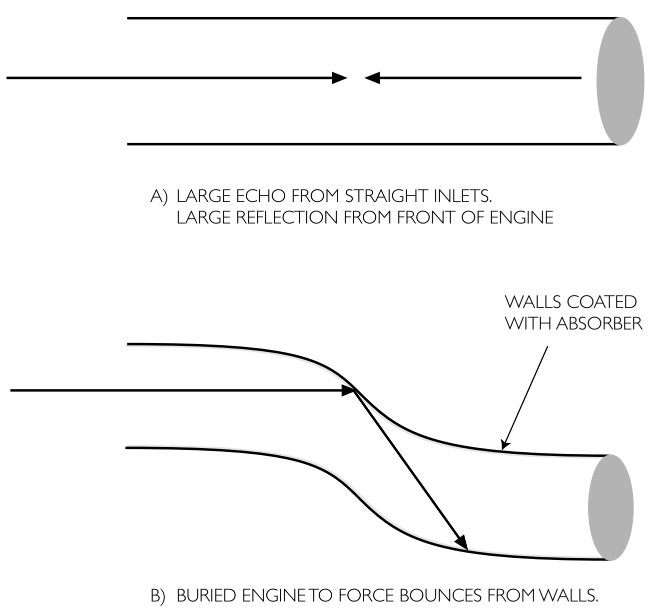


FIGURE 12: STEALTHY INLETS USE WALL ABSORBERS AND MULTIPLE BOUNCES TO REDUCE ECHO

A straight inlet with wall absorber, Figure 12a, will not work because incident energy is not forced to bounce from wall to wall. The inlet must be twisted and turned to force multiple bounces, Figure 12b. This technique is called buried engines.

Another design approach, often coupled with the buried engine, is to place the inlets topside. Then, when the aircraft is naturally flying with nose up, the inlet openings are shielded from radar illumination from below. This has been done on the F-117 and B-2.

The rim edge of the engine inlet opening also has a significant radar echo and it also must be suppressed. This is accomplished by utilizing edge absorbing material and by shaping so that the rim bounce reflection goes into the same direction as the major body line spike reflection.

ABSORBING MATERIALS

Absorbing materials are utilized on stealth aircraft designs as an adjunct to hard body shaping. Absorbing materials alone cannot suppress echo returns low enough to significantly reduce aircraft detection range. If absorbing materials are added ***after*** initial shaping, however, additional echo suppression is obtained.

Electromagnetic (EM) absorbing materials for aircraft are similar to shock absorbers in automobiles. They produce the same effect as a billiard ball hitting a soft pillow. Electromagnetic absorbers dissipate incident EM energy into heat.

Aircraft EM absorbers take several forms: sheet coating materials, perimeter edges and specular materials for coating engine inlet walls. The design of these materials is non-trivial and is the subject of much research and development. Computer modeling is heavily utilized and, in fact, pushes the state of the art in computational electromagnetics.

SURFACE ROUGHNESS

From our previous discussion of the physics of radar detection range as a function of aircraft echo strength, we saw that in order to reduce detection range by a factor of ten we have to reduce our radar echo by a factor of 10,000. This is a very significant reduction. In order to further reduce the residual reflections after shaping and absorbing material application, we must pay attention to the scattering caused by surface imperfections such as gaps, cracks, drain holes, bolt heads, rivets, construction joints, etc.

Aircraft surfaces, as viewed by a threat radar, need to be angled way back so that incident radar bounces as far away from the view direction as possible. Radars need to view aircraft surfaces at grazing angles. Grazing angle viewing, however, exacerbates scattering from surface imperfections. Surface roughness becomes significant at higher radar frequencies and near grazing angles.

Surface imperfection scattering can be reduced by coating the vehicle with magnetic absorbers. These absorbers are very effective, but they are notoriously heavy. This added weight is unacceptable for large aircraft, such as a long-range bomber, because of fuel consumption requirements. In these cases, heavy surface coating cannot be utilized, so the aircraft design must be smooth with no surface scattering imperfections.

OTHER ATTRIBUTES

Designers of stealth aircraft must also reduce echoes from a multitude of other scattering sources. These include:

- Onboard antennas for radar systems, communications, identification friend or foe, etc.
- Windows for sensor systems, such as infrared targeting
- Cockpit crew stations. These scatter somewhat like cavities. This echo is reduced by applying optically transparent metal coatings to the windshield canopy. This bounces the incident EM energy away from the threat sector and prevents this energy from going into the crew station cavity.
- Air data sensors such as angle of attack and pitot tubes. Flush sensors are required.
- Access door cracks such as landing gear and weapons bay doors. These echoes are reduced by designing special electrical seals and/or by geometrically lining up the gap echo spike with the main aircraft spike echoes.

From this list of requirements for stealth aircraft, we see that significant changes in design are required for greatly reducing the radar echo from the threat sectors.

Highly survivable aircraft of the future will look considerably different than their non-stealthy, non-survivable cousins of the past.

RADAR ECHO CHANGES WITH WAVELENGTH

Billiard ball shaping to reduce radar echo works over all of the radar wavelengths of interest, from 6 feet to 1/2 inch. This approach produces a radar echo which is smaller at the short wavelengths and higher at the longer wavelengths, Figure 13.

While the billiard ball bounce echo is the dominant scattering mechanism for all wavelengths, separate additional echo mechanisms occur at the very long and very short wavelengths.

When the wavelength is long, approximately one to six feet, edge wave echo mechanisms occur. This echo is reduced by application of absorbing materials on the edges and tips of the aircraft.

When the wavelength is less than one inch, surface imperfections begin to cause significant echo. This echo is reduced by paying close attention to detail construction of the aircraft by making sure the surfaces are very smooth and by careful control of gaps, cracks, and fastener heads.

STEALTH DESIGN EXAMPLES

We cannot visualize or evaluate all of the changes required to make a stealthy aircraft. Only specialized radar echo measurement facilities can do this. We can, however, see the changes in hard body shape required by stealth design.

Let us first compare a traditional aircraft echo signature with the echo of a stealthy, faceted arrow target, Figure 14. Traditional aircraft echo is very loud because curved surfaces point in these directions. The stealth target, in contrast, has a much reduced echo because the surfaces do not point or face the radar. The few spike echoes which occur when we are perpendicular to an edge, are pointing away from the frontal threat region. In the front, the echo is very small. Each ring on the radial scale represents a factor of ten change in echo amplitude.

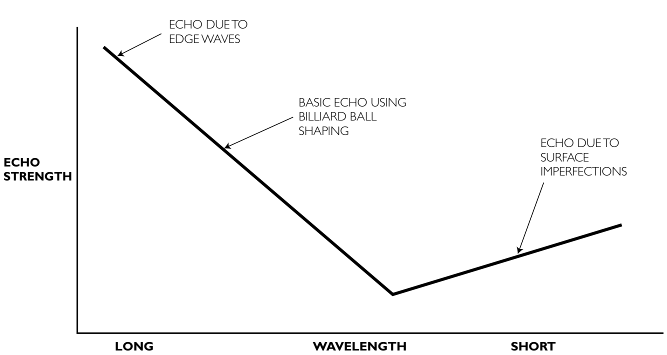


FIGURE 13: RADAR ECHO STRENGTH CHANGES WITH WAVELENGTH

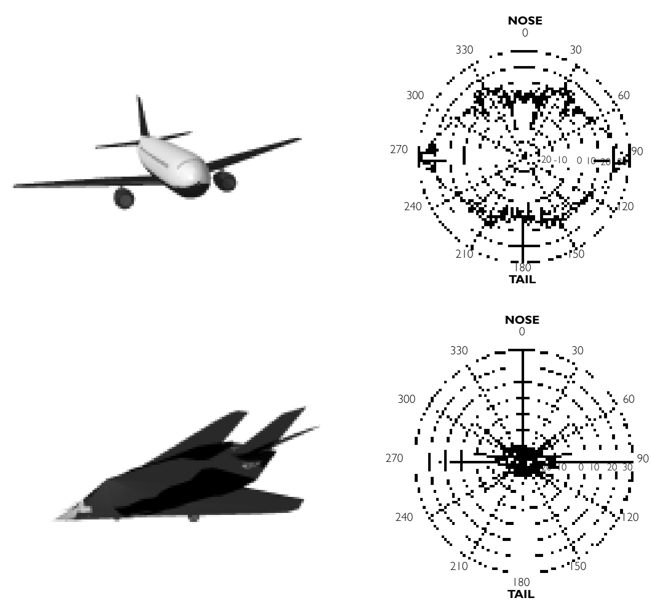


FIGURE 14: ECHO PATTERN FOR TRADITIONAL AND FACETED SHAPES

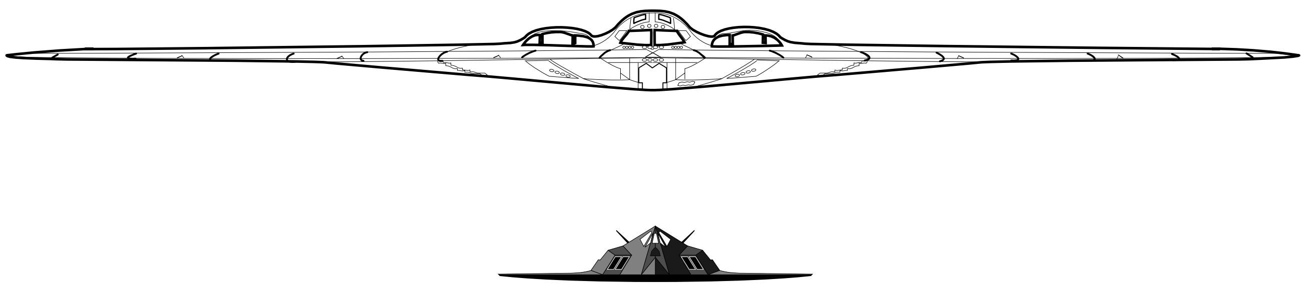


FIGURE 15: RADAR FRONT VIEW OF STEALTH. SURFACES DO NOT POINT AT RADAR, THUS NO BACKWARD BOUNCE (AIRCRAFT TO SCALE)

Now let us look at the shape of some stealth aircraft. We can't show the echo RCS patterns directly, but we can see how the principles of hard body shaping have been applied. Before examining these shapes, remember that the primary threat sector is from the front and in the plane of the wings. When looking at these shapes, visualize yourself as a radar system, with one eye as the transmitter and the other eye as a receiver. Remember that radar energy bounces like a billiard ball, and that you don't want that billiard ball to bounce straight back to you. That is, you want that billiard ball to bounce away from your receiver eye. Then think of how these aircraft would look to your radar eyes from the front and horizontal azimuth plane.

Shown in Figure 15 are frontal aspect illustrations of the F-117 and B-2. There are no surfaces or edges pointed back to the front sector to cause a backward bounce. A billiard ball from your transmitter eye does not bounce back to your receiver eye.

Shown in Figure 16 are top views (planform) of the F-117, B-2, and the F-22. There are no surfaces or edges pointed toward the front. In each case, a radar would not be perpendicular to an edge until moved away from the front sector. Each aircraft shape (in planform) has a limited number of edges which define from four to six echo spikes.

Figure 17 presents illustrations of how a radar might view these vehicles in the horizontal azimuth plane. Note that with exception of the four or six spikes, there are no other surfaces or edges to cause a billiard ball to bounce directly backward. Except for the spikes, the billiard ball bounces away from where it came.

Also note that when these targets are viewed from the top or bottom, a billiard ball has many chances for a backward bounce. However, the top and bottom are not threat sectors. Threat radars would not view from these regions.

Another way to gauge the degree of stealth is the simple optical view. Using the B-2 as an example, this vehicle has a very small profile when viewed in the azimuth plane, Figure 15, but has a very large profile when viewed from above or below, Figure 16.

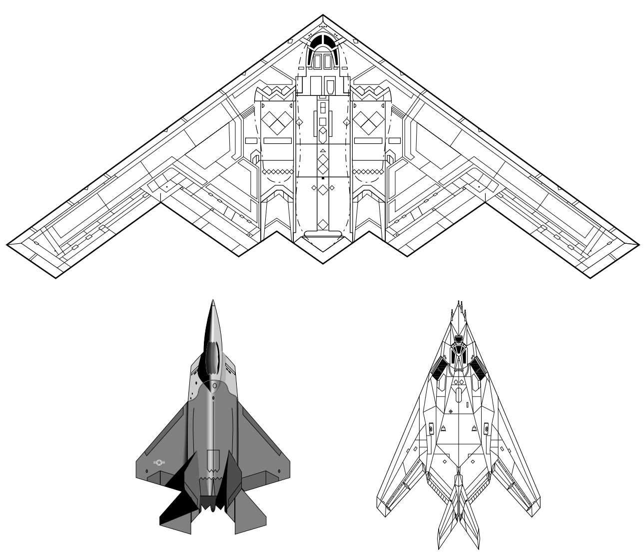


FIGURE 16: TOP VIEW OF STEALTH AIRCRAFT (TO SCALE) SHOWING WHERE ECHO SPIKES OCCUR PERPENDICULAR TO MAJOR BODY EDGES

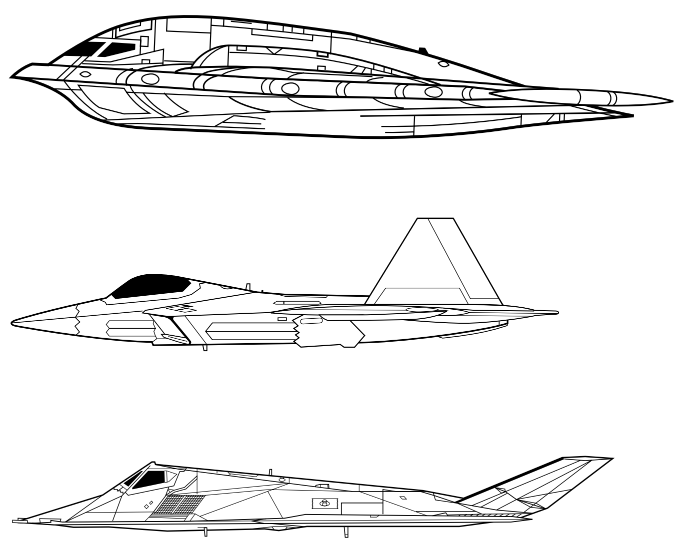


FIGURE 17: HORIZONTAL VIEW OF STEALTH AIRCRAFT (TO SCALE)

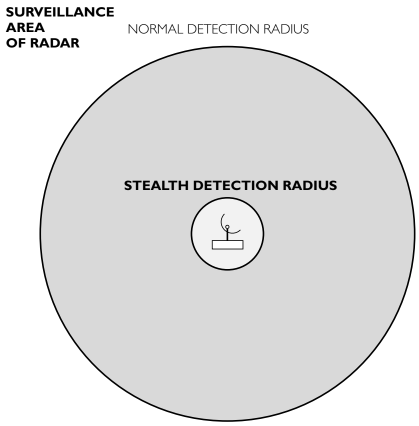


FIGURE 18: STEALTH AIRCRAFT, WITH 90% REDUCED DETECTION DISTANCE, HAS 100 TIMES MORE AREA FOR MISSION OPERATION

BENEFITS OF STEALTH

The benefits of stealth include more than reduced detection range, reduced threat response time, and increased survivability. Stealth aircraft can operate over a greater area surrounding a threat radar. The area coverage of a radar is proportional to the square of the detection radius, $A = \pi r^2$. Consider Figure 18 which shows the area coverage of a threat radar against a non-stealth target compared to a stealth target. The stealth target, with a factor of ten reduction in detection range, has one hundred times more operational area surrounding the radar in which it can perform missions. Aircraft with extremely small RCS can operate covertly, i.e., completely without detection. This is beneficial for special operations missions such as hostage rescue situations.

There are benefits in developing aircraft with only moderate stealth. For example, an aircraft with a factor of ten reduction in echo has its detection range reduced by forty-four percent. This reduction significantly aids the traditional electronic jamming or electronic countermeasures (ECM) approach to survivability. With reduced signatures, the jamming power requirements go down directly with echo RCS. Thus, in this example, a factor of ten less in jammer power would be required. Alternately, the jamming aircraft could stand off at a greater range and still electronically mask or hide the moderately stealthy aircraft. In addition to ECM, the chaff false target defense gambit is made much easier because the chaff RCS has to hide or mask a smaller RCS target.

Mission cost reduction is another benefit. While the unit cost of a stealthy aircraft is greater, the mission and mission life cycle costs are reduced because fewer aircraft, support aircraft and aircrews are required for a mission. Prior to the development of stealthy aircraft, a wartime bombing mission might require bombers, escort fighters, electronic ECM jammer aircraft, and tanker refueling aircraft. Using stealth aircraft, the same mission could be accomplished without the escort fighters and ECM jammer aircraft. This translates into reduced resources required for a mission, particularly when considering aircrew training and aircraft maintenance, as well as the mission planning requirements. Replacement costs are less because of reduced attrition.

COST OF STEALTH

Stealth, coupled with precision guided weapons, is significantly less expensive when we look ***at the total "mission package" cost***. Let us select as a target mission the destruction of a central communications hub or fuel depot in the center of a heavily defended enemy city. Prior to stealth and precision guided weapons (smart bombs), such a mission would require the following resources[4], called the standard package:

BOMB DROPPER AIRCRAFT: Thirty-two aircraft to carry and deliver the non-precision (dumb) weapons. Many more bombs are needed since there is a lower probability of a dumb weapon hitting a target than a precision weapon. Also, we must factor in possible attrition of these aircraft to enemy radar controlled surface to air missiles.

AIR ESCORT AIRCRAFT: Sixteen air escort aircraft to protect the bomb dropper aircraft from enemy forces.

ENEMY AIR DEFENSE SUPPRESSION AIRCRAFT: Twelve aircraft are needed to suppress enemy air defenses. These include electronic jamming aircraft to confuse the enemy radars and aircraft which can destroy active radar sites using anti-radiation missiles.

TANKER AIRCRAFT: All of the above aircraft do not have the required operational range to fly to the target and back. They must be in-flight refueled. Fifteen such tankers are required.

The ***standard package*** cost is therefore composed of 75 aircraft and 132 aircrew. Of course, these vehicles must be

- purchased
- additional systems purchased due to expected attrition
- maintained and serviced
- aircrews and maintenance personnel trained

This is a significant total cost, particularly in today's declining defense dollar environment.

PRECISION WEAPONS

Smart bombs have a much higher probability of hitting a target, hence fewer weapons are needed and fewer bomb dropper and support aircraft are needed. The estimates to accomplish the same mission are shown in Figure 19. Total cost is now 55 aircraft and 116 aircrew.

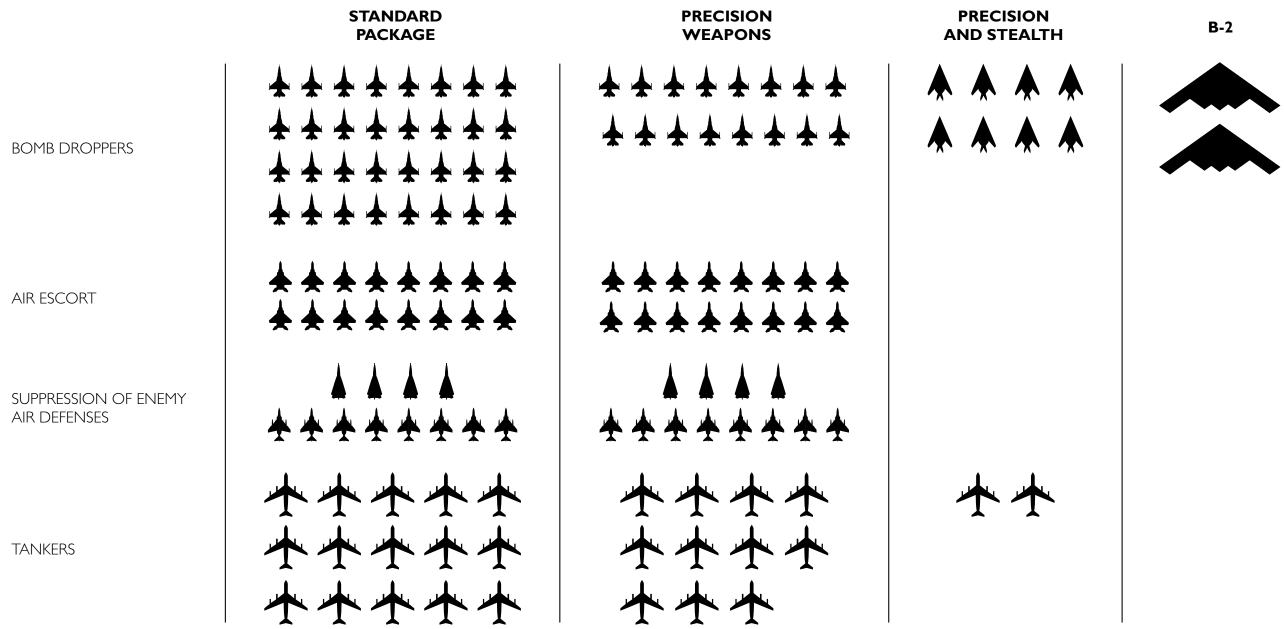


FIGURE 19: THE VALUE OF STEALTH AND PRECISON WEAPONS

STEALTH AND PRECISION WEAPONS

The addition of stealth significantly reduces the number of bomb droppers and completely eliminates the need for air escort and enemy air defense suppression aircraft. The mission cost estimates, Figure 19, are now ten aircraft and 16 aircrew.

STEALTH BOMBER AND PRECISION WEAPONS

A stealth bomber can carry a much higher payload of precision weapons and has a much longer range. The mission cost estimates are now two aircraft and four aircrew.

As a total mission cost, the value of stealth combined with precision weapons is very clear. Unit aircraft cost is higher but total mission cost is significantly reduced.

WHY STEALTH IS DIFFICULT TO DEFEAT

Investment in stealth is clearly not warranted if it can be easily defeated. This section examines approaches for defeating stealth and explains why these approaches are not viable.

EXISTING THREAT SYSTEMS

Weapon system development when viewed over a long time frame has always been a development counter-development reaction. Stealth was a reaction to the success of radar guided surface-to-air missiles (SAMs) and their ability to inflict heavy losses. SAMs negated air power superiority. Success of the F-117 in the Gulf War is a good example of the stealth reaction to SAM threats.

In order to ensure national security, our defense planners must try to determine what the threat will be ten to thirty years from now. With the conclusion of the Cold War, one of the more likely scenarios is that future threats will involve second to third tier powers who must buy weapon systems on the open market rather than invest heavily in their own research and development. We may even have to face our own radar systems if they fall into foreign hands.

The first question to be considered is: Can present day radar systems be modified to detect stealth aircraft at the same range and performance as conventional targets? The answer to this is no. Present radars are already optimized to detect targets. This was accomplished by choosing transmitter power, antenna gain for transmit and receive, receiver sensitivity, and signal processing. Let us see what modifications a factor of one thousand reduction in RCS (a value demonstrated by the HAVE BLUE program[1]) would impact on radar system design. In order to detect a target at the same distance as a non-stealth target, a radar system design would have to do one of the following: 1) increase transmitter power by 1000, 2) increase transmitter antenna gain by 1000, 3) increase receiver antenna gain by 1000, 4) increase receiver sensitivity by 1000, or 5) increase the signal processing capability by 1000. Stealth significantly reduces the capability of existing radars. Some radar improvements might be made, but stealth capabilities are such that it is not likely to bring back performance comparable to conventional targets.

ALTERNATIVE RADAR CONCEPTS

TYPES OF RADAR SYSTEMS

There are two types of radar systems – monostatic or backscatter and bistatic. Backscatter radars, as the word implies, detect energy bounced directly back to the transmitter. This is the traditional radar system with the receiver and transmitter at the same location. Bistatic radars have the receiver and transmitter at different locations.

MONOSTATIC RADAR

Military radar systems are backscatter systems against which stealth aircraft have been designed. Echo RCS reduction is accomplished by shaping the aircraft so as to bounce incident energy away from the illuminating radar. Inherent in this design is the requirement that the radar transmitter and receiver be collocated. They each "view" the target from the same location. The echo in this back direction we call the backscatter or monostatic radar cross section. While the backward echo bounce has been significantly reduced, the forward bounce has been increased.

BISTATIC RADAR

Detection of present day stealth aircraft requires separating the radar transmitter and receiver so that the target aircraft is between the two. The incident radar energy bounces forward toward the receiver, Figure 20. Since the receiver is no longer located at the transmitter, we call this a bistatic radar system where the prefix "bi" indicates two locations – one for the transmitter and one for the receiver.

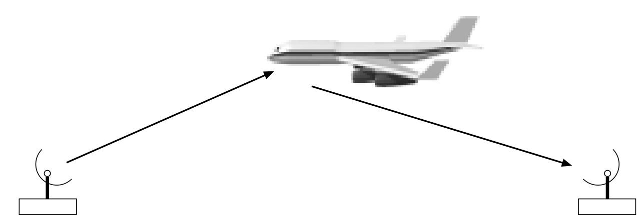


FIGURE 20: BISTATIC RADARS PUT RECEIVER WHERE THE ENERGY BOUNCES

The question now arises: Is bistatic radar a way to defeat backscatter stealth?

Bistatic radars seem like an obvious counter stealth approach for detecting backscatter stealth targets. A number of very difficult technical issues arise, however, when the receiver is not collocated with the transmitter.

- In a military scenario where point targets are usually defended with radar, where should the transmitter and receiver antennas now be located?
- Two antenna beams, one transmit and one receive, must intercept each other.
- The receiver antenna beam must "chase" the transmitter pulse ***at the speed of light***.
- A transmitter reference signal is required for coherent processing.
- Distance measurement is much more difficult because echo time is the sum of the distance from transmitter to aircraft to receiver.
- And for extreme forward scattering, how is the echo distinguished from the direct transmitted pulse?

ANTENNA LOCATIONS: In a military scenario, radar sites are often located near high value targets which are to be defended. For a bistatic radar, the receiver antenna should be located where it can listen for the aircraft forward target echo, Figure 20. This means that the transmitter and receiver should be located on opposite sides of the desired target detection zone (located near the defended asset). This may not always be possible, e.g., when the required real estate is not under the radar owner's military control. Neither is this possible for a naval sea application where separate ships would be required for transmit and receive.

INTERCEPTING ANTENNA BEAMS: The receiver antenna beam must intercept the transmit beam in order to detect a target, much like Darth Vader dueling light swords. Pointing two high gain antennas is like trying to find something at night with two flashlights, Figure 21. Targets can only be seen where the transmitting and receiving beams intersect.

BEAM CHASING: Not only must the receive antenna beam intercept the transmit beam, it must follow the transmit pulse moving at the speed of light, Figure 21. This means the receiver/transmit beam intercept point must move at the speed of light, which is no easy task. Even if this problem was easy, the issue of scanning a volume of space must be addressed.

DISTANCE MEASUREMENT: Distance, obtained by measuring echo time, is not a simple process. Both the transmitter and receiver must synchronize timing for comparing transmit pulse time to echo receive pulse time. This echo time is then the sum of the distance from transmitter antenna to the target and the target to the receive antenna. These two distances are not the same as in the backscatter case. Distance measurement is more complicated for bistatic radars.

TRANSMITTER REFERENCE SIGNAL: The receiver must have a transmitter reference signal in order to perform coherent processing, i.e., separating real target echoes from false clutter echoes. When the receiver and transmitter are separated by many miles, this reference signal is more difficult to obtain.

ECHO VERSUS DIRECT ILLUMINATION: If the receiver antenna is located on a straight line formed by the transmitter and target, then the direct signal from the transmitter is stronger than the echo

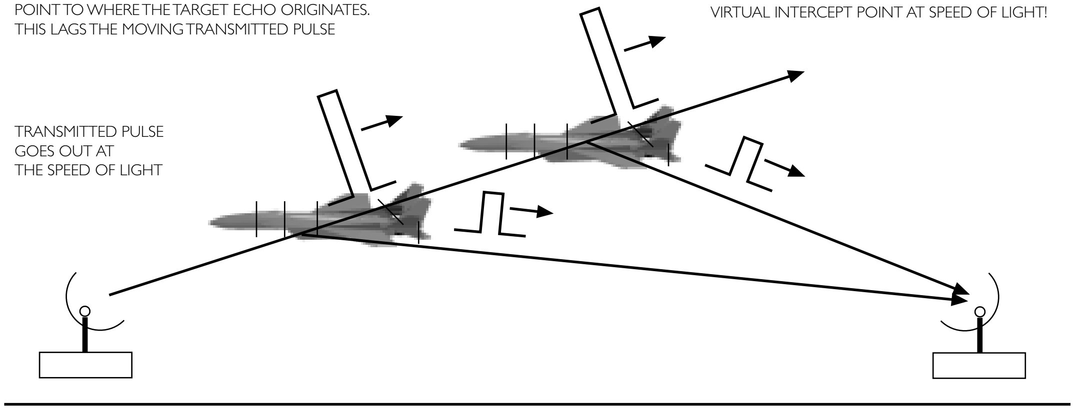


FIGURE 21: BISTATIC RADAR RECEIVER ANTENNA BEAM (DARTH VADER LIGHT SWORD) MUST CHASE TRANSMITTED PULSE TO RECEIVE ECHO

bounce signal. In this case the target echo becomes masked by the direct transmitted pulse. This is similar to looking into the sun for light scattered from Venus. The scattered light is overwhelmed by direct sunlight, Figure 22.

Bistatic radars, while simple in concept for the detection of stealthy vehicles, have many fundamental technical and operational issues to overcome. It is unlikely that a stealth defeating practical bistatic radar system will be developed.

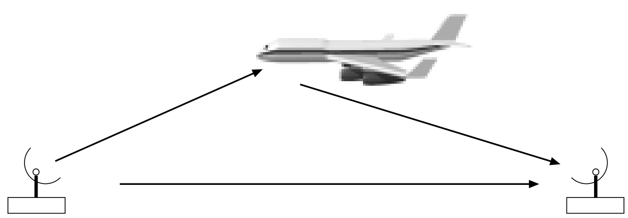


FIGURE 22: FORWARD ECHO SMALL COMPARED TO TRANSMITTED SIGNAL

ULTRA WIDE BAND RADAR

There has been recent interest in the use of ultra wide band width (UWB) radar to detect stealth. This type of radar sends out a very short pulse which is composed of a number of wavelengths, from one inch to over several feet. Normal radars operate at single wavelengths much like monochromatic single color light, e.g., blue. The UWB proponents argue that transmitting a spectrum of wavelengths, much like white light composed of many wavelengths, makes stealth vehicles more visible. This notion is based on the fact that the echo strength of stealth aircraft increases at longer wavelengths.

Let us examine this problem in terms of available power and compare a single wavelength radar, e.g., red light, transmitting 100 watts of energy to a UWB radar transmitting the same 100 watts, but now over five wavelengths, i.e., 20 watts each in red, green, yellow, violet, and blue wavelengths. If a stealth aircraft were more visible to red wavelengths, then why not transmit all of the available energy in the red region of the spectrum? This is the most basic problem of UWB radar. It is much more efficient to use a single wavelength than multiple wavelengths.

There are many other problems with UWB radars:

- Shaping as the first approach to stealth works regardless of wavelength. The stealth billiard ball bounce principle works for all of the wavelengths used in UWB radar.
- The UWB antenna system must work over a factor of ten or more in wavelength. It is not conceivable how such an antenna could be effective over such a wide range. The angular pointing beam width alone would vary significantly over the range. It is extremely difficult to make high gain, narrow beam width antennas over the wavelength range being used for UWB radars.
- A UWB radar receiver would have numerous false clutter targets with which to contend since it is operating over a wider range of wavelengths.

UWB radars offer no unique physics to defeat stealth aircraft.

OTHER OBSERVABLES

The goal of stealth design is to have a balanced design. While radar signature is the most important, because of its long range, designers of stealth aircraft make significant efforts to reduce infrared heat signature, acoustic signature, electromagnetic emissions signature and visual signature.

Infrared (IR) signatures typically are used for short-range tracking. Engine exhaust heat is the primary source of IR signature.

Stealth designers go to great lengths to cool and minimize the engine exhaust. Visual signatures are reduced by use of low contrast paints. Special additives can be injected into the engine exhaust to prevent ice crystal formation which create the contrail.

In a balanced design, all of these signatures are reduced so that they cannot be used against us.

SUMMARY

Stealth is as revolutionary to air superiority as was the introduction of jet engines. Radar stealth has restored air power superiority and has rendered our enemies' huge investment in radar missile defenses ineffective.

Stealth design minimizes aircraft observable signatures which are used for detection. These are our visual, heat, acoustic, radio emissions and radar echo signatures. Radar is the longest range observable. Reducing the radar echo does the most to reduce an enemy's reaction time to shoot us down.

Radar echoes must be reduced by sixteen to reduce detection range by two. Detection range reduction by a factor of ten requires a radar echo reduction of 10,000. Such reductions have been accomplished.

Threat radars view targets from the front sector of an aircraft where we strive to reduce our echo. This is accomplished by shaping the aircraft to avoid surfaces pointing toward the front and by having a small profile from the front. The incoming radar wave then bounces harmlessly away from the radar receiver. Treating the engine inlets, the canopy, the antennas, making smooth surfaces and using special electromagnetic absorbing materials accomplish additional echo suppression. Aircraft shape is also designed to have a minimum number of echo spikes which point away from the front threat sector.

Benefits of stealth include the ability to perform a mission without being stopped by the enemy. Fewer resources are required to accomplish a mission since attrition and support aircraft for protection and radar jamming are no longer required. Stealth means that our pilots are much more likely to come home. The cost of stealth coupled with precision munitions, evaluated on a dollars per mission basis, is much less than conventional air power because significantly fewer aircraft are required. Stealth also allows new missions to be considered, such as special operation rescues.

Radar stealth is highly unlikely to be defeated. Backscatter radars have been refined for fifty years and cannot be modified to make up for the factor of 1,000 to 10,000 reduction in received echo[1]. Bistatic radars, while simple in concept, have horrendous technological and operational hurdles to overcome before a useful system can be deployed.

REFERENCES

1. Ben R. Rich and Leo Janos, ***Skunk Works***, Little, Brown and Company, 1994.
2. Eugene F. Knott, John F. Shaeffer, and Michael T. Tuley, ***RADAR Cross Section***, Second Edition, Artech House, 1993.
3. ***Radar Cross Section Reduction*** Short Course Notes, Continuing Education, Georgia Institute of Technology, March 26-29, 1996.
4. Headquarters, United Stated Air Force, ***"The Value of Stealth,"*** 1991.

John Shaeffer
MARIETTA SCIENTIFIC, INC.
376 Powder Springs St., Suite 240A
Marietta, Georgia 30064
(770) 425-9760