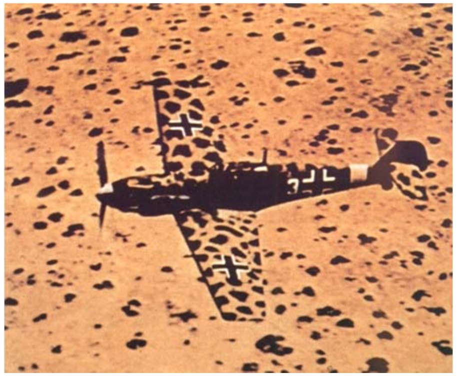
Stealth Aircraft Design
(“Low Observability”)



Stealth Aircraft Design ("Low Observability")

There are four key ways to make a military airplane hard to detect by the enemy:

- Visual Camouflage & Low Visibility
- Low Noise
- Low Infra-Red Emissions
- Small Radar Cross-Section

"Stealth" technology includes all four, but the word typically refers to radar cross-section (and maybe infra-red). Reducing the RCS breaks down into…

- Passive wave cancellation
- Active wave cancellation
- Radar Absorbent Materials
- Radar reflection away from source due to surface geometry

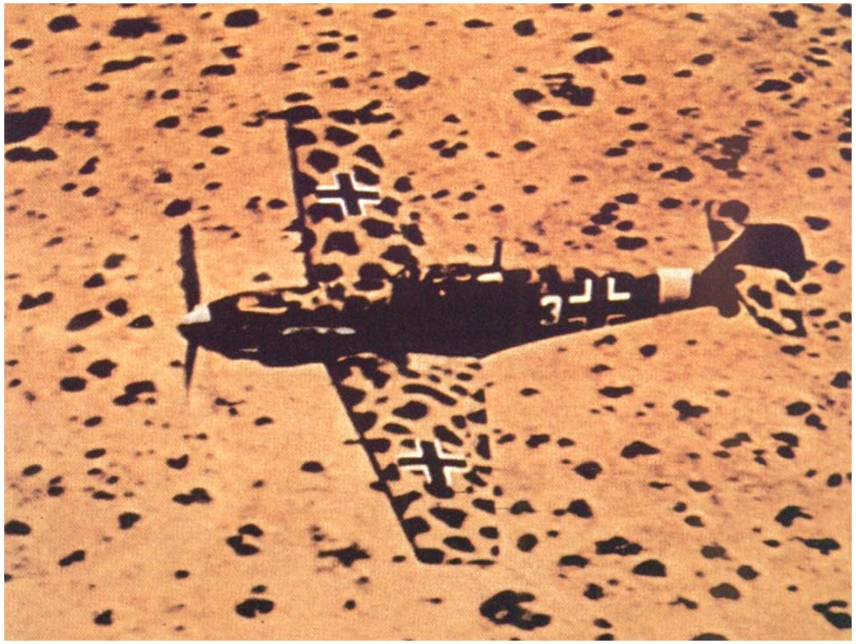
That last one is by far the most important, and is the key to why stealth airplanes look the way they do.

Stealth: Camouflage

Fokker D.VII

Wildcat

F/A-18F



Bf-109

Stealth: Camouflage

- The original way to make airplanes harder to spot by the enemy: Camouflage!
- If you know the terrain over which you will be flying, camouflage can be surprisingly effective.
- Many modern military airplanes are still camouflaged.

Stealth: Low Visibility

Wildcat with white underside and darker top

Land Rover
“Pink Panther”

Spitfire

F-15, horizontal upper areas have darker “blobs”

Blackbird

B-2

Higher Flyer = Darker Grey

KC-10

A-10

Lower Flyer = Lighter Grey

Stealth: Low Visibility

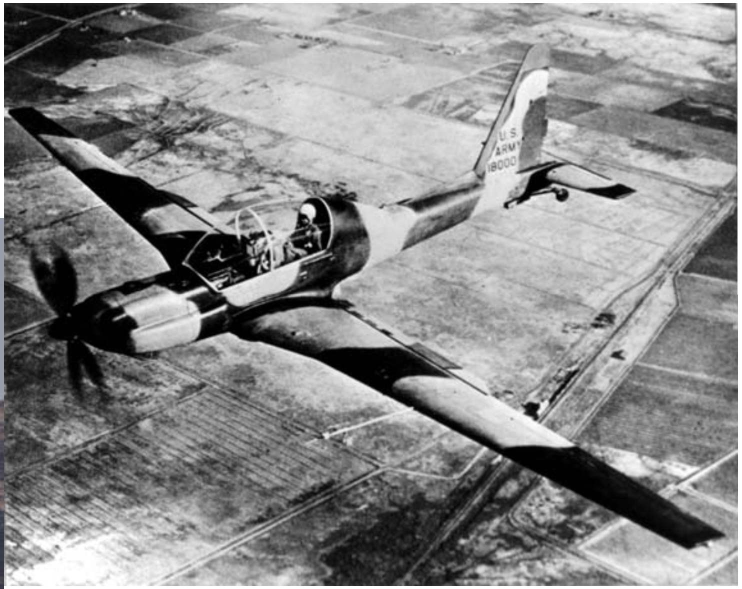
- How to make airplanes blend visually with their background when viewed from multiple angles/altitudes?
  - Paint the top a darker color, so that it blends in with the ground when viewed from above.
  - Paint the underside white, so that it blends in with the air when viewed from below.
  - The sides can be an in-between shade.
  - (This was "new" in aviation starting around the 1930s, but has been used by animals such as sharks and seagulls for many millions of years)
- Starting around 1950, the question was first asked: Airplanes are first spotted from miles away, when these different colors blend together, so maybe camouflage and three-tone blues/greys don't help that much. What one color would make it hardest to spot an airplane when it's still a "point", miles away?
  - The British studied this and determined that the least-visible color was actually pink!
  - In general, the least visible color for low-flying aircraft does tend to be very pale e.g. pink… or, more typically, light grey or pale green or blue. (Note how this A-10 still has some of the "top slightly darker, underside slightly brighter" technique, even though overall it is light grey. Note also the fake canopy painted under the cockpit, to make it harder to tell which way the airplane is turning).
  - However, a very high-flying airplane encounters other factors. (1) The sky above it is almost black, and (2) its underside is illuminated by light scattered by the atmosphere, i.e. the atmosphere effectively "glows". So any high-flying airplane will look almost white from the ground… unless it is painted black, or dark grey.
  - Generalizing the previous two points: **Low flying military aircraft tend to be light grey, and other military aircraft tend to get painted darker and darker shades depending on how high they typically fly.**
  - Black makes a low-flying airplane easier to spot than yellow, red, orange, white, or any other color. Therefore, a growing number of air forces paint their training aircraft black, for high visibility.
  - The sun overhead shines in such a way that horizontal surfaces, such as the tops of the wings and fuselages, look brighter than the rest of the airplane. Many military aircraft have darker "blobs" painted on these flat surfaces, to diminish this effect and make the entire airplane look closer to a single color.

Stealth: Low Noise

X-26B

QT-2

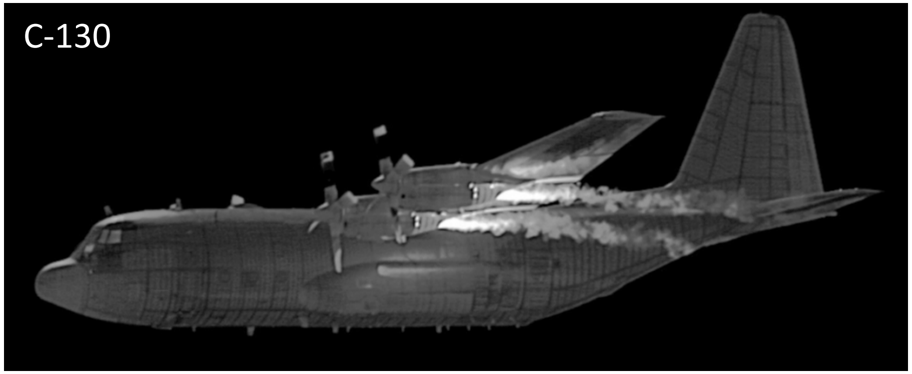
YO-3

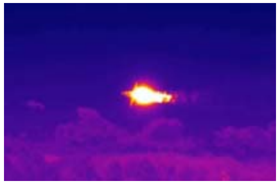


Stealth: Low Noise

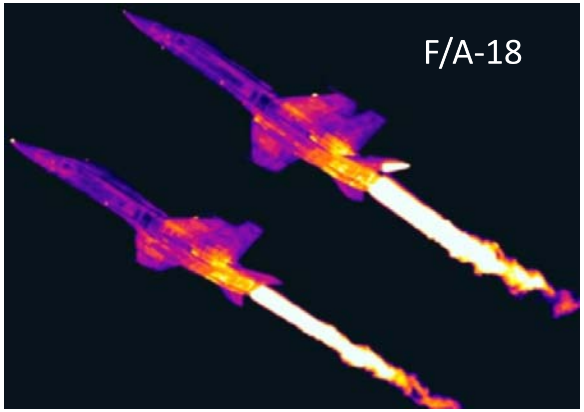
- During the Vietnam war, the US Army wanted to develop ultra-quiet spyplanes so they could do reconnaissance of enemy activities at night, from the air at low altitudes, without being spotted.
- They approached Lockheed in 1966 about this. Lockheed borrowed two Navy X-26 (Schweizer SGS 2-32) gliders and added engines and slow-turning propellers.
- The airplanes were designated X-26B, and then QT-2 for "quiet thrust". The engines, propellers, and various aerodynamic systems such as air scoops were iteratively modified so as to eliminate nearly all aircraft noise. Engines included an O-200 (used in many light airplanes) and a Cutiss-Wright RC2-60 Rotary engine, supposedly the first airplane to fly with a Wankel-style engine.
- The two X-26Bs, ultimately designated "QT-2PC", received upgraded avionics, camouflage, and other airframe modifications… and flew over Vietnam in 1968 and 1969. They were then returned to the US Navy, because…
- In 1969, Lockheed first flew the YO-3, which had been in development based on the lessons from the X-26B/QT-2 program. Eleven were built, powered by IO-360 engines, and flew over Vietnam starting in 1970. They were barely audible.
- The YO-3s have since been operated by NASA, by the FBI… and by the Louisiana Department of Fish and Game to catch poachers.

Stealth: Infra-Red Radiation





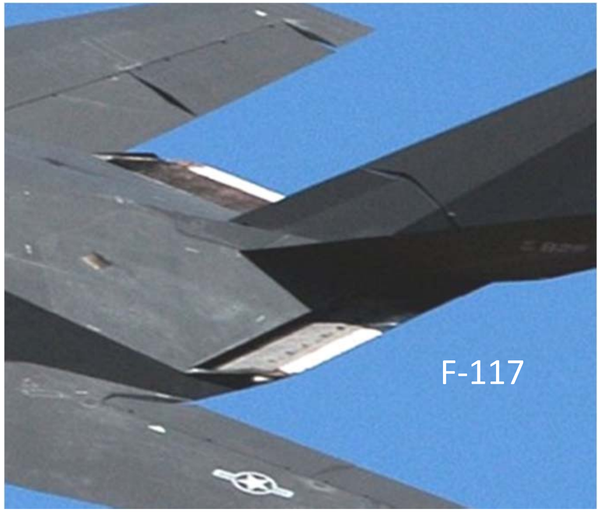
FLIR/IRST in
Su-27, F-16, F-14,
AH-64, & C-130



Stealth: Infra-Red Radiation

- Anything hotter than absolute zero emits some electromagnetic radiation.
- Typically, this radiation is in the infra-red part of the spectrum, i.e. longer wavelengths than what we can see.
- (As things get hotter, the emitted wavelength gets shorter, until we can see it: things become "red-hot", then yellow-hot. Very hot things burn blue).
- Infra-red cameras and "heat-seeking missiles" look for the infra-red radiation from hot aircraft engines and exhaust plumes in order to spot and chase them.
- Many aircraft carry FLIR (forward-looking infra red) or IRST (infra red search & track) sensors, i.e. a powerful infra-red camera typically mounted on a round "R2-D2" ball or turret near the nose. Most modern fighters have pods on the belly. Most military helicopters (and the F-117) have no radar at all, just the FLIR. It can detect aircraft many miles away, and detect whether missiles have been fired.
- Aircraft can protectively minimize their infra-red signatures in a few ways. One is to have engines on top of the fuselage or between the tail fins (e.g. A-10, RQ-4).
- Water in the atmosphere absorbs certain frequencies of infra-red. Materials that emit infra-red radiation at those frequencies can help airplanes not be spotted by FLIR from more than a couple miles away, because the atmosphere absorbs and scatters most of the radiation, like a fog. Most military aircraft are painted using low-emissivity paints made with these materials.

Stealth: Flattened Nozzles


F-117

YF-23


F-22


B-2

X-47B

Stealth: Flattened Nozzles

- The best way for a jet to avoid detection by FLIR and heat-seeking missiles is to mix the hot exhaust gases with the cool outside air ***as quickly as possible***.
- Most stealth airplanes therefore have flattened exhaust nozzles (and some also have internal mixing) so that the exhaust is cooled by the surrounding air relatively quickly.

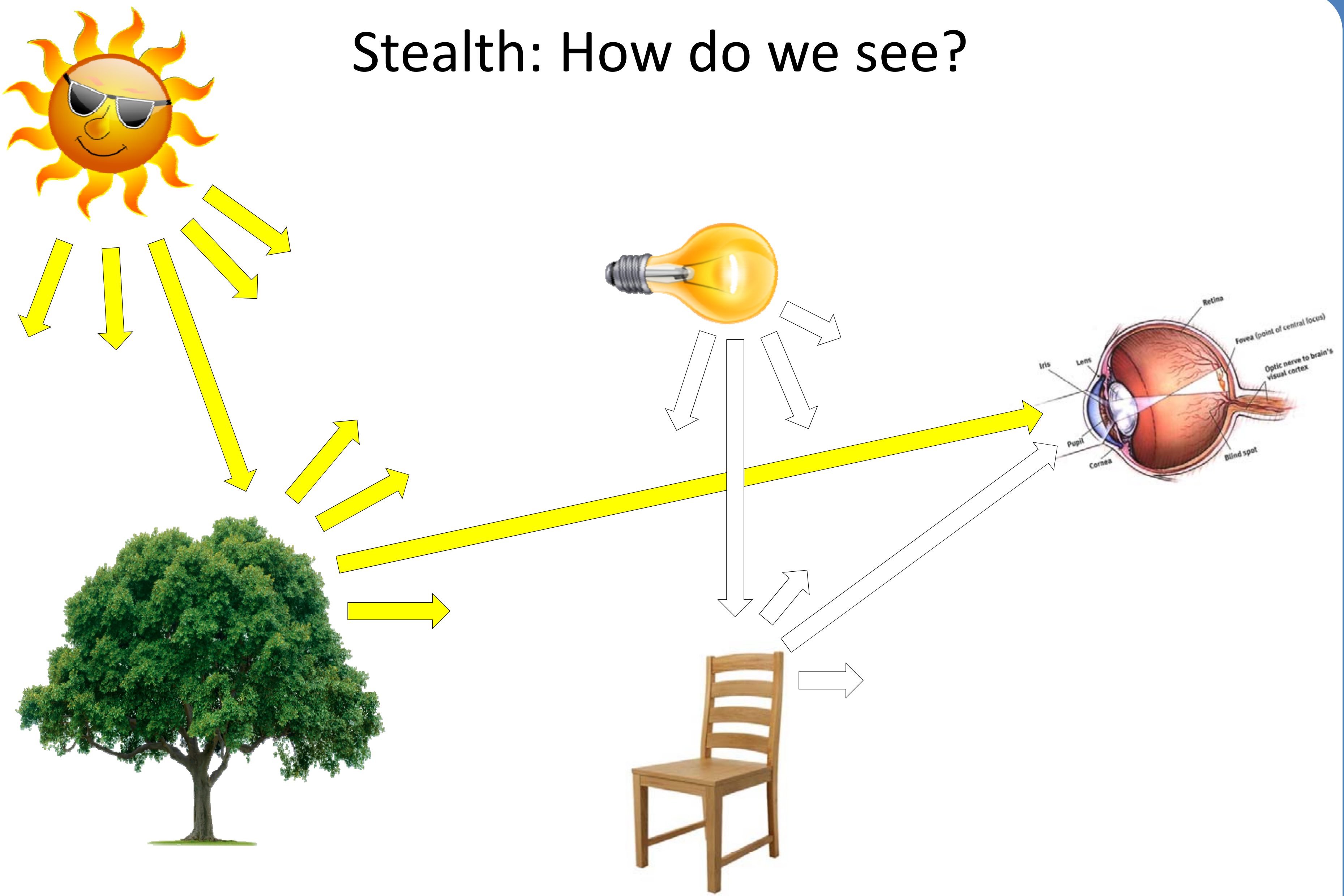
Stealth: Radar

- Electromagnetic radiation (light to "see" airplane with)

Stealth: Radar

- Of course, the most distinctive features of stealth airplanes – and what is typically meant by the words "stealth technologies" – have the objective of making the airplane harder to detect by radar. Just to be clear: This enables the airplane to be flown over enemy territory without being found, and without being "locked onto" with radar-guided missiles.
- (Disclaimer: Most people who have actually worked with stealth aircraft development will not talk about it publicly: They typically want to be cautious and make sure they don't come anywhere close to violating the terms of their security clearances. Therefore, nearly all public information about stealth aircraft was published by academics, journalists, or people only superficially involved with how stealth technology works, such as pilots. I am none of these, just an enthusiast who has never actually worked with stealth aircraft. The sources of my limited knowledge about stealth are the books listed at the end of this section, plus what can be found through internet research. This material is only as accurate as those sources).
- How does radar "see" an airplane (or ship, or rain, etc.)?
- Once we understand this, we can think about how to make an airplane that would be harder to "see" with radar.
- Like infra-red, radar is just electromagnetic radiation at a very long wavelength, i.e. light of a "color" that our eyes cannot see.
- So let's think for a little while about how our eyes see objects, i.e. about how light from some source bounces off of objects and then into our eyes in such a way that we can tell where the objects are. We will develop some insights that are applicable to figuring out why most airplanes are easy to see on radar, and how to make an airplane that would be harder to see.

Stealth: How do we see?

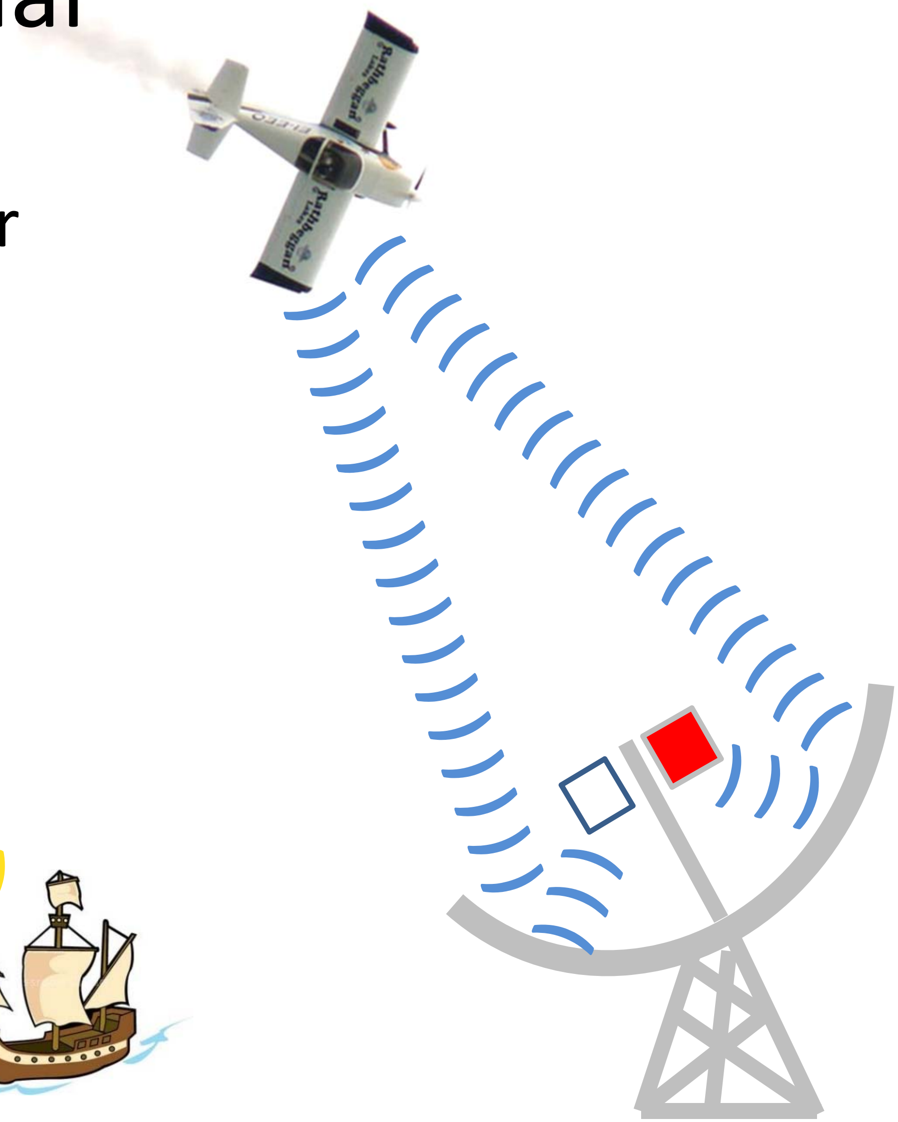


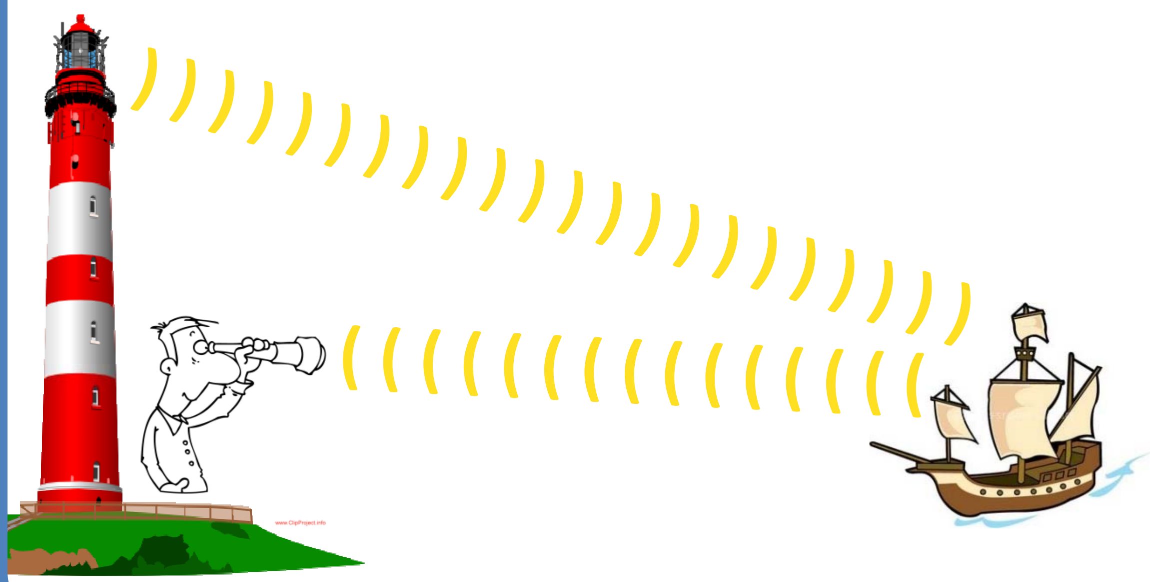
Stealth: How do we see?

- Sources of light, such as light-bulbs and the sun, shoot lots of light all over everything.
- The light hits each objects and then scatters off from every object in every direction.
- This means that, wherever you are, some of the light bouncing off the surface of every object is headed towards your eye. So you can see every object around you (except the objects that are behind something that blocks the light).
- You know where (in what direction) something is because you know from where (from what direction) that light, from that object, is coming from (because your eyes can focus and because you can move your head).

Stealth: Radar

- Emitter, Bounce, Receiver
- Same as a lighthouse

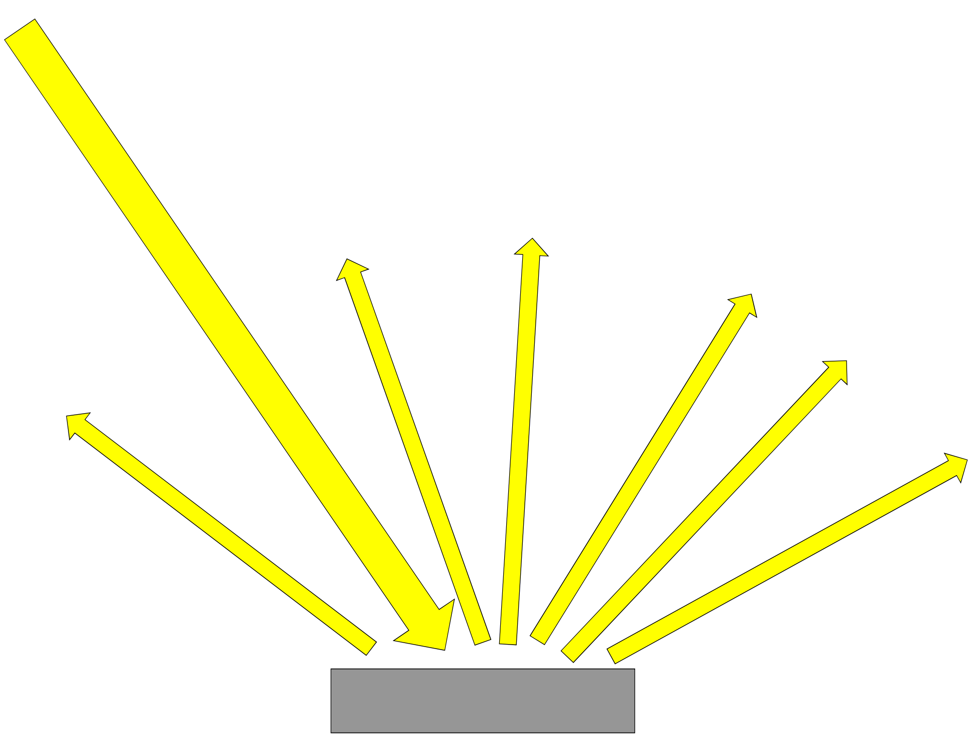




Stealth: Radar

- Imagine you're on an island, at night, trying to find ships nearby.
- You use a lighthouse. It emits electromagnetic radiation (light), spinning around to emit it at every direction at some point.
- If there is a ship nearby, at some point the light from the lighthouse will hit it. It will then bounce off from the ship, in every direction.
- Some of that bounced (reflected/diffused) light from the ship will hit your eyeballs, and you will see the ship!
- Radar works the same way. It emits electromagnetic radiation in a scanning pattern, and has a detector (basically like a digital camera) looking for any radiation that bounces back.
- The main difference between using radar and looking with your eyes is that, during the day, we have a source of light that shines on everything and bounces light from everywhere. Using radar is like looking for something in the dark with a flashlight or lighthouse.

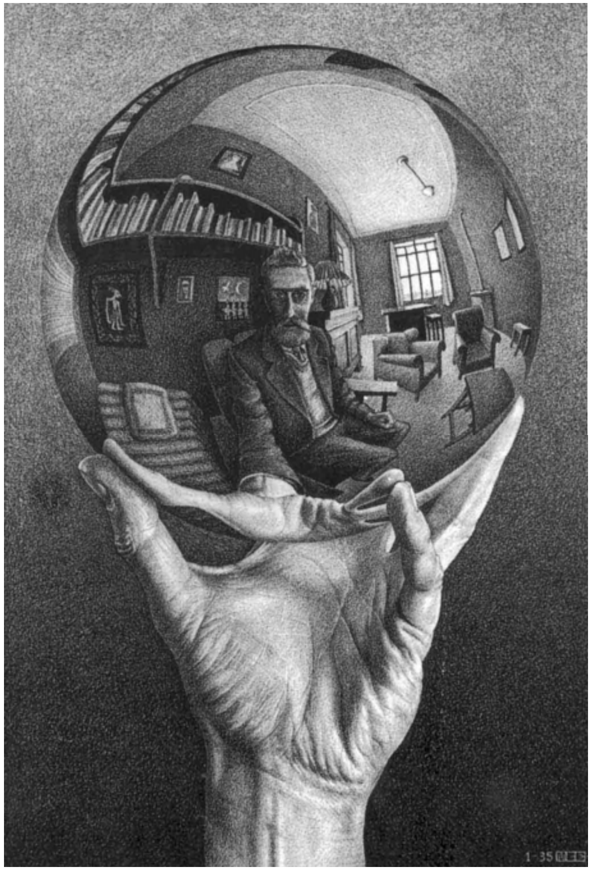
Stealth: Dull versus Shiny



Stealth: Dull versus Shiny

- When a dull thing is illuminated from any direction, photons bounce off in every direction. (Shine a light on a dull object from any direction, and you can see it from every direction).
- When a shiny thing is illuminated, photons bounce off only in one direction, at the same angle at which they hit the surface. If they do not bounce towards you, then you cannot see the shiny thing. (When they do bounce into your eye, you see the "glint" of the shiny thing).
- Airplanes are pretty "shiny" to radar. So let's think some more about how shiny things reflect light.

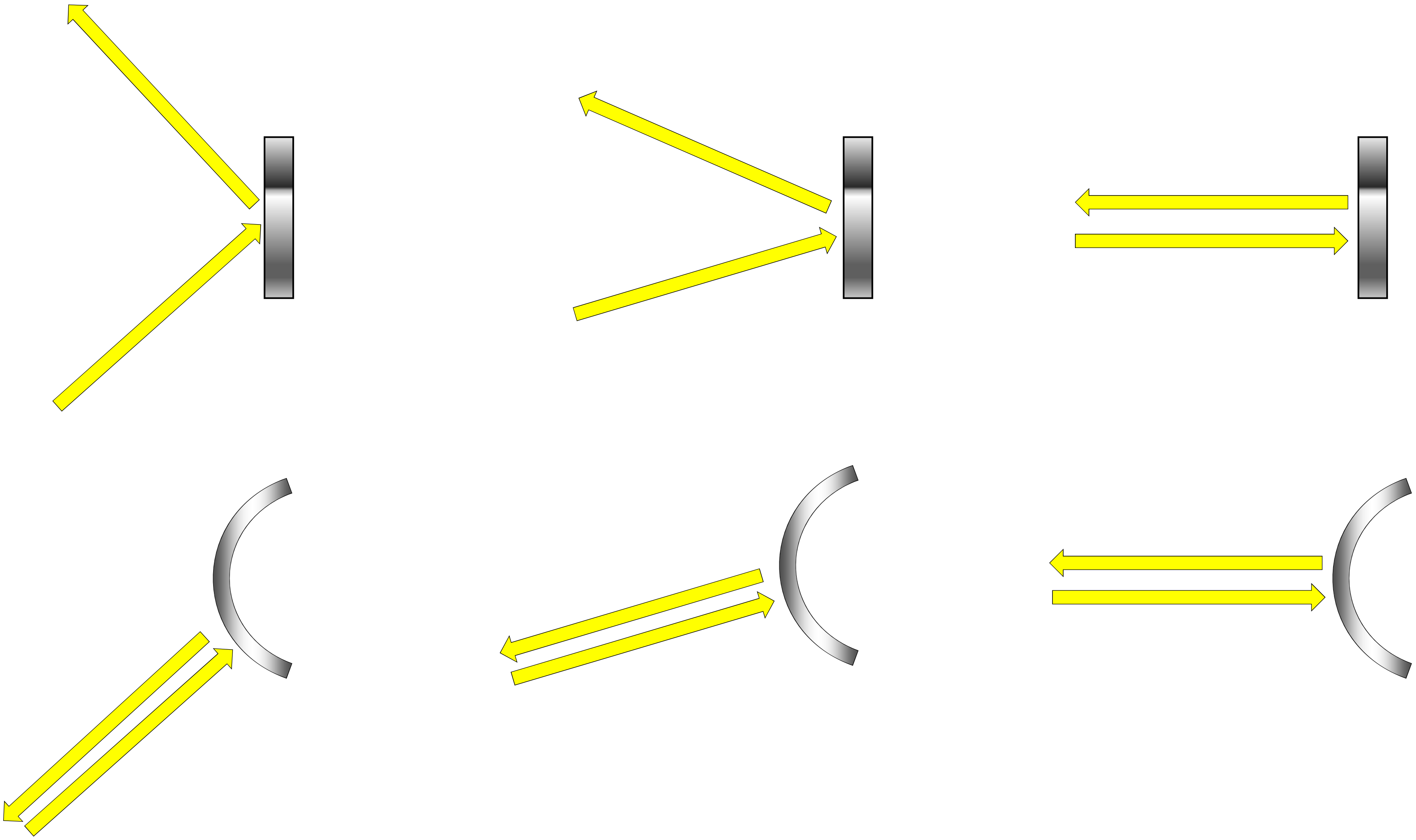
Stealth: the Mirror, the Spoon, and the Christmas Ornament



Stealth: the Mirror, the Spoon, and the Christmas Ornament

- Think about a mirror. When you see your reflection, this means photons are leaving your face, bouncing off the mirror, and then hitting your eyes. You are seeing photons that came from your own face. (This is like the radar and the lighthouse).
- This will only happen if your face is located in the volume of space that is perpendicular to the mirror surface. If the mirror is at an angle to you, then you will not see your face, you will see off in some other direction of the room.
- There are lots of "mirror selfies" (self-portraits) out there where the camera is visible in a mirror. Notice how the camera is always in the place on the mirror that is perfectly perpendicular to the line between the camera and the mirror. The camera is never in a region of the mirror that is "at an angle", it is always flat, straight-on.
- Now think about a shiny sphere like a Christmas ornament. You can ALWAYS see your face, right in the middle, no matter where you are relative to the ornament. That's because the "middle" of the sphere surface (as you see it) will always be perpendicular to the line between you and the center of the sphere. A shiny sphere will always reflect some of your face's photons straight back to you.
- A spoon is somewhere in between. There is a wide range of spoon orientations where you can see your reflection on the spoon. If the spoon is relatively rounded and deep (like a ladle), then you can see your reflection from almost any direction, i.e. almost no matter how you turn the spoon (like the ornament). But if the spoon is relatively flat, then you can only see your reflection if you hold it just right (like a small flat mirror).

Stealth: Flat versus Curved, Perpendicularity



Stealth: Flat versus Curved, Perpendicularity

- THIS IS THE MOST IMPORTANT CONCEPT FOR UNDERSTANDING STEALTH AIRPLANE DESIGN!
- In order for you to see your reflection on a **flat** shiny thing like a small mirror, i.e. in order for photons to leave your face and bounce off the mirror and go back towards your face, your line-of-sight must be perpendicular to the mirror surface. This only happens inside a narrow region. Shine light from any **other** angle (other than perpendicular to the mirror surface) and it will bounce **away from you**.
- In order for you to see your reflection on a curved shiny thing like a Christmas ornament, i.e. in order for photons to leave your face and bounce off the ornament and go back **towards you**, your line-of-sight must be perpendicular to any point on the ornament surface. This happens from many angles, pretty much from **anywhere** in the room, because the ornament is **curved**.
- In a sense, a Christmas ornament is like lots of little mirrors – like a disco ball – at least one of which will be perpendicular to your line of sight.

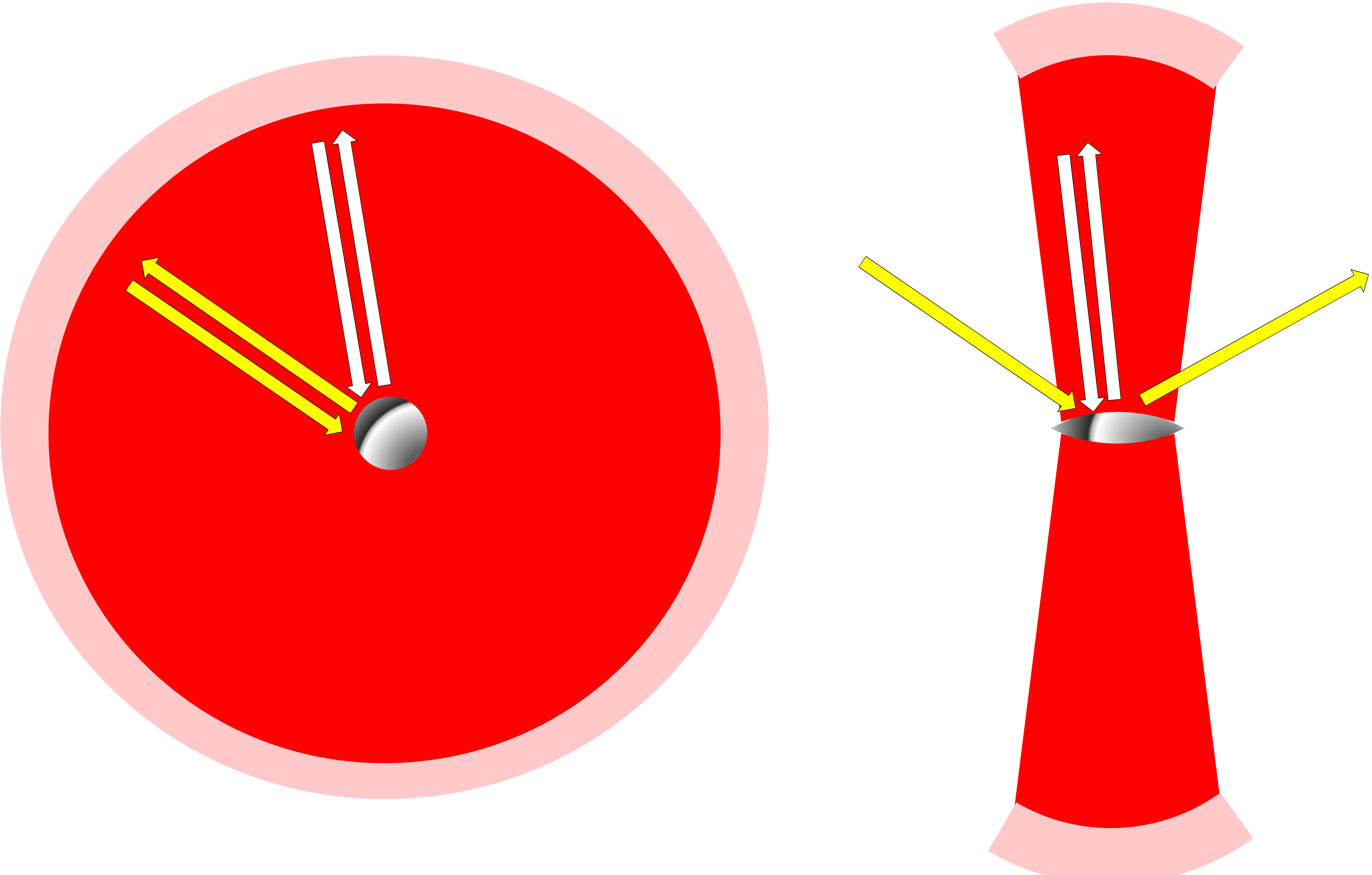
Stealth: Flattened Fuselages

One of these things is not like the others…

Stealth: Flattened Fuselages

- Most normal airplanes have lots of circular cross-sections.
- Most stealth airplanes have flat shapes.
- Why?

Stealth: Flattened Fuselages

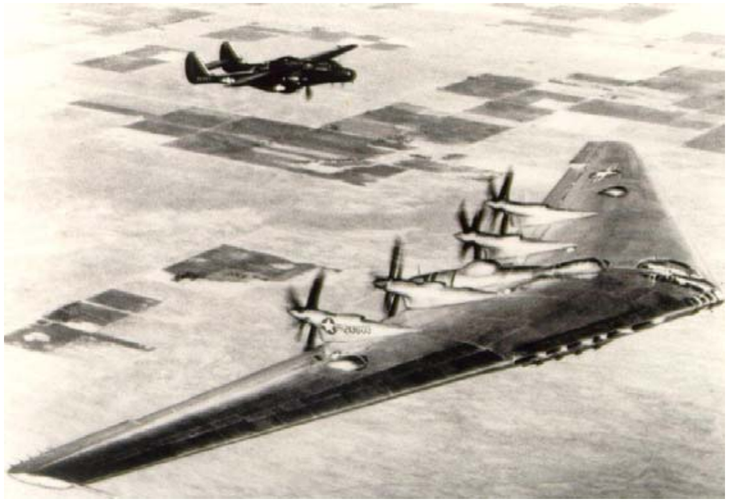


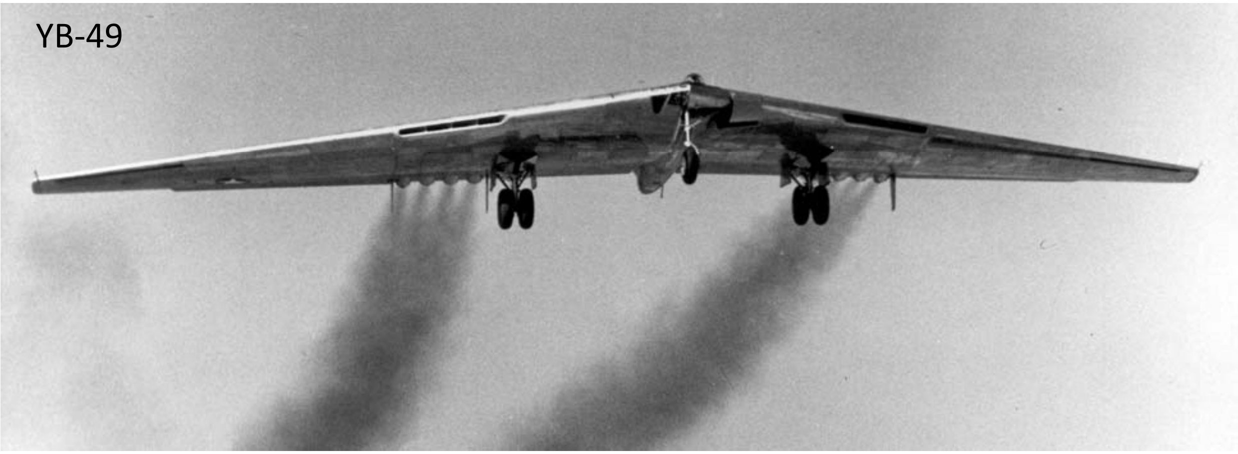
Stealth: Flattened Fuselages

- As with the Christmas ornament versus the small mirror:
- The regions from which you can shoot photons towards a round thing and have them come back towards you… is: anywhere!
- The regions from which you can shoot photons towards a shiny flat thing and have them come back towards you… is: only if you’re right on top of it or right below it. Any other photons, e.g. from the side, will bounce off and not go back the way they came.
- The red zone in the diagram represents the region around the object where someone could fire off some photons at the object and the photons would bounce off the object straight back to the source, i.e. the object would be detected.

Stealth: The Importance of Flattened Shapes


Vulcan

YB-35


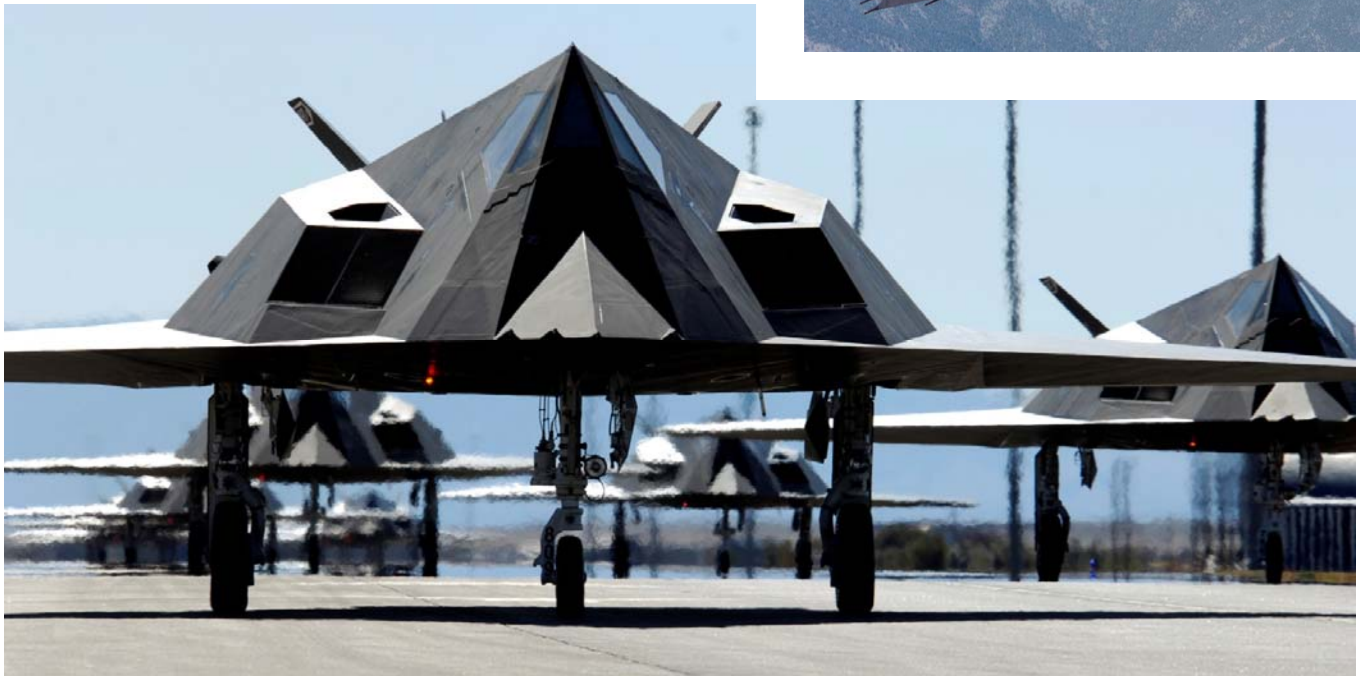

YB-49


N-9M

Stealth: The Importance of Flattened Shapes

- The vast majority of the radar reflectivity of an airplane is determined by its shape.
- We will talk soon about radar-absorbent materials, about wave cancellation, and about minor tweaks to the shape such as aligned edges, faceted surfaces, no right angles, toothpick leading edges, serpentine intakes, and things like re-entrant triangles… However, these all have a relatively small effect.
- Just making an airplane with a flattened fuselage, i.e. one whose fuselage is not a tube, gets you most of the way to a stealthy airplane.
- Northrop’s early flying wings, as well as the RAF’s Vulcan bomber, would sometimes disappear from radar. They were accidentally stealthy. And they even had small tails, some round shapes, perpendicular intake walls, etc.

Stealth: Faceted Design

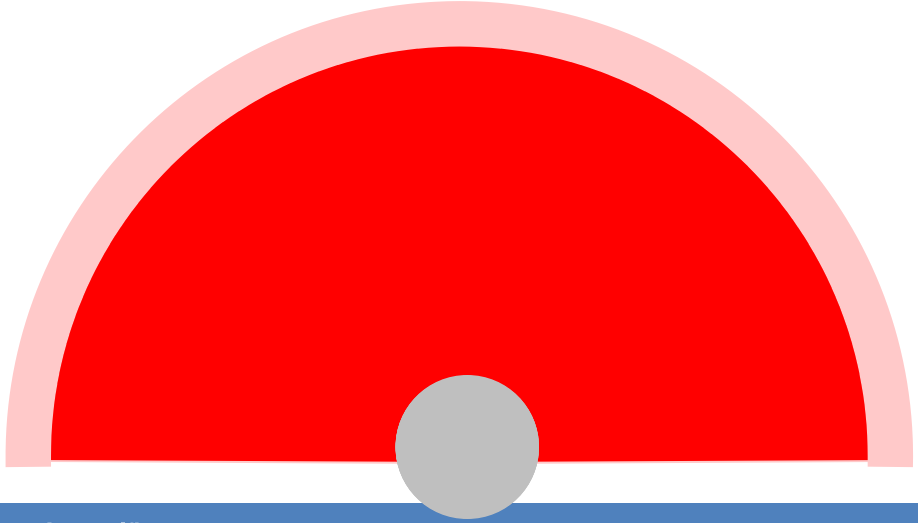


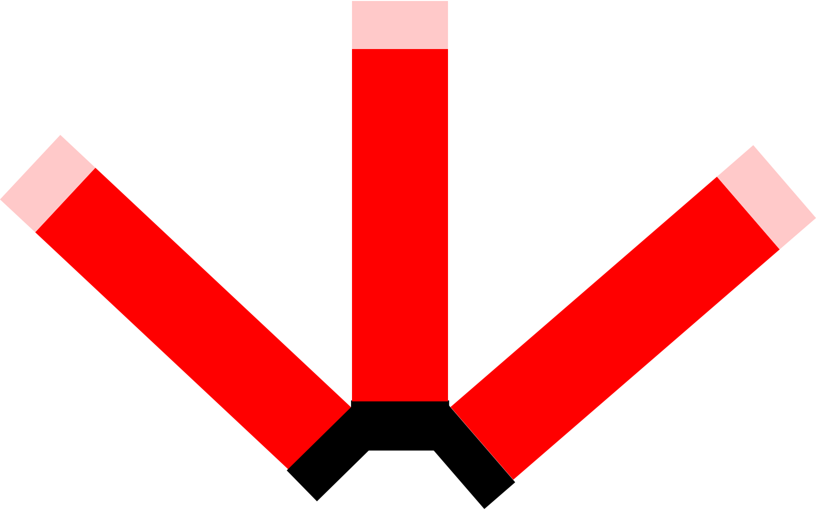
F-117

Stealth: Faceted Design

- Some stealth airplanes have surfaces made of flat polygonal facets rather than smooth curves.
- Why?

Stealth: Faceted Design

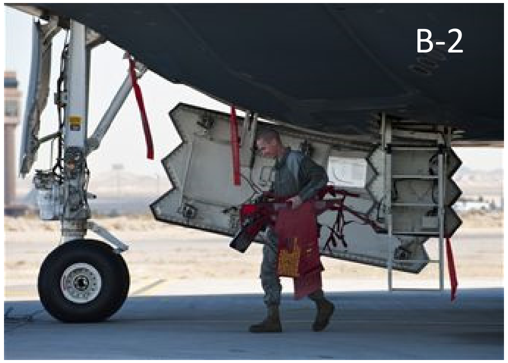


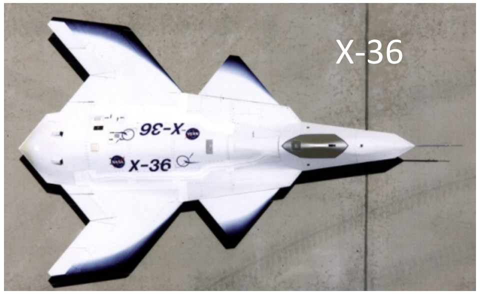


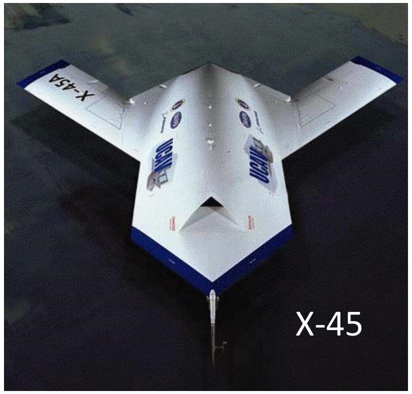
Stealth: Faceted Design

- Same idea as the flattened fuselage: Photons will only bounce back towards you if you are perpendicular to one of the facets, i.e. in one of the narrow “columns” that stick out over each segment of the surface.

Stealth: Aligning Edges



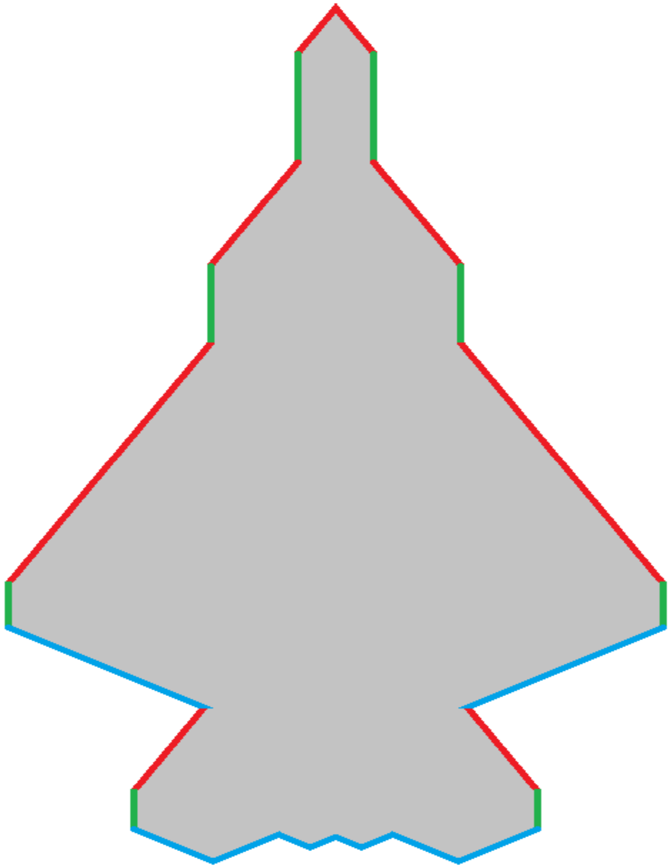


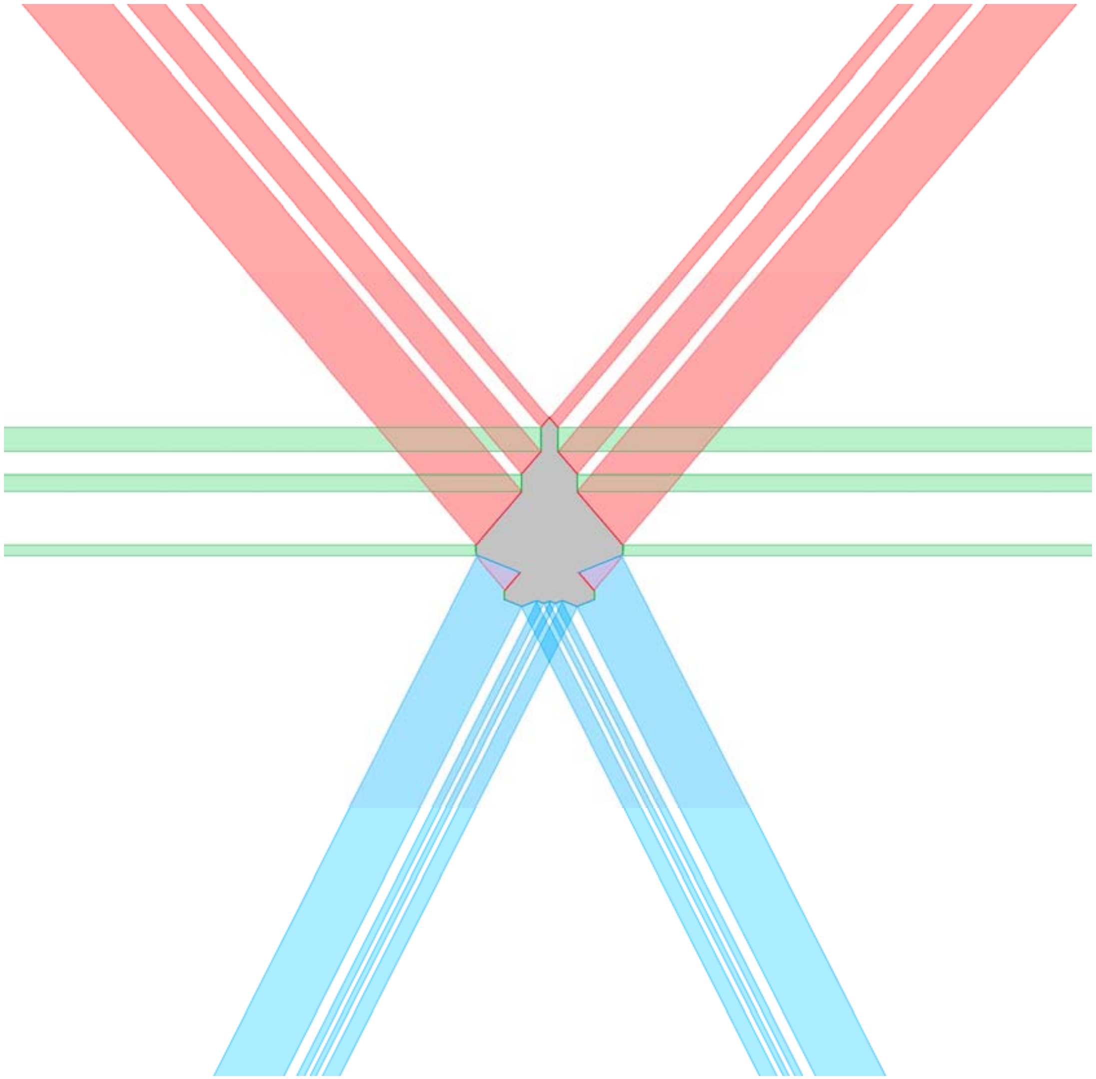


Stealth: Aligning Edges

- This is the same as the faceted design, but about the edges of the airplane's planform, rather than its surface.
- Even airplane features like the landing gear doors and the bomb bay doors have serrated edges that are parallel to the wing and tail edges

Stealth: Aligning Edges





Stealth: Aligning Edges

- Radar will bounce back towards you from the airplane's edge (e.g. the front or back edge of the wing) if some segment of that edge is perpendicular to the line of sight.
- Solution: Make edges straight, and group them into parallel groups, so that there are only a handful of narrow directions that are perpendicular to any edge. These few narrow directions can be shown as colored "beams" on the image, radiating from the airplane in only a few directions. Most directions are not perpendicular to any part of any edge (white regions of the image).
- In other words, a radar within a colored "beam" will see the airplane, but a radar in the white regions will get a much smaller reflection, because it will not be perpendicular to any edge. And a radar within a colored "beam" will not be in there for long, because the airplane flies and turns.
- A B-2 style planform will have even fewer directions!

Stealth: No Right Angles!

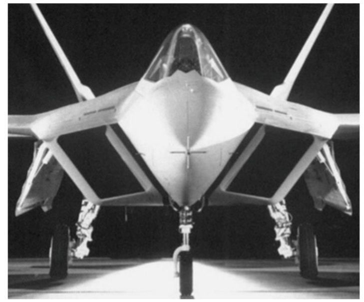
F-15

F-22

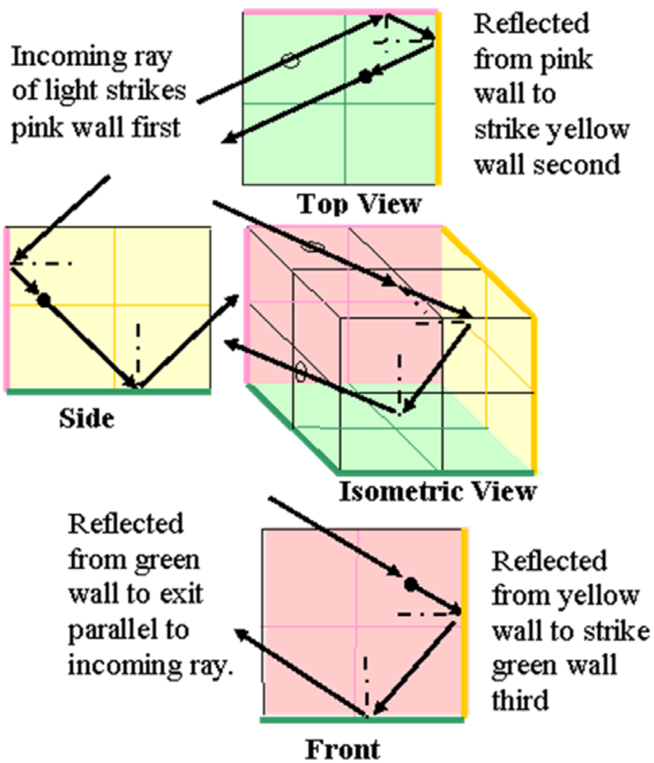
Stealth: No Right Angles!

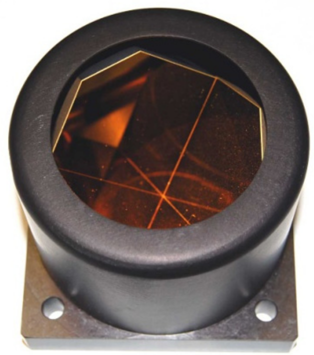
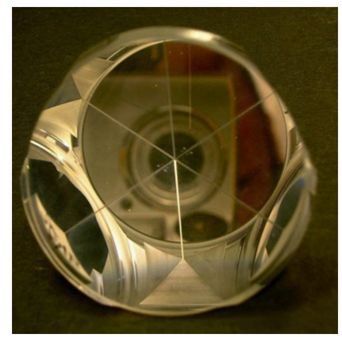
- Most airplanes have right angles: Rectangular air intakes, the tail fins are at 90 degrees to each other, the pylons are at 90 degrees to the wing or to the belly…
- Most stealth airplanes have no right angles, only diagonal surfaces. Why?

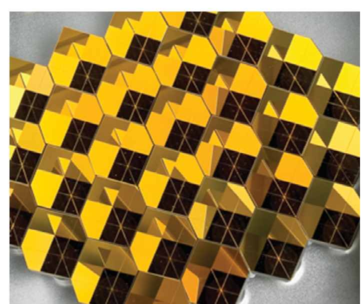
Stealth: Retroreflectors

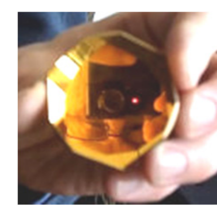




How a Corner-Cube Retro-Reflector Works



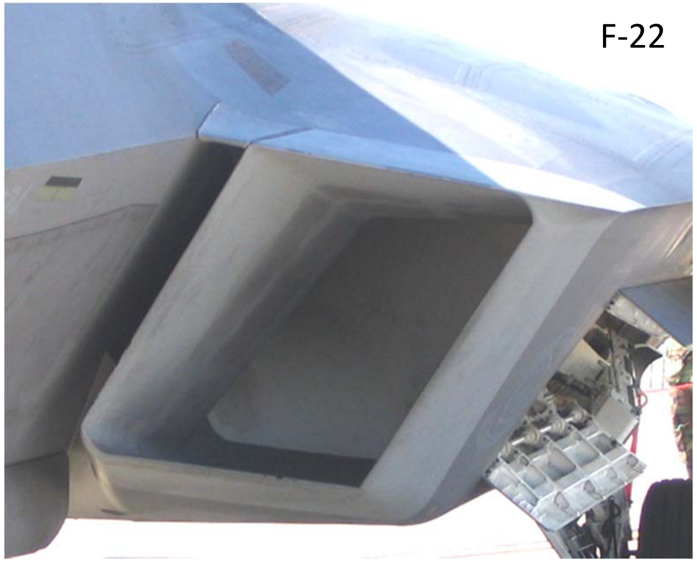


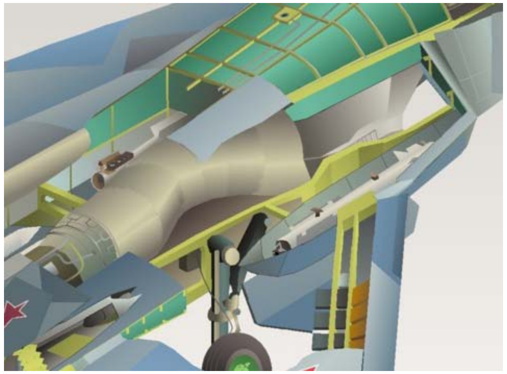


Stealth: Retroreflectors

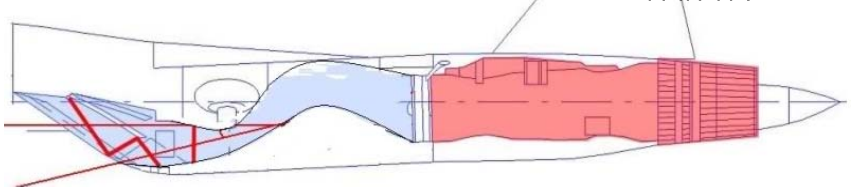
- It can be proven mathematically (or seen in the diagram) that a photon that bounces off a 90-degree corner will always go straight back the way it came, no matter from which direction it came.
- This is a retroreflector. “Corner cubes” are used to send light straight back from where it came (useful in surveying, etc… We even left some on the moon!). Lots of little ones make up the small plastic retroreflectors that you see between lanes on the road, that you wear while riding your bike, etc. People near a source of light (e.g. car drivers) see these as glowing bright. (Many animal eyes work the same way when a light is shone at them at night). Notice how there is always a camera in the middle of every photo of a corner cube.
- Stealth airplanes use canted tail fins and diagonal-sided air intakes to avoid 90-degree corners that could act as radar retro-reflectors.
- (Even better is to be like an X-36 and have no tail fins at all!)

Stealth: Serpentine Intakes





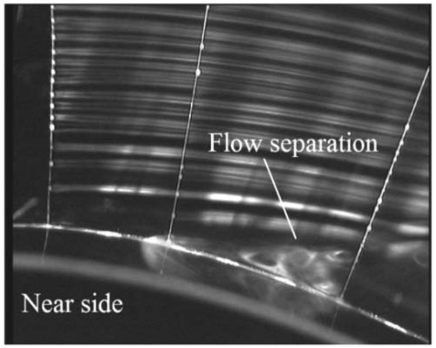
PAK-FA



Stealth: Serpentine Intakes

- One of the most radar-reflective things on an airplane is the first stage of the engine compressor (i.e. the turbofan).
- The turbofan is typically hidden by an S-shaped or “serpentine” inlet duct. Look at a stealth airplane head-on and you will only see the inside of the inlet duct as it curves away, not the fan.
- The serpentine intake can significantly reduce the radar reflectivity of non-stealthy airplanes too. It is one of the features applied to airplanes like the Super Hornet and the Rafale to make them slightly less detectable from the nose-on direction.

Stealth: Serpentine Intakes



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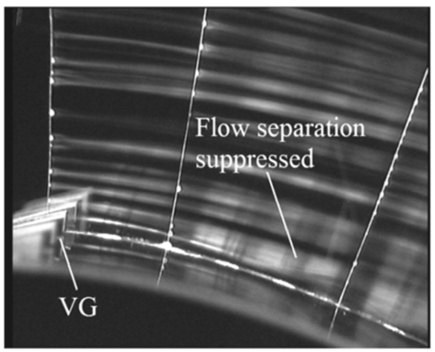

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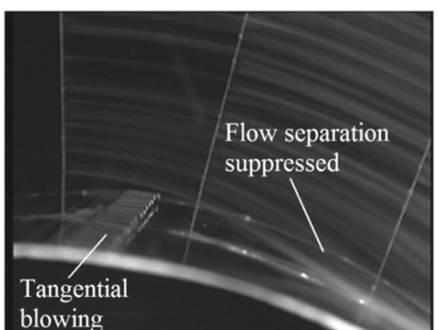

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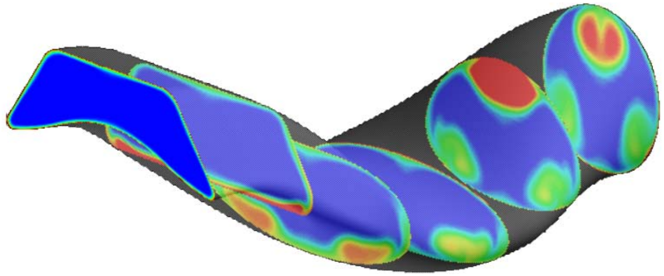


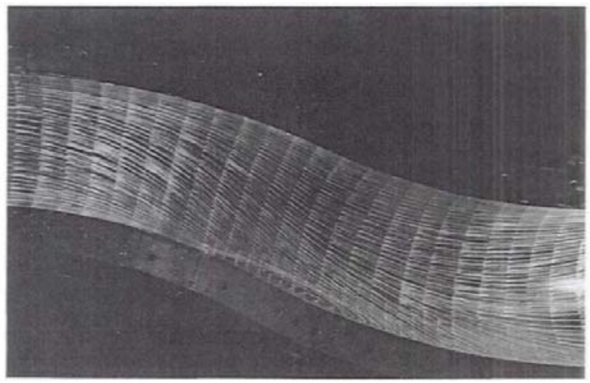
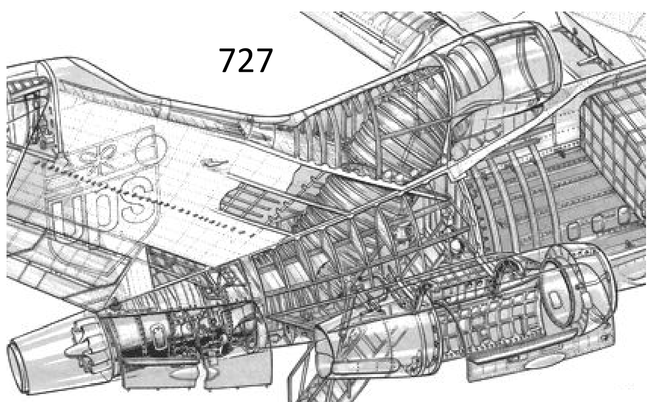
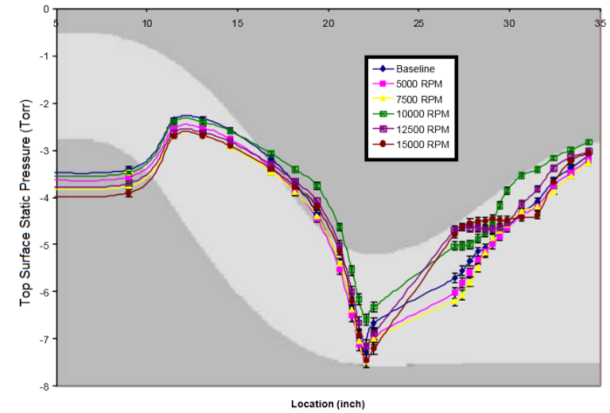
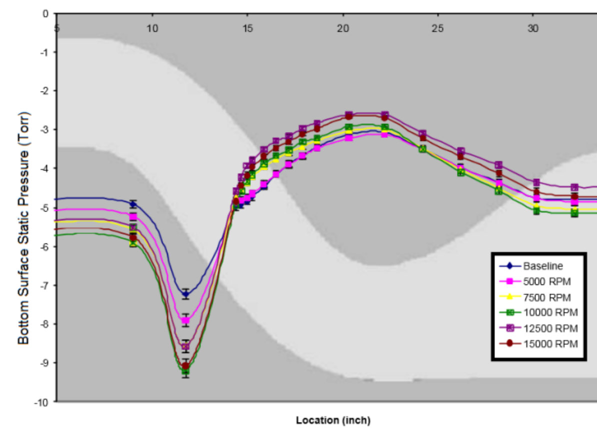
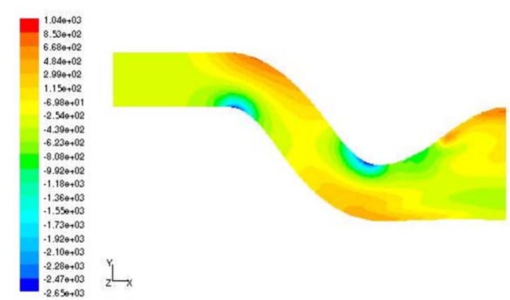


Figure 4.3 Surface oil flow streak-lines on a middle cross-sectional plane of the S-Duct showing flow separation at the bottom surface [5].







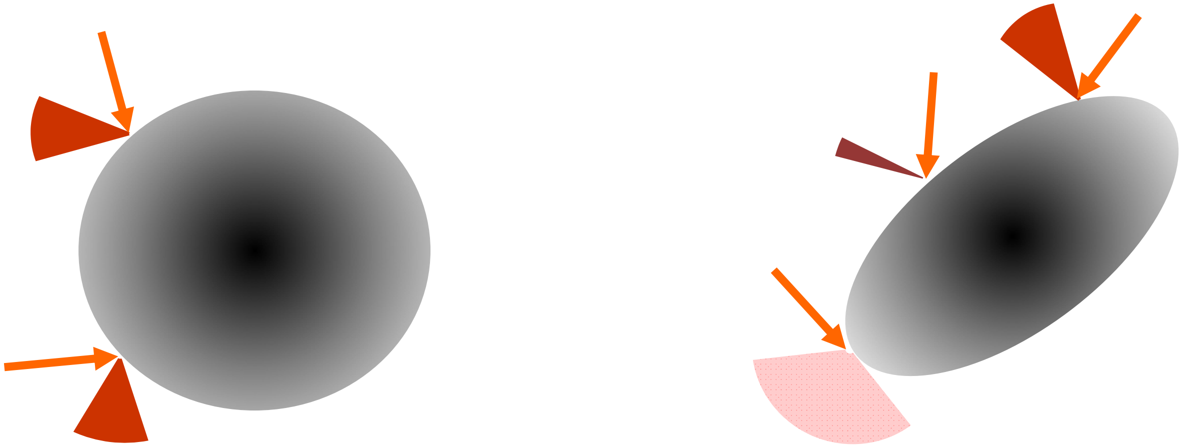


Stealth: Serpentine Intakes

- Unless they are very carefully designed, serpentine intakes can have flow separation problems, especially behind and inside the “bend”.
- Some have flow control features such as blowers, suction, vanes, VGs, etc., to keep the flow attached to the wall.
- Lots of patents and academic papers about this. (The problem is not unique to stealth jets, or new: Dates back to at least the 727 and L-1011).

Stealth: Non-Constant Radii of Curvature

X-47B



Stealth: Non-Constant Radii of Curvature

- So far we have only talked about ways to keep radar from going back the way it came from.
- But a little bit of radar inevitably does bounce back towards the sender.
- One thing you can do about this: Avoid circular shapes in your airplane, such as cylinders and spheres. Use other curves, i.e. make each spot on the airplane surface have a different local radius of curvature.
- A circular shape has the same reflection at various angles. (If I spin the shiny Christmas ornament, the reflection on it does not change).
- An irregular shape will have a different reflection, depending on its orientation relative to you. (If I spin the shiny spoon, the reflection on it changes).
- So the radar return from a non-circular surface changes constantly. It looks like static and it's harder to "lock on" to.

Stealth: “Toothpick” Leading Edges

Stealth: “Toothpick” Leading Edges

- The compromise between aerodynamics and radar reflectivity can be clearly seen along the leading edges of many stealth airplanes.
- A rounded leading edge generates more lift, but reflects radar back to more directions.
- The worst place for reflectivity is near the corners, i.e. the tips and the edges of the control surfaces and flaps/slats.
- Compromise: Leading edge is thin and sharp near corners, round near middle, i.e. “toothpick”.

Stealth: Radar Absorbent Materials


F-117


F-22

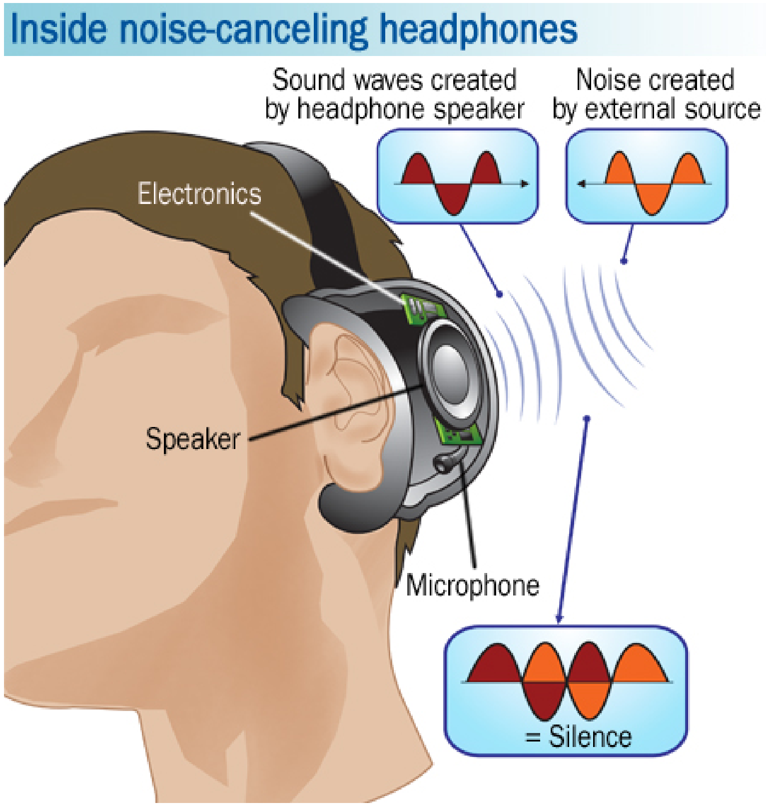

B-2

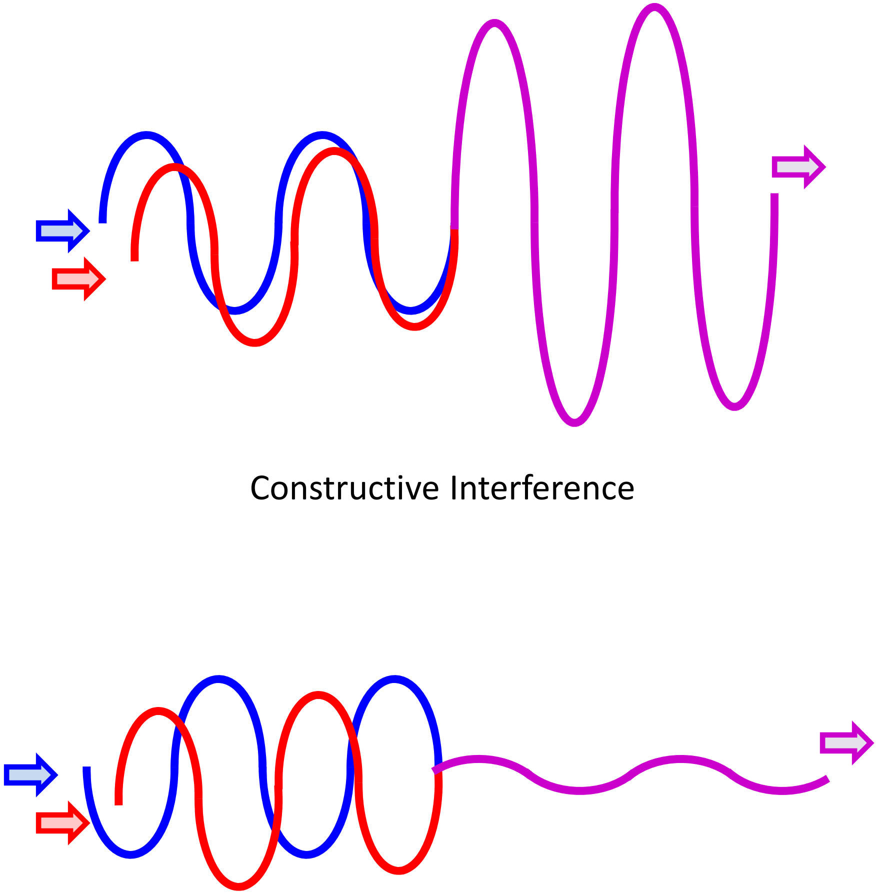

F-22

Stealth: Radar Absorbent Materials

- So far we have mostly just talked about how "shiny" surfaces reflect light at the same angle the light came in, and how the best way to make an airplane hard to detect is to shape it such that the radar waves reflect off the airplane shape in a direction away from the source.
- But what if the airplane simply absorbed the radar waves? Could an airplane be "black" in that wavelength?
- Research on RAM dates back to World War 2. As with most other stealth technologies, the first successful application was in the Have Blue / F-117 program in the late 1970s / early 1980s.
- Atoms absorb electromagnetic radiation when the energy of each photon – which depends on the frequency of the radiation, i.e. on the color of the light – matches the energy levels of the electrons, or the vibration modes of the molecules, or their magnetic fields. Thus, different materials (made of different atoms bonded in different ways, whose magnetic fields may or may not be aligned) have different colors.
- It turns out that iron absorbs electromagnetic radiation relatively well for the frequencies in most radars. Specifically, the oscillating magnetic field pushes on the particles and causes much of the energy to be turned into heat, rather than into photons that bounce back out.
- Carbonyl iron and ferrite are available in very small spherical particles that look like grey powder, known as "iron balls". These have been applied to stealth airplanes by being embedded in neoprene tiles or suspended in paint or glue.
- These tiles / paints do not make the airplane "invisible" to all radar, or even to radars of any given wavelength. (Fighter radars tend to use relatively short wavelengths, ground-based radar tends to use longer wavelengths). It simply reduces the intensity of the reflection.
- RAM is most effective against shorter-wavelength radar, such as on radar-guided missiles and on most fighters. It is less effective against longer wavelengths such as from ground-based radar.
- While early stealth airplanes made copious use of RAM, modern ones rely almost solely on their shape, and use small amounts of RAM in a small number of critical spots such as corners, openings, gaps, etc.
- Many RAM substances are toxic, making airplane maintenance difficult.
- Some RAM has been claimed to lose effectiveness in the rain.

Stealth: Active Wave Cancellation





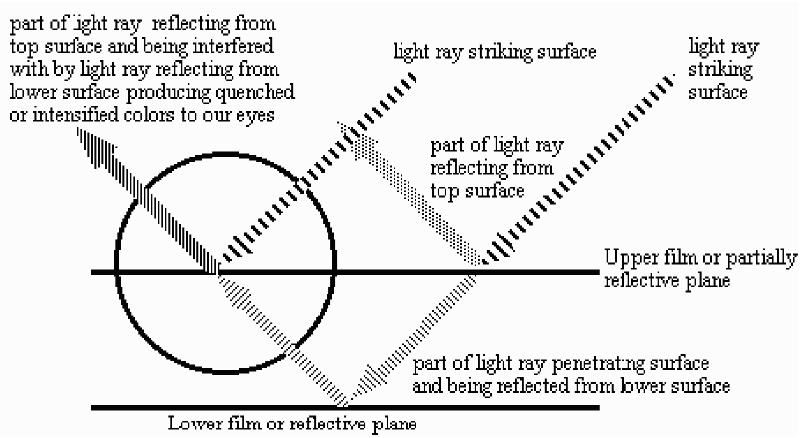
Constructive Interference

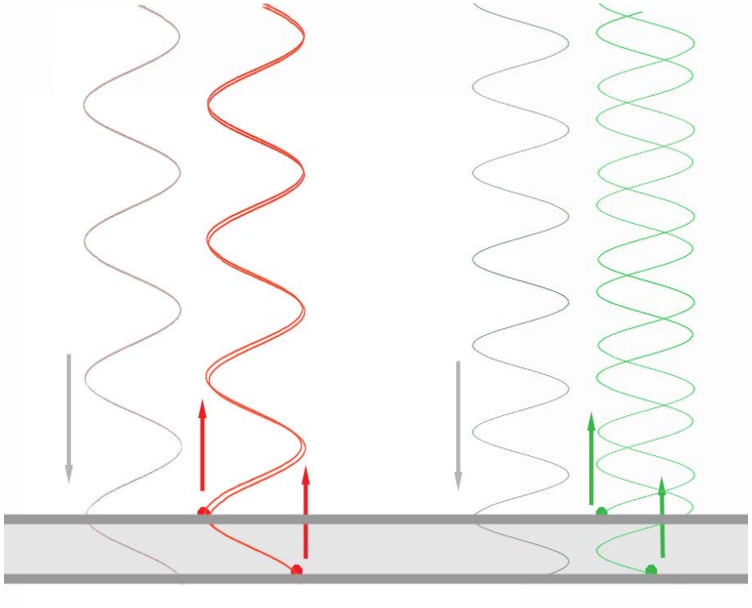
Destructive Interference

Stealth: Active Wave Cancellation

- Noise-cancelling headphones work by listening in to the sound waves coming from the outside world, and generating sound waves that are their mirror-image (i.e. 180 degrees out of phase, i.e. half a wavelength "off"). When these waves are added to the ambient waves from outside, they cancel out by negative interference.
- A similar idea could be applied to military airplanes. If they detect radar coming from a certain direction, they could know (from a database created from previous tests or simulations) what their radar reflection waves would look like from that direction, and they could generate and emit some "noise-cancelling" radar waves in the direction from which they sensed the incoming radar waves.
- There have been rumors that the B-2 and the Rafale do this, but they have been "neither confirmed nor denied".
- (Some moths "jam" bat sonar in this way).
- (Currently, radar jamming is far more crude than this, and aims to simply overwhelm the radar receiver by emitting lots of "noise-like" radar energy into it on various frequencies).

Stealth: Passive Wave Cancellation



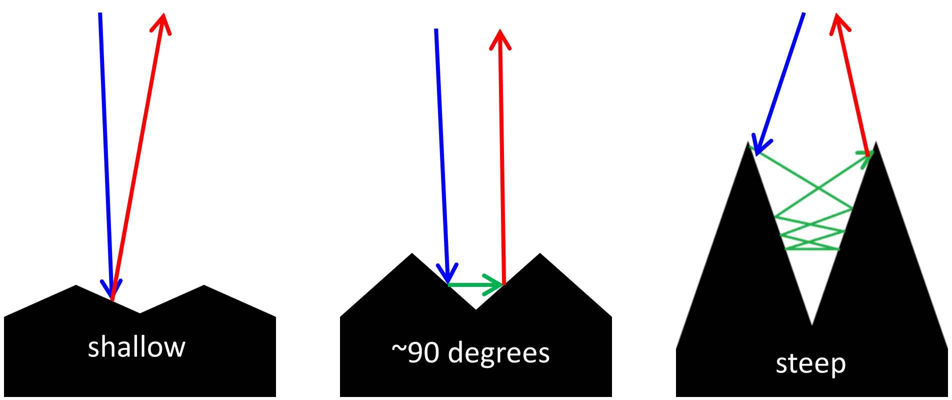


Stealth: Passive Wave Cancellation

- Instead of actively emitting “cancelling” waves, could such waves be naturally generated?
- Something similar happens in nature: When light reflects off of a transparent material, some of it reflects off the outer surface and some of it reflects off the inner surface. If the material is thin, then these two sets of photons may only be half a wavelength off (or may only be X many wavelengths off, where “X” is “something point five” wavelengths). Because materials are not perfectly flat, some wavelengths (some colors) interfere destructively in some regions but constructively in others, while different colors interfere destructively or constructively in different sets of areas. This is called iridescence/ goniochromism and causes the rainbow colors on sea shells, oil slicks, etc.
- If an airplane can have an “outer skin” and an “inner skin”, then radar reflections will be somewhat cancelled out if the radar wavelength is approximately twice the distance between the outer skin and the inner skin.
- Radar waves slow down while traveling through solids. This means that even if the radar wavelength is several feet, only a few inches between the “inner skin” and the “outer skin” are needed. Honeycomb or foam can be used to achieve this.
- In addition, the honeycomb or foam density can be increased with depth. Longer-wavelength, more-penetrative radar waves would make it deeper before bouncing back out… so this density gradient could allow for multiple wavelengths to be reflected “half a wavelength deep” and interfere with themselves destructively.
- From Bill Sweetman’s ***Inside the Stealth Bomber***: *While the leading edges of the B-2 cannot be described in detail, a wide-band radar-absorbent structure used on the edges of stealth aircraft has been compared to a stereo syste with a “tweeter” and a “woofer”. The “tweeter” is a high-frequency ferromagnetic absorber, applied over a resistive layer that reflects higher frequencies but allows low-frequency signals to pass through. Beneath this layer is the low-frequency “woofer”: A glass-fiber honeycomb core, treated from front to back with a steadily increasing amount of resistant material. Behind this is a sharp-edged, wedge-section reflective surface*. That brings us to…

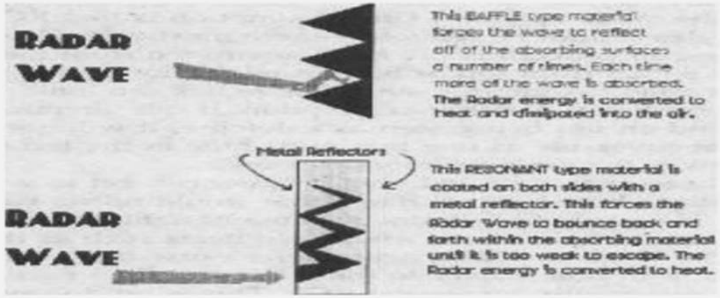
Stealth: Re-entrant triangles

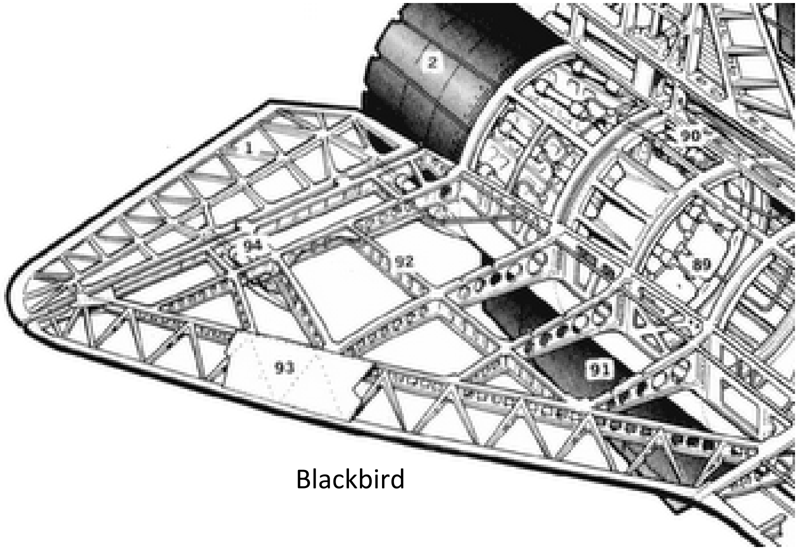
Eurofighter



Absorption of electromagnetic waves:

- Internal construction that must be re-entrant triangles, so that radar waves reflecting off the internal faces and losing energy.
- Incoherent scattering +destructive interference+10dB of attenuation + the pyramid shapes + maximize number of bounces.



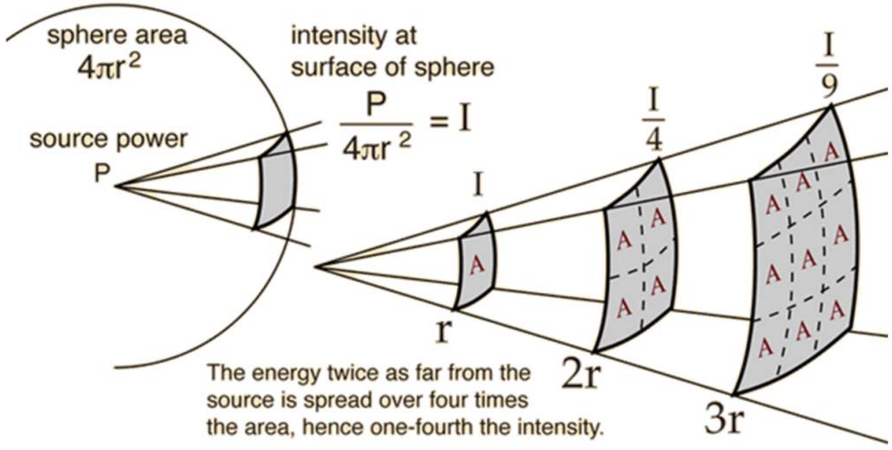


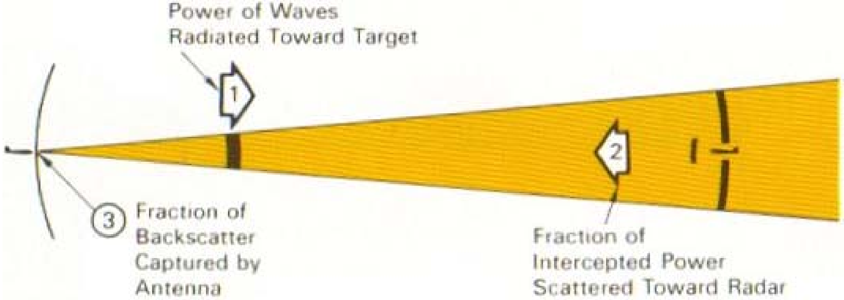
Blackbird

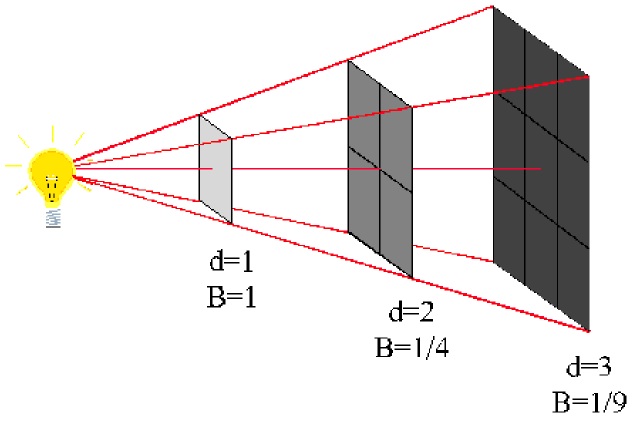
Stealth: Re-entrant triangles

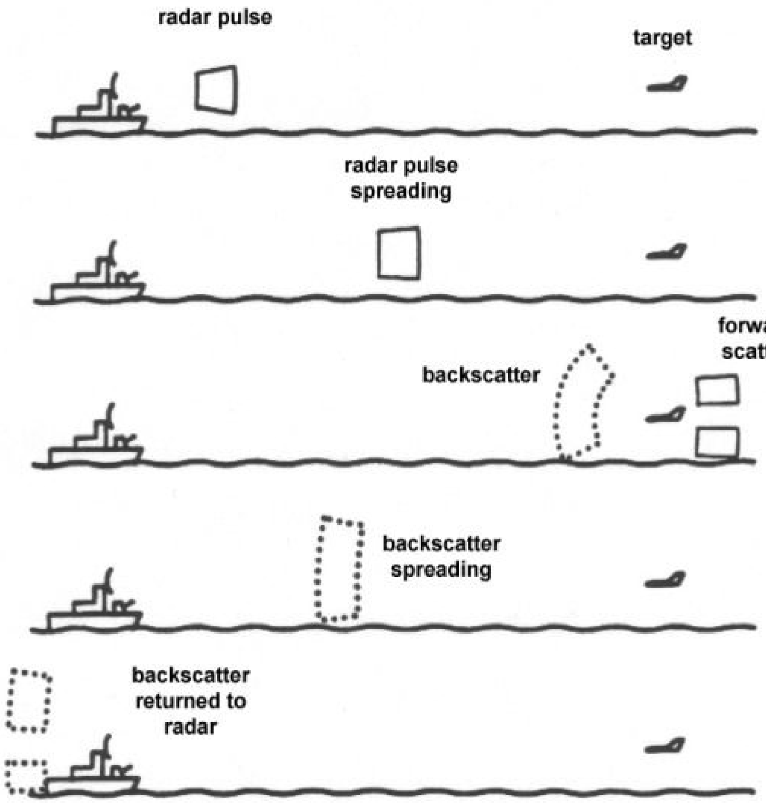
- An “anechoic chamber” is one where echoes are suppressed. This is useful not only for sound-related tests of all kinds (from engine sounds to musical instruments) but also for suppressing electromagnetic echoes so that antennas (from cell phones and bluetooth devices to radars) can be tested.
- The chamber walls absorb waves of all kinds. They do this by being covered in re-entrant triangles, i.e. pyramids. Any wave will flow into the gap between the pyramids and bounce at least twice before coming back out. The sharper the pyramid (i.e. the more vertical the walls of the gap), the more times a wave will bounce before coming out.
- It is said that, under the skin of some stealth airplanes especially around the edges, re-entrant triangles can be found. The only confirmed location is under the chines of the Lockheed Blackbird (e.g. see cut-away of wingtip). It is widely believed that they are also inside the F-117, and possibly inside the B-2.

Stealth: "Inverse 4th Power" Rule





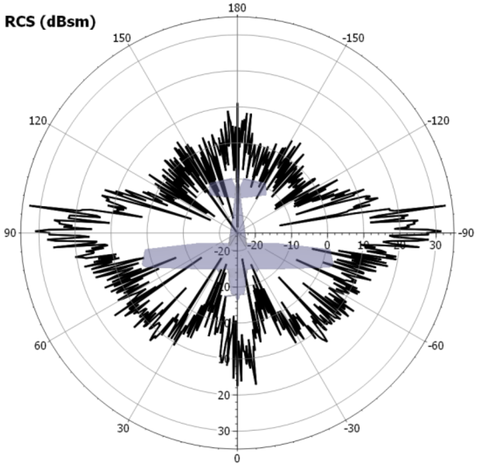


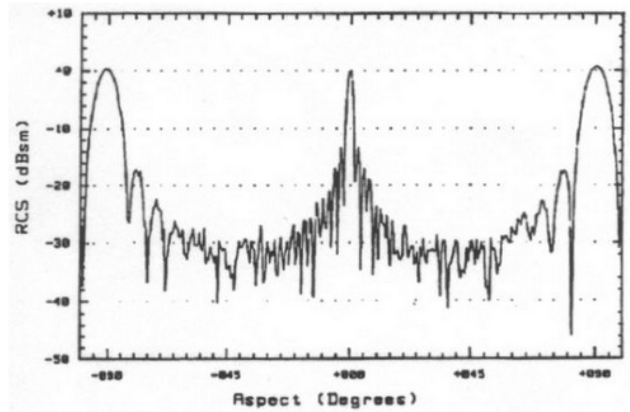


Stealth: “Inverse 4th Power” Rule

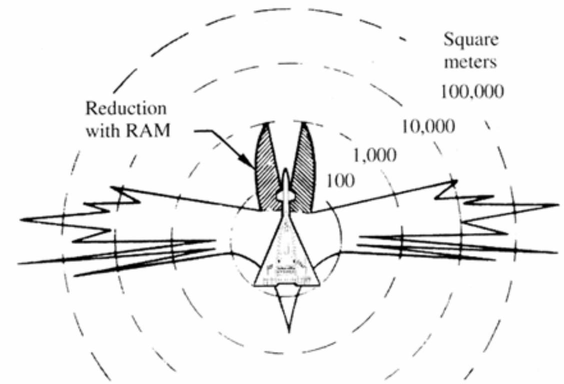
- So far this discussion has been kept free of any math. But just before we wrap it up, let’s quantify it just a little bit. First, one interesting insight:
- Imagine an expanding spherical shell of energy. It starts out as a small point, grows into a ping-pong ball, then a basketball, then a beach ball… then it is several feet wide, 100 feet, a mile, many miles… But the total amount of energy in the sphere stays the same. So the expanding spherical shell gets thinner and thinner, each square foot contains less and less energy (i.e. a smaller fraction of the total).
- The ***inverse-square law*** says that any energy that propagates outwards in 3D becomes less intense with the square of the distance from the source. This is true for light, sound, gravity, etc. And you can see why. If you imagine this growing sphere (or a square segment of the spherical shell surface) starting at some radius from the source and some size: Once you get twice as far away from the source, the sphere has four times the surface area, i.e. your energy became less intense (per area) by a factor of 4. Once you get three times as far away from the source, the same energy is spread out over nine times as much area. And so on.
- But with radar, it’s even worse. If an airplane is twice as far away, it gets illuminated with ¼ as much energy, its reflection only has ¼ as much intensity… But the receiver is twice as far away from it and only receives ¼ as much of the reflected energy as it did when the airplane was closer. In other words, when the airplane gets twice as far away, its detectable radar reflection is only 1/16th as intense. This is an ***inverse power of four***.
- Alternately, if an airplane halves the distance between itself and a radar, then the radar will see 16 times as much energy being reflected from the airplane.
- **Stealth is not “invisibility”. It just means the radar reflection of the airplane is less intense, so any given radar can only detect it from a closer distance. A radar that can pick up a normal airplane 100 miles away might only be able to detect a stealth airplane a couple miles away (too late!).**
- In order to reduce your detectability range by a factor of 10 (i.e. in order to take a radar that could normally see you from 80 miles away and make your reflection less intense so that this radar can now only see you from 8 miles away), you need to reduce the intensity of your radar reflectivity by a factor of 10,000. ***Ten thousand***.
- This is one reason why stealth technology took so long to come along. Radar was being used to detect airplanes during World War 2, but as soon as someone had the idea of making an airplane that reflects less radar, they were discouraged by this inverse power of four. Maybe they could reduce the radar reflectivity of their arplane to 50% of a normal airplane, maybe 20%, maybe 10%... But that would hardly change the detectability range. (Reduce the reflectivity by 50% and your detectable distance to a radar only goes down by 16%, because (0.50)^(1/4)=0.84). The thought of somehow reducing an airplane’s radar reflectivity to less than 0.01% was daunting.

Stealth: Radar Cross Section





Radar cross section of a cylinder



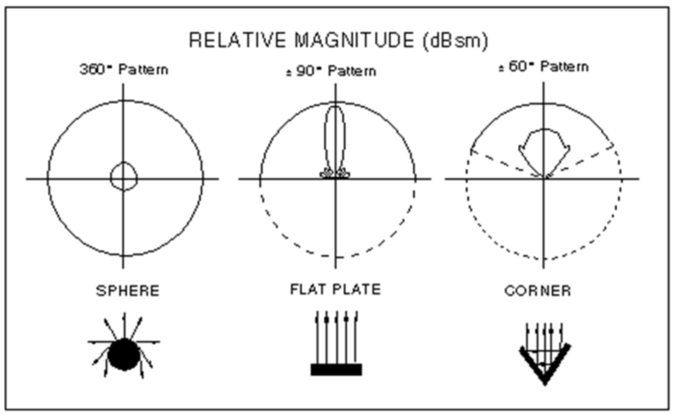
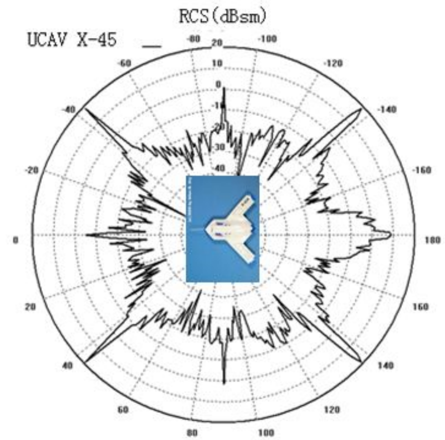
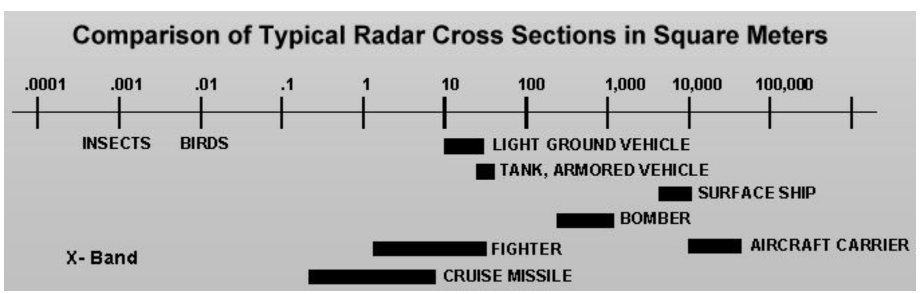
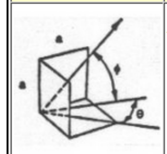
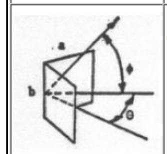
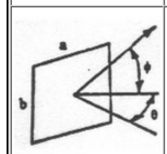
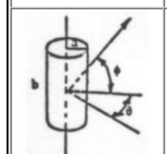
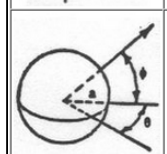


Figure 4. RCS Patterns



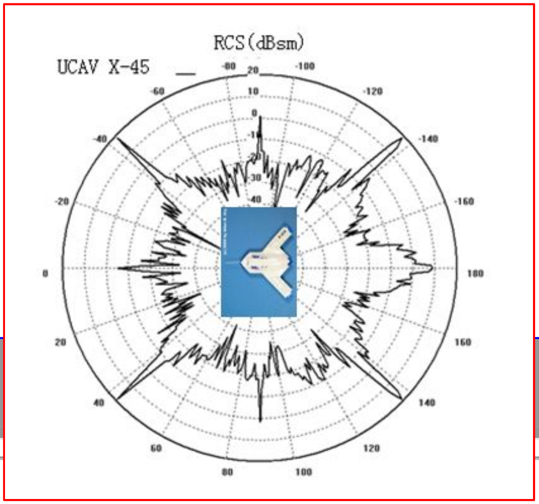


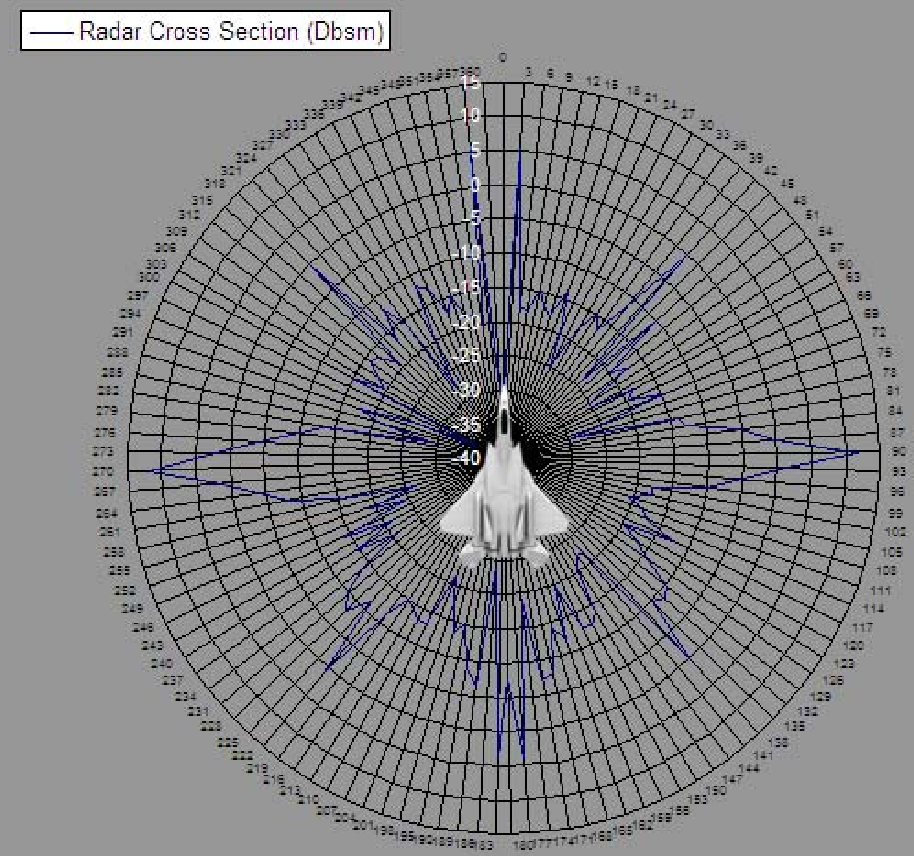
Geometry	Description	Maximum RCS	Comments
	Square trihedral corner reflector	$\sigma = \frac{12\pi a^4}{\lambda^2}$	Strongest radar return due to triple reflection of incident wave
	Right dihedral corner reflector	$\sigma = \frac{8\pi a^2 b^2}{\lambda^2}$	Second strongest radar return due to double reflection of incident wave; decreases from maximum slowly with changing θ and rapidly with changing φ
	Flat plate	$\sigma = \frac{4\pi a^2 b^2}{\lambda^2}$	Third strongest radar return due to direct reflection of incident wave; decreases rapidly as incidence angle changes from perpendicular
	Right circular cylinder	$\sigma = \frac{2\pi a b^2}{\lambda}$	Strong radar return as aspect (θ) changes, but decreases rapidly as azimuth (φ) changes
	Sphere	$\sigma = \pi a^2$	Produces the same isotropic return in all directions

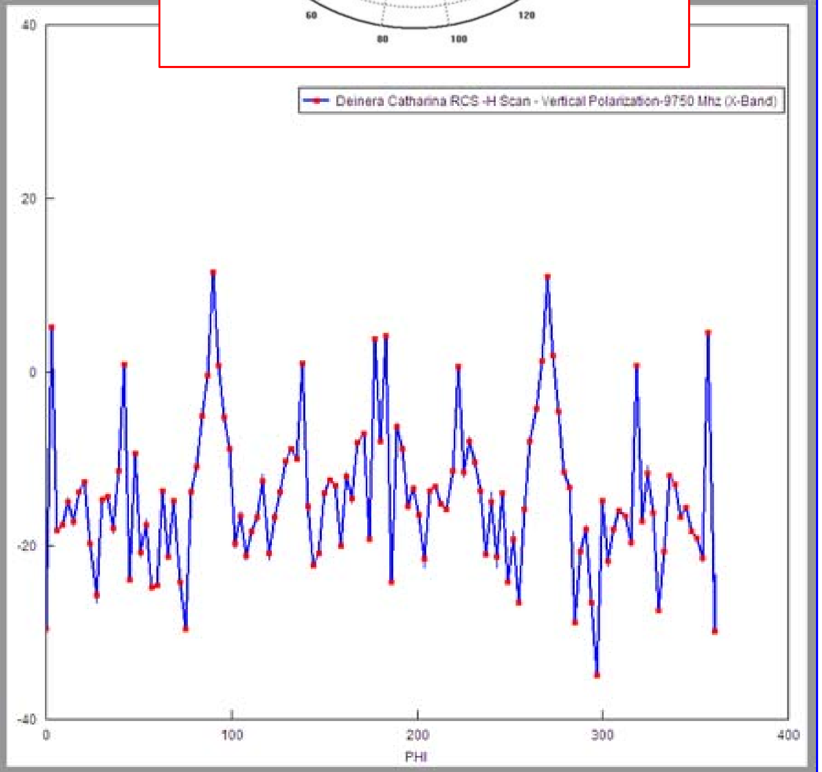
Stealth: Radar Cross Section

- The intensity of an airplane's radar reflectivity is quantified as the airplane's Radar Cross Section, or **RCS**. Stealth is all about reducing the RCS.
- Estimates and numbers vary, and the actual numbers are probably smaller than any publicly available information, but… You will often hear things like "**Head-on, the B-2 has an RCS of 0.1 square meters**". That means that if you take a sheet of metal with an area of about one square foot and hold it so that the flat surface faces a radar antenna, the energy that will be returned to the radar from that one-square-foot sheet is comparable to the energy that would be returned from a B-2, pointing at the radar, from the same distance.
- The RCS depends on what angle the airplane is at, relative to the radar. **You often see RCS shown on a polar plot (circular graph) with the airplane in the middle and a squiggly RCS line going around it. The RCS line is close to the airplane at angles around the circle where the RCS is low (e.g. head-on) and further from the airplane at angles around the circle from where the airplane is more reflective.**
- Most stealth airplanes' circular RCS graphs are generally low, with a handful of huge spikes. Each spike shows the high RCS at one of very few narrow directions that are perpendicular to many features on the airplane. (The YF-23 got its nickname "Black Widow" from its spider-like RCS plot).
- Most airplanes have a relatively high RCS from any angle. However, **just reducing the head-on RCS can be very useful for tactical situations, because the enemy will not be able to "see you coming" as clearly**. This will allow the airplane to attack the radar before the radar can see it. This is why airplanes that are not "all-out" stealth incorporate some stealth features like serpentine intakes and serrated doors (i.e. doors whose front and back edges are not perpendicular to the direction of flight): They want to reduce their head-on RCS. The Super Hornet is a good example.
- **It is possible to calculate the RCS of simple shapes by hand**. A sphere or cylinder or flat plate reflect light in ways that are easy to analyze geometrically, so it is possible to figure out how the intensity of the return compares with the energy that was sent out, i.e. what fraction of the energy returned by a "perfect retroreflector" would be reflected by each shape, as a function of how the surface material scatters light (i.e. how shiny or dull it is) and its basic shape.
- An airplane is just many such simple shapes connected together. Modern stealth technology got its start when Denys Overholser and his mentor Bill Schroeder (an electrical engineer and a mathematician, respectively, at Lockheed), realized that one could write a computer program to do these reflectivity calculation for many simple shapes, and break down an entire airplane into many simple shapes, thus predicting the radar reflectivity of an airplane. Computing power at the time (early 1970s) was only sufficient for doing the calculation on flat shapes, not cylindrical or spherical surfaces. The engineers then realized that flat shapes made the airplane harder to detect from more directions than curved surfaces would. Long story short ("Hopeless Diamond" and Have Blue), Lockheed used this technology to develop the F-117.

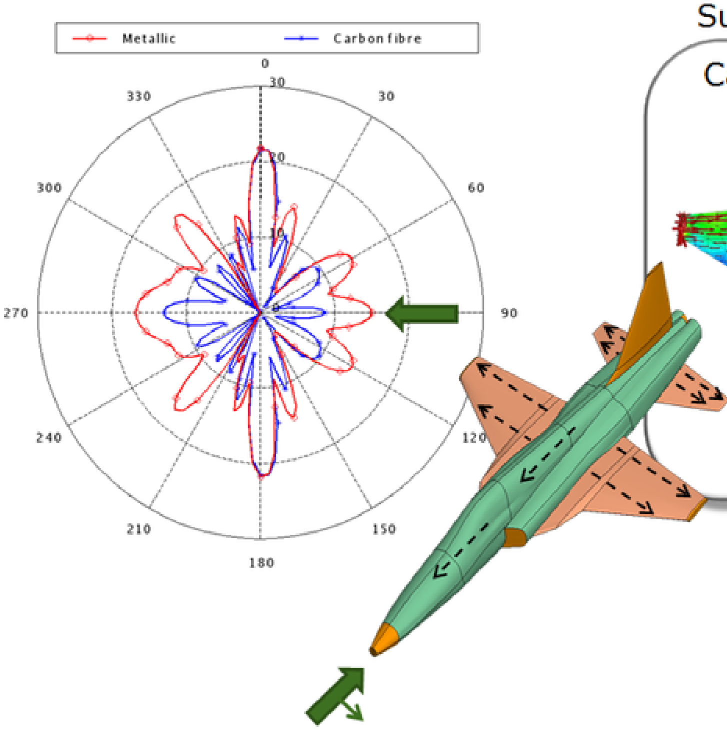
Stealth: Radar Cross Section

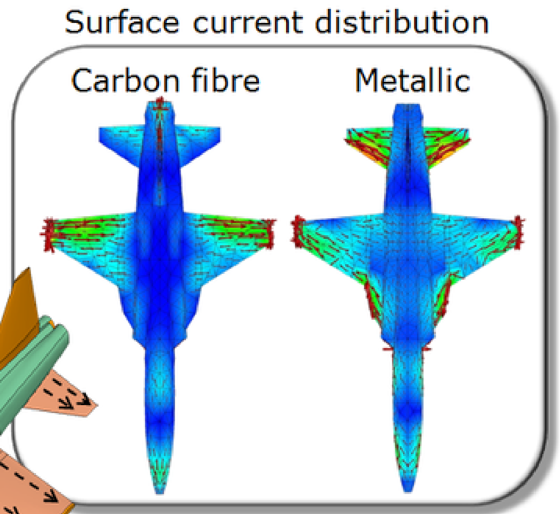


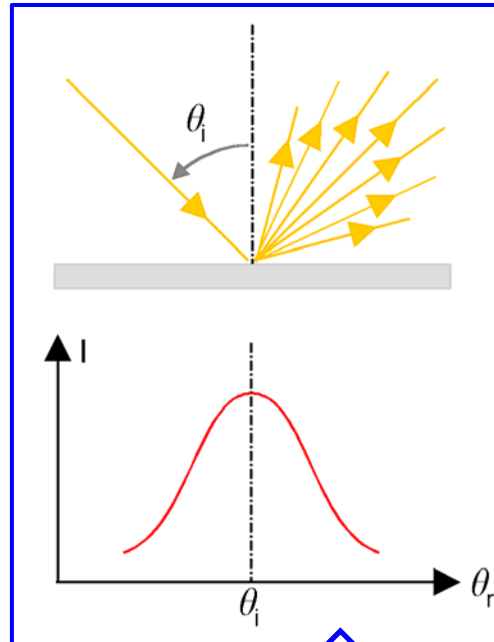




Stealth: Radar Cross Section

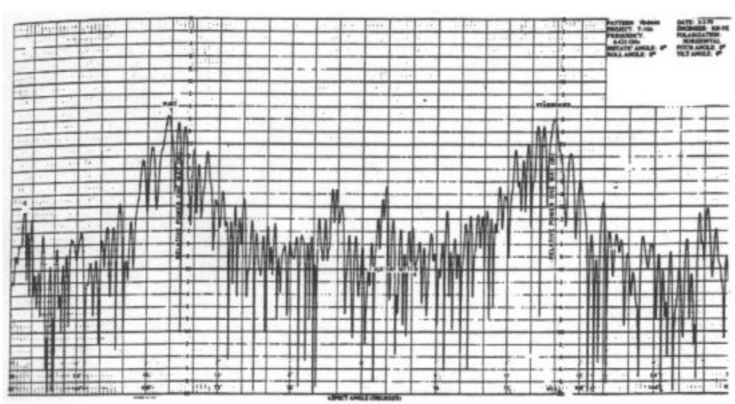




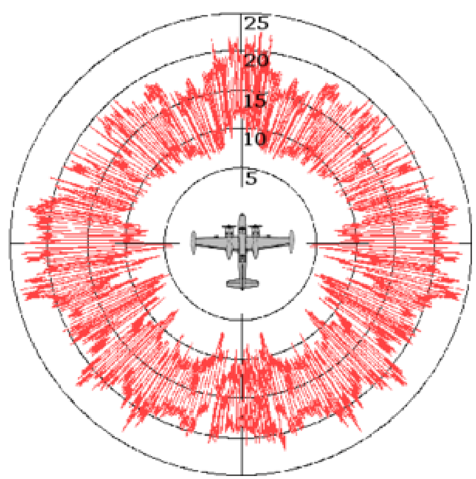


Note: The electrical (induction) properties of the surface material play a big role in RCS.

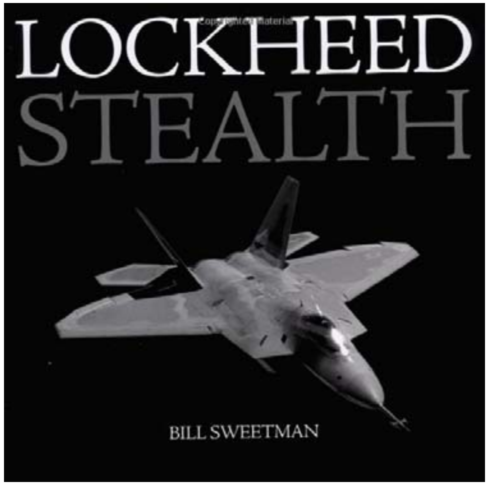
Note: In practice, surfaces are not perfectly shiny, i.e. light does not reflect only at one angle. Some light scatters to the sides of the "main" angle. This means that some radar is reflected back to the antenna even if the airplane surface is not perpendicular to it. This distribution of intensity over angles can be determined for each airplane material and for each kind of radar.

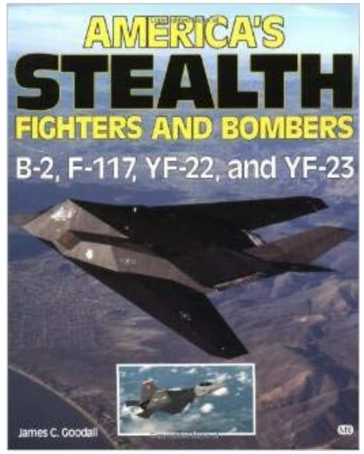


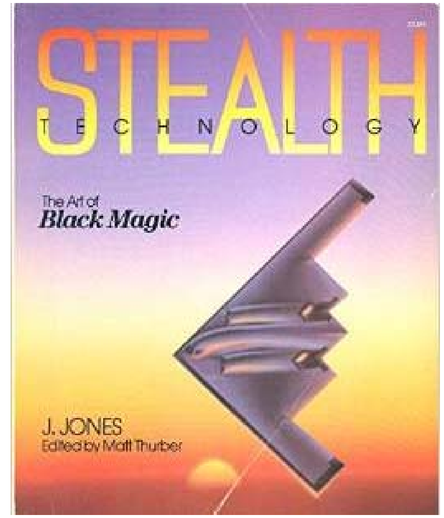
T-33 radar cross section

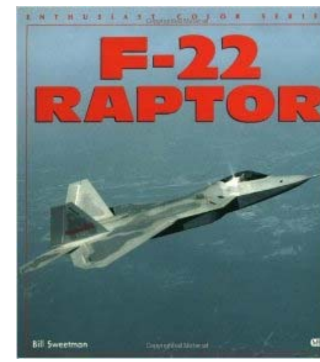


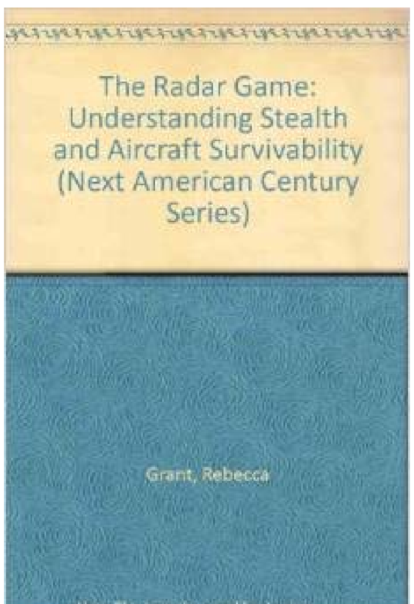
For more info on stealth…

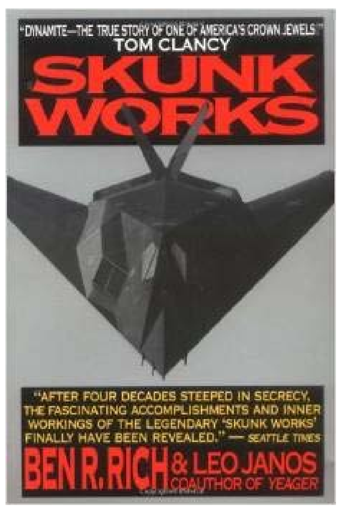


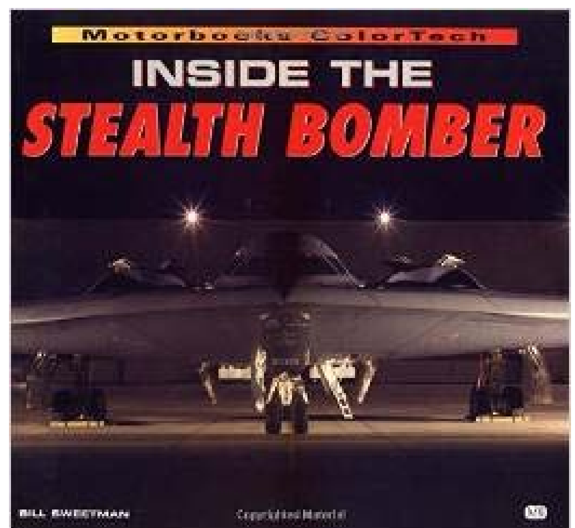


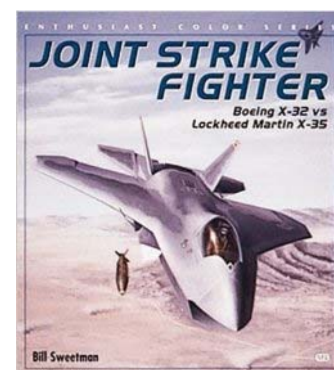












For more info on stealth…

No shortage of great books out there that explain these principles and go over the stories about how they were discovered and applied to aircraft development.

In order of technical complexity…

- Bill Sweetman's books are probably the most readable and fun.
  Lots of great pictures, stories, and layman-level explanations.
- Rebecca Grant's "The Radar Game" is terrific. The first half is a pre-history of stealth (e.g. radar in WW2). The second half covers all the principles in detail, as well as mission planning and tactics which depend on what kinds of radar and defenses the enemy has. It also goes over the details of F-117 missions in Desert Storm, and future scenarios where different aircraft have different kinds of RCS signatures:
  www.tinyurl.com/TheRadarGame
- Many technical books and websites and papers cover the equations used to compute the radar reflection intensity of different shapes. A simple Google search for ***radar reflection equation sphere cylinder plate RCS*** will return various lecture slides and academic papers with detailed descriptions of the mathematical models used to predict and describe the radar reflections of various shapes as a function of the angle from which the radar is shining:
  google.com/search?q=radar+reflection+equation+sphere+cylinder+plate+RCS

About **Bernardo Malfitano**:

Bernardo currently works in the Airplane Configuration group within the Product Development organization of Boeing Commercial Airplanes. He performs analyses, studies, and sometimes tests, around proposed features and configurations for future airplanes. This determines the optimal shapes, materials, locations, and manufacturing processes for new airplane parts, so as to minimize drag, weight, cost, and risk.

For the previous 10+ years, Bernardo worked as a structures engineer / researcher, specializing in fatigue testing, analysis models, and maintenance planning. Bernardo was one of Boeing's experts on "airplane aging" issues, and taught new Boeing engineers how to do fatigue analysis and to plan airplane maintenance.

Bernardo earned his BS from Stanford University and his MS from Columbia University, both in Mechanical Engineering. Most of his academic career leaned towards aerodynamics and propulsion: i.e. many hours designing and running experiments in the wind tunnel and in the engines lab. He has also helped to design, implement, and test control/autopilot systems in UAVs and spacecraft.

In his spare time, Bernardo enjoys flying single-engine airplanes, especially his aerobatic RV-6. During summer weekends, he works as a journalist, covering airshows for aviation magazines and websites. He has flown himself to airshows as far away as Oshkosh. He has also built and flown models ranging from gliders and quadcopters to rockets and flying wings.