Stealth
Radar stealth

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This article discusses the technology of radar stealth, but not the (classified) specifics.

Mainly, the term *stealth* is used with respect to radar stealth. Other terms include *low observables (LO), very low observables (VLO),* and (much more loosely and less commonly) *invisibility* or *cloaking.*

The basics—shaping and materials

Radars of course transmit beams of electromagnetic radiation and detect the small portion of the electromagnetic energy that is reflected from the target and radiated back to the radar. How can this reflection be prevented? The simple answer is that it can't, not altogether. But it can be weakened to an extent that seriously degrades radar performance.

We're all familiar with another form of electromagnetic radiation—light. The only difference that really matters between the radar radiation and light is in the size of the alternating waves of energy, their *wavelength.* Light has a wavelength that is roughly 0.5 micrometer (a millionth of a meter—µm is the international standard abbreviation, to avoid confusion with millimeter) while the U.S. naval *Aegis* SPY-1 radar (to take one prominent example) operates at a wavelength of about 10cm—about 200,000 times as long. So looking at a ship or aircraft with radar is like looking at something very small with light. If we shrank a Boeing 747 down by a factor of 1:200,000, for instance, it would come out about 0.35mm long—about 1/70".

With this difference in scale in mind, we can apply what we know about light to understand radar and stealth better. Suppose we were in a darkened chamber (one with perfectly absorbent walls) using a powerful laser flashlight to illuminate at a tiny scale model airplane which we look at through a very sensitive TV camera with a powerful lens. Of course we would need somehow to filter out the glow from the laser beam itself. (Radars do this by shutting down the transmission before the reflection arrives, or by other tricks, of course.)

Painting the model airplane dead black would cut its reflection, of course. But if we up the brightness of the laser by a factor of ten or so, we'll overcome the effects of paint. Or we could get the same effect by cutting the range by 44%—that's enough to make up for a 10:1 shortfall in radar power. Of course, anti-radar coatings really are better at cutting radar reflection than paint is at killing light reflections. If the coating could cut the amount of energy coming back by a factor of 100 then it take a laser 100 times as bright to ensure that we could see the tiny airplane. Or if we didn't have a brighter laser we would have to move into a distance of 32% of the initial range to get the same return.

Cutting the range of radars by nearly 70% is impressive, but not enough to qualify as much stealth for most operational purposes. Rather than relying entirely on anti-reflective coatings, stealth designers combine them with shapes that make the targets hard for radars to see. We don't usually think of the shape of an object—as opposed to its size—as having a great effect on its visibility. But that's because we are used to looking at things whose surfaces are rough compared to a wavelength of light and so scatter light diffusely. Stealth is done with mirrors—surfaces that are mirror-like.

Suppose we replace our tiny model 747 with a tiny square plate of silver, highly polished and perfectly flat. If we set this up in the chamber so that its surface is at right angles to the line of the laser beam, it will give a very bright flash, visible from a distance. But suppose we tilt it back by 30 degrees. Now most of the laser beam will reflect from the highly polished surface at an angle and be deflected upwards. That is, most of the energy we direct at the tiny mirror will not come back to us to be seen.

This loss of energy isn't absolute, of course. For one thing, even with the plate tilted back we'll get a pretty bright flash from its edge, much as if we shone the laser on a fine wire strung perpendicular to its beam. Actually, we'll see not only the bottom edge but the top one as well. Simply tilting the plate back won't cut the range of visibility greatly.

But now let's skew it so that no edge is close to lying at right angles to the laser beam. Now the edges also will be reflecting the beam away from us, so we won't be able to see them. All we will see will be the points at which the edges intersect.

Of course, this isn't really the whole story. There will still be a bit of light scattered back at us from the polished surface and edges, even though they are at an angle to our line of sight. (This effect is more pronounced when the target is not hugely bigger than the wavelength of light (or radar) that illuminates it.) We may have to increase the power of the laser by 1,000 or even more in order to see these faint reflections. And if we also paint our mirror with absorbing coatings then we can imagine cutting reflection by a further factor of 100 perhaps, for a total reduction in the brightness of the reflection by 100,000:1. If we don't increase the laser's brightness to compensate then we can expect the range at which the plate will be visible to fall off by 94%.

The first thing most people think of in connection with stealth is radar transparent materials, radar absorbing materials, and anti-radar coatings. That's what all the early stealth experimenters thought about too, and it slowed progress a lot. As we've seen, shape is a very powerful tool for stealth. A good stealthy airplane design will have all its edges—whether of its wings or the access panels in its skin—lined up in the same direction so that edge reflections can be seen only from a few very narrow and specific angles. All the surfaces of its skin will be set at angles which tilt them well away from enemy radar beams. Its engine inlet ducting will be arranged to prevent a radar beam from seeing the front of the engine. These and many other tricks of shaping can do a great deal to reduce radar reflections from an airplane or (with suitable modifications in technique) from a ship or ground vehicle.

But shaping is not enough to achieve what people call "true" stealth. For that, we do need materials and coatings to further reduce radar reflections.

When a beam of electromagnetic radiation strikes a material object, it gives up its energy to the electrons in the material and sets them in motion in synchrony with the beat of the electromagnetic waves. If the body is made of metal, with a great many free electrons, the part of the electromagnetic beam that hits the metal will lose all of its energy. But even materials that we don't think of as conductors of electricity—wood, plastics, etc.—will convert a portion of the energy to the flow of electrons. They don't reflect as brightly as metal, but the difference is not great enough to count for much.

These moving electrons within the body of the target are the source of its radar signature. Whenever an electron lying near the surface accelerates—changes the velocity or direction of its motion—it emits electromagnetic radiation. The various stealth coatings and materials work to interfere with the processes of setting the electrons in motion and their re-radiation as a result of accelerations. There are several ways in which they do this which we won't go into here. The terms *radar absorbent materials (RAM)* and *radar absorbent structures (RAS)* are used cover all of them.

Ratio, *r*		Decibel level (dB)
in fractions	in decimals	
1,000,000	1,000,000	60
100,000	100,000	50
10,000	10,000	40
1,000	1,000	30
500	500	27.0
100	100	20
50	50	17.0
10	10	10
9	9	9.5
8	8	9.0
7	7	8.5
6	6	7.8
5	5	7.0
4	4	6.0
3	3	4.8
2	2	3.0
1	1	0
3/4	0.75	-1.2
1/2	0.5	-3.0
1/3	0.333	-4.8
1/4	0.25	-6.0
1/10	0.1	-10
1/20	0.05	-13.0
1/100	0.01	-20
1/1,000	0.001	-30
1/10,000	0.0001	-40
1/100,000	0.00001	-50
1/1,000,000	0.000001	-60
1/8	0	-8

RCS, dB and range

The strength with which a radar target returns energy to the radar is denoted by its *radar cross section*, abbreviated RCS or sometimes by the Greek letter σ (sigma). It's also called *backscattering cross section*.

The RCS is expressed in units of area, usually square meters (m^2), but this does not mean that it is related to the physical area of the target. The actual RCS of the target depends crucially on its shape and properties, as we've outlined above. If the target has an inside corner, like two mirrors coming together, its RCS can be much larger than its physical area. On the other hand, with the right shaping and coatings, its RCS can be a great deal smaller.

There's another way of expressing RCS, in *dBsm*. The *dB* here is for decibels, while the *sm* refers to square meters. It's a mathematical trick that is convenient in dealing with very large or small numbers. If *r* is a ratio between two measurements of electrical power then its decibel level is given by the formula $10 \cdot \log_{10}(r)$. But it's not necessary to do logarithms in order to make sense of decibels. At left is a table of some values of *r* and their decibel values.

From the table we can see that in rough terms the dB level is simply ten times the number of decimal places in *r*, with a negative dB level for ratios where the decimal is to the left (i.e., a fractional *r*).

The dBsm level is just dB where *r* is a ratio of RCS values and the denominator of *r* is one square meter. That is, 0 dBsm is the level of $1m^2$, 10 dBsm is $10m^2$, 20 dBsm is $100m^2$, etc. Sometimes people talk of *dB below a square meter*—10dB below a square meter is the same as –10dBsm, 20dB below equals –20dBsm, etc.

For a given radar in a given set of conditions, the smaller the RCS the shorter the range at which the target can be detected. In general, the range is proportional to the fourth root of RCS. In symbols, $Range = k \times \sqrt[4]{RCS}$, where *k* is a constant that depends on the radar and the situation. Thus if target A has an RCS that is 10,000 times as great as that of target B, a radar should be able to detect A at a range that is 10 times as great as that for B, since $\sqrt[4]{10{,}000} = 10$. By the same logic, if C has an RCS that is 16 times as great as that for D then the ratio of detection ranges should be 2, since $\sqrt[4]{16} = 2$.

In reality, the RCS of targets is not a single number. For one thing, it varies greatly with the angle at which the target is being viewed, both in azimuth and elevation. At one angle the radar may see a highlight that makes the target very "bright" and easily detectable. A few degrees to the right or down the highlight may be obscured by other features, making the target much less visible. In fact, the RCS of non-stealthy airplanes commonly fluctuates by a factor of 100 (i.e., 20dB) or more every few degrees. This usually makes little practical difference since the angle from which the radar views the aircraft changes constantly, thus averaging out these fluctuations. There are also broader peaks of 10dB or more, usually when viewing the aircraft from dead ahead or from the sides.

Keeping this variability in mind, we can list rough average RCS for a variety of non-stealthy targets of interest:

Target	RCS (m^2)	RCS (dBsm)	Relative range
Aircraft carrier	100,000	50	1778
Cruiser	10,000	40	1000
Large airliner or automobile	100	20	316
Medium airliner or bomber	40	16.0	251
Large fighter	6	7.8	157
Small fighter	2	3.0	119
Man	1	0	100
Conventional cruise missile	0.5	-3.0	84
Large bird	0.05	-13.0	47
Large insect	0.001	-30	18
Small bird	0.00001	-50	6
Small insect	0.000001	-60	3

Note that the family car has an RCS that is comparable to that of a Boeing 747, and a standing man is only half as large, in radar terms, as a non-stealthy fighter aircraft. This illustrates the importance of shape, even when shaping is not influenced by RCS considerations.

It might seem surprising that radars can detect birds and even insects, but in fact they do. Ordinarily, radar designers try to suppress the returns from birds and insects in order to keep the display uncluttered. If the RCS of a target can be reduced to that of an insect, the problems are obvious. The radar's problem is slightly eased because insects do not fly at Mach 0.9 at 25,000 feet, however.

Effects of wavelength

The RCS values in this table really represent typical results for the so-called *microwave* radar wavelengths, ranging from about 2 cm to about 20 cm. At both shorter and longer wavelengths the picture can change a great deal.

The following table shows the range of wavelengths (and corresponding frequencies) generally used by radars. Frequency is inversely related to wavelength—since all radar waves travel at the same velocity (the same as that of light, 299,792,458 meters/second), the shorter the waves, the more of them pass by each second. In fact, frequency = (299,792,458 meters/second)/wavelength. Frequency is expressed in units of Hertz, meaning one wave cycle per second. Gigahertz (GHz) means one billion Hertz, megahertz (MHz) means one million Hertz, etc. (For most purposes, the speed of light may be taken as 300 million meters/second = $3 \cdot 10^8$ m/s.)

Band	Maximum frequency	Typical center frequency	Corresponding wavelength	Typical applications
mm	300 GHz	100 GHz	3 mm	Fuzes, very short range imaging radars
K_a	40 GHz	35 GHz	8.6 mm	Fuzes, very short range seekers
K	27 GHz	24 GHz	12.5 mm	(Little used due to strong attenuation)
K_u	18 GHz	16 GHz	18.7 mm	Short range seekers, navigation
X	12 GHz	9.5 GHz	3.2 cm	Airborne intercept, seekers, navigation
C	8 GHz	5.5 GHz	5.5 cm	Ground & shipboard fire control
S	4 GHz	3 GHz	10 cm	Multifunction, AEW
L	2 GHz	1.3 GHz	23 cm	Air surveillance, AEW
UHF	1 GHz	450 MHz	67 cm	Air surveillance, AEW
VHF	300 MHz	225 MHz	1.3 m	Long-range air surveillance
HF	30 MHz	10 MHz	3 m	Over the horizon surveillance

Even at a wavelength of 3 centimeters the typical aircraft looks as if its surfaces are highly polished. This is because the imperfections in its surfaces are quite small compared to the wavelength, so that the radar beam averages out the small nicks and bumps. So in terms of light we can think of the target as very small but perfectly reflective. At very high frequencies—the three K bands and the mm band—the wavelengths of the radar grow short enough that surface details start to become important. Unless the surfaces are made especially smooth, the RCS tends to approach the physical area of the target regardless of shaping. RAM can help at these frequencies, but it must be tailored to the demands of the short wavelengths, which impose some added complications.

At lower frequencies, we encounter the opposite problem—the shaping we rely on to cut RCS in the microwave region becomes more and more indistinct as the wavelength starts to approach the dimensions of the target. (For reference, the length of an F/A-18C is about 17 meters.) It's like the case of light and dust particles—the complexities of the particle's shape make no difference because its size is close to a wavelength of light. Like dust particles dancing in a shaft of sunlight, when viewed at low frequencies targets tend to scatter radar energy in all directions regardless of shape.

Low frequencies are a problem also for RAM and RAS. The effect of radar absorbers is affected by their thickness relative to the wavelength—one quarter of the wavelength is best. As the wavelength reaches a foot or more, radar absorbers become impractical for most targets.

The net effect is that at very low frequencies, the RCS of normal stealthy targets tends to approach that of non-stealthy targets of similar physical size—close to the physical area of the target. This is called *resonant scattering* because the wave is in resonance with the target, leading to scattering of radiation in a broad fan. If the radar's wavelength is actually large relative to the target (as can happen with very small UAVs illuminated by the lowest frequency radars) it is found that RCS drops off sharply as wavelength increases further. This is the case of *Rayleigh scattering*.

Active cancellation

There is one other possibility for reducing RCS as we approach the situation of resonant scattering—active cancellation. (In theory there is also a method of passive cancellation, but it's not of much practical use.) Active cancellation works by actually transmitting a radar beam from the target that is intended to cancel out the reflected signal. We can understand how this is possible if we remember that the electromagnetic beam of the reflected signal is actually a force that acts on the electrons of the radar's antenna—it's the motion of those electrons that the radar actually senses. So if we can transmit a beam that sets up an exactly equal and opposite force then there is no net force on the antenna's electrons and no signal for the radar to sense. This can be done of the canceling signal is exactly like the radar reflection in every respect except for being *180º out of phase*—that is, it must lag the reflection by exactly half a wavelength.

To make active cancellation work, the target has to know exactly what its radar return will be, in detail, for every frequency and angle. And it must have the equipment to transmit a highly accurate out-of-phase replica. This is pretty demanding, and it becomes more so as the wavelength becomes shorter. That is, unlike shaping and RAM/RAS, active cancellation is more effective at low frequencies and less so at high.

Designing for stealth

Like other forms of engineering, stealth design depends on physics and experience. But experience-based and physics-based logic and rules of thumb are not sufficient to get very far in designing genuinely stealthy aircraft or ships. Stealth engineers need very highly sophisticated computational models and a great deal of measured data for input to them. These allow them to simulate in the computer the RCS signatures of the designs they envision and recognize where changes are needed. The computations require extremely powerful computers and demand great expertise on the part of those who make the inputs and interpret the results. One reason that the F-117A Nighthawk stealth fighter's shape is composed of flat diamonds is because at that time the computational models were adequate only for flat-plate shapes.

The data for the computations need to be obtained from *radar ranges*. At a range, a highly-precise and calibrated radar illuminates a test target and records data on its RCS. The stealth designer needs data on all the different components and materials that may be used in the design, recorded at all angles and frequencies. Both outdoor (*far-field*) and indoor (*near-field*) ranges are used; each has its strengths and limitations and both are generally needed. One of the easiest ways to gauge how seriously a firm is pursuing stealth is to look at its ranges (which are too big to hide): if it lacks first-class range facilities, it is unlikely to get first-class results.

Maintaining stealth

When glass cutters want to make a mirror sparkle, they cut bevels and grooves in it. To avoid having their equipment "sparkle" in the radar beam, those who maintain stealthy vehicles need to avoid any nicks or gouges. In early stealthy aircraft, every time a maintenance access was opened and re-closed, its edges needed to be carefully re-sealed to avoid increasing RCS. And any ding on a wing edge needed to be carefully repaired, even if quite small. These problems are being eased with improved materials and designs.

For very stealthy aircraft and other vehicles, surface cleanliness also is important. If your airplane has the RCS of an insect, bug spatter on its surfaces can affect signature quite significantly.

For similar reasons, it is necessary to avoid hanging things on the outside of stealthy aircraft. Even if a bomb or pod is itself treated to be very stealthy, interference between it and the aircraft will usually result in compromise of stealth overall. Early stealthy aircraft had no provisions for external stores at all. Newer designs, like the JSF, incorporate stores stations for greater mission flexibility, but will not be fully stealthy when carrying external ordnance.