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ANSER

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ABSTRACT

In the last twenty years, radar cross section (RCS) reduction has emerged as an important *and achievable* way to improve the survivability of military aircraft. Specifically, the first manned aircraft to achieve a tactically significant reduction in RCS was the Lockheed Have Blue technology demonstrator, which was designed starting in 1975 and first flew in 1977. This was followed by a true military aircraft, the F-117A, which became operational in 1983. Several very low observable (VLO) aircraft have been designed since then. All of them benefit from significant advances in the ability to predict and improve the RCS of an aircraft in its early design stages. The present paper describes these advances and their impact on aircraft design, using examples of reduced RCS aircraft designed before and after the techniques were evolved.

INTRODUCTION

The importance of RCS reduction has been recognized since before World War II. The earliest attempts at RCS reduction consisted of little more than the application of radar absorbent materials to all or part of a vehicle. These efforts, more fully described in reference 11, met with little or no success. By the late 1950s, it was beginning to be realized that a very low RCS would not be achieved through "parasite treatments" alone (paints, coatings and other additions to existing aircraft) but would have to be "designed in" from the beginning. In order to accomplish this, designers needed a way to evaluate the effect of various design features on the RCS of the vehicle during the design process. This can be accomplished either by analysis or by the testing of models.

Having, in general, little knowledge of electromagnetic theory, designers first turned to experimental techniques. The first RCS measurement ranges were built in the late 1950s, and RCS model testing was used in the design of certain aircraft, including the Lockheed A-12 (the CIA-funded predecessor to the better-known SR-71). RCS values were reduced, but not to the extent necessary to permit an aircraft to avoid detection. Although designers could test, and make trial-and-error modifications, there was little in the way of theoretical knowledge or experience to guide their attempts at RCS reduction. It was becoming recognized that analytical prediction techniques capable of providing practical insight for realistic aircraft shapes were needed, to complement the use of testing.

The fundamental laws which govern the propogation and scattering of electromagnetic waves were formulated by James Maxwell more than 100 years ago. However, exact mathematical solutions to Maxwell's equations are very few and are limited to simple shapes such as a sphere, an ellipsoid, an infinite wedge, and a few others. For readers who are familiar with aerodynamics, the number of exact solutions to Maxwell's equations is roughly analagous to the number of exact solutions to the Navier-Stokes equations. Thus, in order to predict the radar return from an object of arbitrary shape (such as an aircraft) one must resort to approximate techniques which capture the dominant scattering mechanisms under certain sets of simplifying assumptions. Considerable effort has been devoted to the development of such techniques, particularly since the 1960's. The present paper describes some of these techniques and their impact on low RCS aircraft design practices.

DEFINITION OF RADAR CROSS SECTION

When an object is illuminated by radar waves, energy is scattered in all directions, with various degrees of intensity. In most cases, referred to as monostatic, the radar receiver is in the same location as the transmitter; so one is interested in the amount of radiation scattered back toward the source. This is called backscatter. The present discussion is confined to this case.

Radar cross section is defined as the ratio of the scattered power density in a given direction (usually the backscatter), to the incident power density, normalized so as to be independent of the distance R at which the scattered power is measured:

$$\sigma = \lim_{R\to\infty} 4\pi R^2 |S_s|/|S_i| \qquad (1)$$

where S_s and S_i denote the energy flux of the scattered and incident radiation, respectively. Because the scattered field is radiated spherically outward from the object, its intensity decays as $1/R^2$; so the power density ratio is multiplied by R^2 to eliminate the dependence on R, giving a result which is a property of the object and not of the measurement distance. The RCS does depend on the frequency of the incident radiation, on the aspect or orientation of the object relative to the incident radiation, and on the polarization of the incident wave (i.e., the orientation of the respective magnetic and electric field components of the incident wave; see Figure 1).

Units of measurement for RCS are square meters. However, because objects of interest (ranging from birds to major geographical features) have radar cross sections which span a range of several orders of magnitude, it is convenient to use decibels. In this form, the common unit of measurement is dBsm, or dicebels relative to a one square meter reference RCS:

$$\sigma_{dBsm} = 10\cdot\log_{10}(\sigma) \qquad (2)$$

The maximum range at which an aircraft can be detected by radar is given by the well-known radar range equation:

$$R_{\max} = \left[P_t G^2 \lambda^2 \sigma / (4\pi)^3 P_{\min}\right]^{1/4} \qquad (3)$$

where P_t is the transmitted power, G is the radar antenna gain, λ is the wavelength, and $P_{\min}$ is the minimum detectable returned signal power. This equation shows that detection range is proportional to the fourth root of the radar cross section. Therefore a very large change in RCS is needed to achieve a tactically significant reduction in detection range. (ref. 10, 17)

ELECTROMAGNETIC SCATTERING

Maxwell's equations in differential form are given below (ref. 12):

$$\nabla\cdot\vec{E} = \rho/\varepsilon_0 \qquad (4)$$

$$\nabla\cdot\vec{B} = 0 \qquad (5)$$

$$\nabla\times\vec{E} = -d\vec{B}/dt \qquad (6)$$

$$\nabla\times\vec{B} = \mu_0\left(\vec{J} + \varepsilon_0\, d\vec{E}/dt\right) \qquad (7)$$

(Nomenclature is defined at the end of this paper.) These equations can be readily manipulated to show that electromagnetic waves exist, and that in a vacuum they propogate at a speed

$$c = 1/\sqrt{\varepsilon_0\mu_0} \cong 3\times 10^8 \text{ m/s} \qquad (8)$$

The waves consist of an electric field component E and a magnetic field component H which are normal to each other and normal to the direction of propogation. Furthermore, the two fields are periodic and in phase with each other, as illustrated in Figure 1 below:

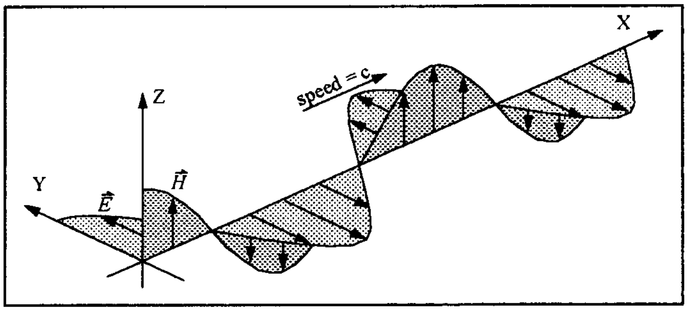


Figure 1: Electromagnetic Waves

Note that in the notation, the magnetic induction B has been replaced by the magnetic field intensity H. In free space these are quite simply related to each other by the relationship:

$$\vec{B} = \mu_0\vec{H} \qquad (9)$$

The total energy flux of the wave is given by the cross product of the electric and magnetic components, also known as the "Poynting Vector" (ref. 12):

$$\vec{S} = \vec{E}\times\vec{H} \qquad (10)$$

The Poynting Vector is always oriented in the direction of propogation of the wave (ref. 12).

If an electromagnetic wave encounters an object, the boundary conditions at the surface of the object determine the distribution of charges and currents induced on the object by the incident radiation. Once these currents and charges are known, the scattered field is determined by performing a surface integral around the object. However, as noted in the Introduction, exact solutions do not exist for practical aircraft shapes, so one must resort to making assumptions which simplify the problem.

SIMPLIFYING ASSUMPTIONS

It is often assumed, as a starting point, that the entire surface of the object in question is a "good conductor," i.e., metallic. The effects of radar absorbent materials and/or disruptions in the conductive surface are considered separately. The next assumption regards the wavelength of the incident radiation relative to the physical size of the object and its important features. Three major scattering regimes exist: low frequency or Rayleigh scattering, in which the wavelength is assumed to be much larger than the object; resonant scattering, in which wavelength is comparable to the size of the object (or important physical features of the object); and high frequency scattering in which the wavelength is assumed to be much smaller than any feature of the object. Furthermore, within each scattering regime, there are various theories which capture different sets of scattering mechanisms. Which theory one uses, depends on which set of mechanisms is expected to be dominant in a particular situation.

LOW FREQUENCY METHODS

If the incident radiation has a wavelength much larger than all characteristic dimensions of the object whose RCS is being calculated, then the phase and amplitude variation of the incident field over the length of the object is negligible, as illustrated in Figure 2 below:

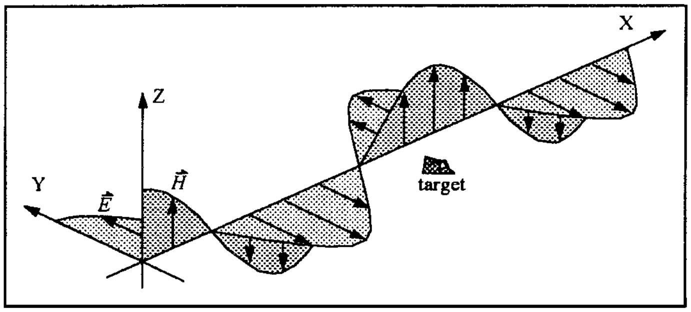


Figure 2: The Low Frequency Case

The field therefore appears as a spatially uniform field which varies only in time; and the variation is slow enough that the charge distribution can be found for some reference value of the incident field strength, as if the incident field were constant in time. This assumption is referred to as a "quasi-steady" assumption and allows the techniques of electrostatics to be used. Mutual influence (i.e., the effect of the charge at one point of the body, on the field at another point) is important, but electrodynamic effects are not, and the problem is relatively tractible. Once the charge distribution is found for some reference value of the incident electric field, the "shape" of the distribution does not change, but the magnitude of the entire distribution oscillates in response to the modulation of the incident field. The dipole and multipole moments of the reference charge distribution can be calculated, and the radiation patterns associated with these oscillating multipoles are well known, so the scattered field is readily determined (ref. 10, 12).

Unfortunately this fairly simple case does not apply to most radar problems of practical interest. The assumptions of low-frequency scattering may be considered fairly accurate if the phase variation of the incident wave over the length of the object is, perhaps, $\pi/8$ radians or less (ref. 10). This corresponds to a maximum size of 1/16 the wavelength. The longest-wave radars are VHF early warning radars, which have a wavelength between one and three meters (ref. 18). So it can be seen that low frequency methods can only be applied to objects with characteristic dimensions of a fraction of a meter, which clearly does not include manned aircraft.

MEDIUM (RESONANT) FREQUENCY METHODS

When the characteristic dimensions of an object are of the same order as the incident wavelength, it is necessary to account for the phase variation of the incident field over the length of the object, and for electrodynamic effects (i.e., the magnetic fields induced by currents on the body, as well as the electric fields induced by the charges). It is also necessary, as in the low frequency case, to account for mutual influence: the charges and currents at every point on the object affect the fields at every other point on the object. The solution procedure is very similar to aerodynamic panel methods. A matrix of mutual influence coefficients is set up between a selected number of points on the surface of the body. The current distribution is expressed in terms of a series. Enforcing the boundary conditions on the surface of the object yields a system of linear equations from which the series coefficients which define the current distribution can be determined. This method is called the Method of Moments (MOM).

For accuracy, it is necessary to space the control points at intervals of around 1/5 wavelength or less. As of 1985, it was considered practical to apply the method to objects up to roughly 10 wavelengths in size (ref. 10). Advances in computational power have undoubtedly increased this upper limit in the last ten years. However, apart from the computational issue, the application of MOM to very large objects (or very small wavelengths) is limited because MOM does not capture the physical phenomena of interest for the high frequency regime. In MOM the influence of each point on every other point is taken into account, but only in reference to the spatial positioning of the two points relative to each other, e.g., the field at point A induced by a given charge and current density at point B.

At very small wavelengths, that kind of interaction becomes largely negligible; however, other kinds of interaction become important, which depend not only on the relative position of two points but *on the nature of the surface of the body between the two points*. Points which are close to each other may have very little influence on each other, while points which seem to be very widely separated, for example at opposite ends or sides of the body, may interact strongly through phenomena such as surface traveling waves or creeping waves.

HIGH FREQUENCY METHODS

Most radar frequencies fall into the high frequency regime when the target is a full sized aircraft. High frequency methods are therefore of particular interest for practical RCS prediction. Many different approaches to high-frequency RCS prediction have been used. The most important ones fall into the categories of Geometric Optics (GO), Physical Optics (PO), Geometric Theory of Diffraction (GTD), Physical Theory of Diffraction (PTD), and more recent developments which have improved upon GTD and/or PTD, specifically the Method of Equivalent Currents (MEC) and the Incremental Length Diffraction Coefficient (ILDC).

GEOMETRIC OPTICS (GO)

The oldest high frequency method is called Geometric Optics (GO), and consists simply of tracing the paths of rays. Thus the need to determine surface currents is bypassed. GO can account for the mechanisms of specular reflection (rays "bouncing" off an object, as in Figure 3) and of refraction (rays being bent at the interfaces of mediums with different optical properties, also shown in Figure 3). GO has been used for a long time in the design of telescope lenses and other optical systems.

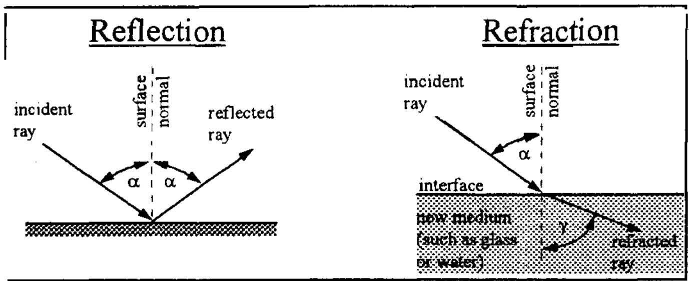


Figure 3: Reflection and Refraction

Geometric Optics is very good for finding the specular reflection from a body, when there is compound curvature at the specular point. However, when one or both principal radii of curvature is infinite at the specular point, GO predicts an infinite value of the radar cross section, which is incorrect (ref. 10).

An advantage of GO is that it can calculate some effects from radar absorbent materials, because it does capture the phenomena of refraction. Rays can be traced through multiple reflections and/or refractions until they finally are scattered away from the vehicle.

PHYSICAL OPTICS (PO)

The next method, Physical Optics (PO), takes the approach of actually finding the surface currents on the body, and performing a surface integral around the body to find the scattered radiation resulting from the surface currents. However, the determination of surface currents is only approximate. Specifically, the current at each point on the body is assumed to be identical to the current in a hypothetical infinite plane at the same orientation as the point of interest. Thus any interactions between different parts of the body are neglected. Nevertheless, PO permits reasonably accurate predictions to be made in certain cases where GO fails. Specifically, PO correctly finds the strength of the specular reflections from surfaces which are flat or which possess curvature in only one direction. These are cases where GO would predict an infinite cross section; because PO determines the scattered field based on an integration of the currents over the surface of the body, PO always yields a finite solution. On the other hand, PO fails whenever a significant part of the currents are different from what they would be in an infinite plane; for example, near edges and corners, or near the boundary of the shadow on a smoothly curved surface (Figure 4) PO hypothesizes the existence of an edge at the shadow boundary, which is incorrect. GO would be a better method in that case.

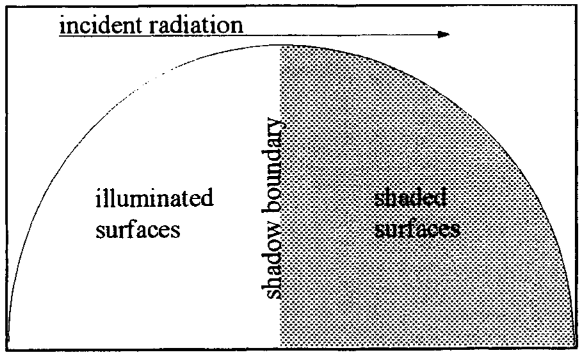


Figure 4: Smooth object with shadow boundary

An example in which this failing may have considerable practical significance is shown in Figure 5. Any time a smooth airfoil is illuminated from the frontal region, there will be a shadow boundary one or both of the upper and lower surfaces.

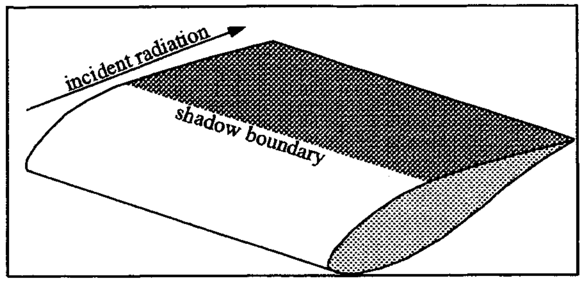


Figure 5: Smooth airfoil illuminated nose-on

Gupta and Burnside in 1987 developed a correction to PO, which allows the erroneous edge contribution at a smooth shadow boundary to be eliminated (ref. 5).

DIFFRACTION

Neither GO nor PO address the mechanism of diffraction. If an object is shaped so as to avoid specular reflections from surfaces, then edge diffraction may be the next most significant scattering mechanism. Diffraction occurs anywhere that the surface slope changes rapidly enough to cause a perturbation from the surface currents that would otherwise exist. A sharp edge is the extreme example of such a situation. Intuitively, one can visualize that if the surface currents are interrupted by a sharp edge, there is no place left for the charges to go except *along* the edge. During the 1950s two diffraction theories evolved in parallel. J.B. Keller developed the Geometric Theory of Diffraction (GTD), and P.I. Ufimtsev in the Soviet Union developed the Physical Theory of Diffraction (PTD). Both of these theories were built upon the exact solution of Maxwell's equations for two-dimensional scattering from an infinite wedge, found by J.A. Sommerfeld in the 1890's. Sommerfeld's two-dimensional solution is schematically illustrated below (ref. 15):

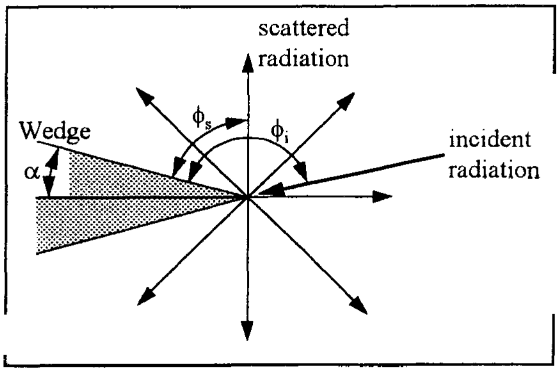
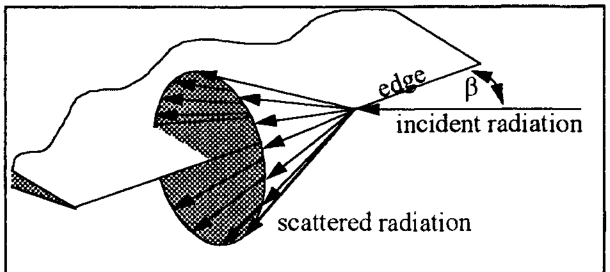


Figure 6: 2-Dimensional Diffraction from a Wedge

Sommerfeld determined the intensity of the scattered radiation as a function of the scattering direction ϕ_s, the incident direction ϕ_i, and the wedge half-angle α. His two-dimensional solution can be applied directly to a three-dimensional problem as long as the incident radiation is perpendicular to the edge, and the edge is long enough for corner effects to be negligible.

GEOMETRIC THEORY OF DIFFRACTION (GTD)

J. B. Keller extended Sommerfeld's results to arbitrary angles of incidence, by stating that the *normal component* of the scattered radiation behaves according to Sommerfeld's solution while the tangential component (i.e., the component along the edge) is unchanged. This provided a solution on a specific locus of points, consisting of a cone whose half-angle is the same as the angle between the incident ray and the object's edge.



3-Dimensional Diffraction - strongest scattering is on a cone whose half-angle is equal to β, the angle formed by the incident radiation and the edge. This cone is referred to as the "Keller Cone."

Figure 7: 3-Dimensional Diffraction by an Edge

Keller devised a series of diffraction coefficients which model the three-dimensional extension of Sommerfeld's exact solution, and form a convenient way to account for edge diffraction (ref. 8, 10).

Like GO, GTD fails in certain cases where an infinite number of the scattered rays are parallel. In the case of edge diffractions, these directions are called *caustics.* Caustics occur when all the points along some section of nonzero length along a curved edge diffract toward the receiver with the same phase. For backscatter, this requires that the section of curved edge be perpendicular to the incident radiation. Caustics may be encountered, for example, when calculating the nose-on radar signature of an aircraft with a sharp axisymmetric inlet lip as in Figure 8 below.

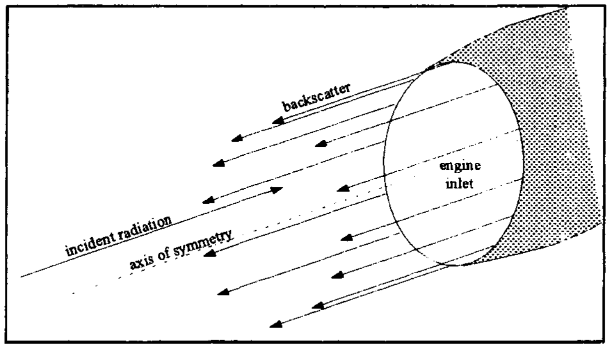


Figure 8: Caustic associated with axisymmetric inlet lip

In these cases, the entire ring of the inlet lip is illuminated, rather than just a single "flare spot" which is often encountered on curved edges. While GTD does not correctly predict the value of the RCS on caustics, one may assume that it is large and that caustics should therefore be avoided on low RCS vehicles.

PHYSICAL THEORY OF DIFFRACTION (PTD)

Ufimtsev devised coefficients analogous to Keller's, which do not model the exact solution, but rather the *difference* between the exact solution and the solution found by Physical Optics. Thus one would first find the scattering using PO, and then apply Ufimtsev's method as a correction. PTD has some advantages relative to GTD, for example that it yields a solution on caustics (ref. 21).

Ufimtsev published the Method of Edge Waves in the Physical Theory of Diffraction, a collection of several of his important results, as an unclassified Soviet technical paper in 1962. The U.S. Air Force Systems Command Foreign Technology Division translated Method of Edge Waves... in September 1971 as part of its technical intelligence exploitation program, and made it available to U.S. military aircraft companies. However, Ufimtsev's work was already known in some research centers, and is referenced in various Northrop reports on radar cross section work performed during the late 1960s and early 1970s (ref. 3, 11, 15). Ufimtsev has also been credited with providing the key to Lockheed's RCS prediction capability for faceted aircraft, thereby enabling Lockheed to design the Have Blue and F-117A aircraft.

Neither PTD nor GTD is valid except on the "Keller Cone." In the context of practical RCS prediction, this means that the methods would only calculate the scattering from those edges, if any, whose diffraction cones contained the observation point. The contributions from all other edges would be neglected.

However, the strongest diffraction is on the Keller Cone, so these theories do give the designer an important shaping principal: avoid having sharp edges whose Keller Cones are directed toward a likeley detector. Note that for the monostatic case, this reduces to the avoidance of edges which are normal to the direction of incident radiation. If there is a curved edge, some portion of it will quite likely be perpendicular to the incident radiation and will therefore diffract toward the receiver; such points are referred to as "flare spots."

These considerations are the basis for edge management, an important practical principle in vehicle RCS reduction. To avoid detectable signatures except in a small number of carefully chosen aspects, one must avoid curved edges, and orient the straight edges perpendicular to those aspects which are not considered critical. The nose-on aspect is often considered the most critical. To minimize signatures in the frontal sector, one must "sweep" all edges as much as possible.

Both diffraction theories were subsequently improved. The Method of Equivalent Currents, developed and refined by various researchers from the late 1950s through the 1980s, extended the applicability of GTD to observation points which do not lie on the "Keller Cone." In the early 1970s, Dr. Kenneth Mitzner of Northrop Corporation developed the concept of Incremental Length Diffraction Coefficients (ILDCs) which similarly extended the applicability of PTD.

METHOD OF EQUIVALENT CURRENTS (MEC)

A key feature of both Geometric Optics and the Geometric Theory of Diffraction is that the radar cross section is determined from a ray description of the scattering: the relevant scattering mechanisms are described in terms of rays, and the divergence of the scattered rays determines the intensity of the radar return at an observation point in the far field. This bypasses the step of finding the currents induced by the incident radiation on the object's surface. Thus the geometric methods are the simplest to use in cases where the ray-tracing models exist and accurately capture the dominant scattering mechanisms. However, there are two important cases where geometric methods do not help, as noted earlier: when an infinite number of rays are returned in the same direction (specular reflection from cylindrical or flat surfaces, and edge diffraction on caustics); and when there is no appropriate ray description of the scattering, for example for scattering directions which do not lie on the Keller cone.

The Method of Equivalent Currents addresses these limitations by supposing the existence of a finite current concentrated in hypothetical filaments along each edge of an object, as illustrated below:

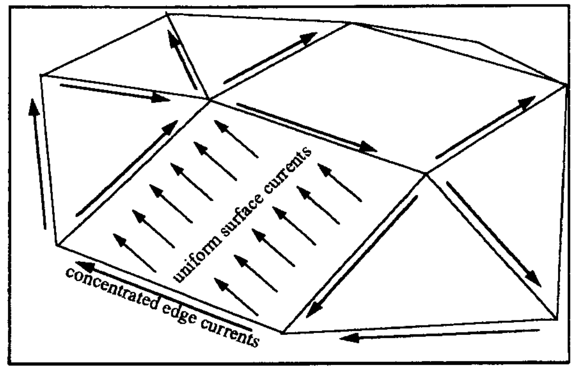


Figure 9: Method of Equivalent Currents (MEC)

The finite currents can be used to calculate the scattered field in any direction, and will always yield a finite result. MEC was applied to certain special cases in the 1950s and 1960s, and was more fully developed by Arie Michaeli in the 1980s (ref. 10, 13).

Unfortunately, the magnitude of the edge current depends on the scattering angle, and is therefore a fictitious quantity: the actual currents on the object can not be affected by the location of the observer.

The reason for this can be seen by revisiting the foundation of MEC, which is the use of currents in a *filament* to simulate the actual edge currents. Since the cross section of the filament is considered to be a point, it is obvious that the filament is incapable of introducing any dependence of the scattered field on ϕ, the azimuth angle relative to the edge of interest. Since the actual diffraction from an edge does have a dependence on azimuth angle, the only way for MEC to capture this dependence is by using a different current in the filament for different values of the scattering azimuth. The current is found by matching the exact solution on the Keller Cone for the scattering azimuth of interest, and the current is then used to find the diffracted field for other values of β at the same value of ϕ_s. Calculations at different values of ϕ_s require a new value of the current to be determined. Nevertheless, MEC is a very useful extension of GTD. It is possible that improved ways of modeling the edge currents will be (or have been) developed to capture the azimuthal variation of the diffracted radiation.

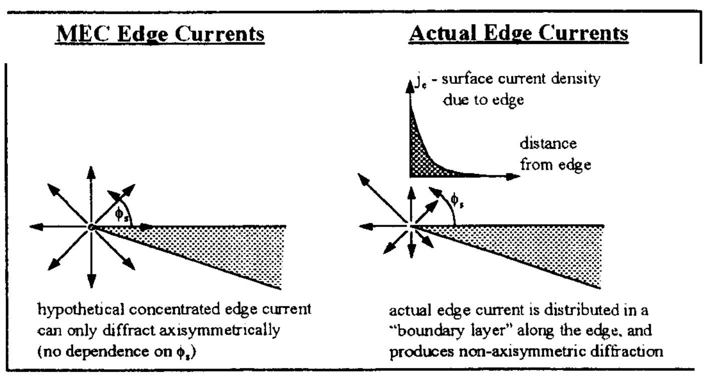


Figure 10: Axisymmetric Scattering from a Filament

INCREMENTAL LENGTH DIFFRACTION COEFFICIENT (ILDC)

In April 1974, Dr. Kenneth Mitzner of Northrop Corporation's Aircraft Division published his Incremental Length Diffraction Coefficients (ILDC), which extends the applicability of Ufimtsev's PTD in a manner that is analagous to what MEC does for GTD, allowing the diffracted radiation to be calculated even for scattering directions which do not lie on the Keller Cone. However, because Ufimtsev's diffraction coefficients do take into account the distribution of current near the diffracting edge (at least implicitly), the method of ILDCs does not require different solutions for different scattering angles.

Like Ufimtsev's PTD, the ILDC solution does have to be added to the PO solution to yield the total scattered field; nevertheless, ILDC is still relatively easy to use. For historical interest, and also because it concisely summarizes important features of Mitzner's method, the following description is quoted directly from his paper:

> "In calculating the scattering from three-dimensional bodies with edges, it is frequently meaningful and useful to consider the scattering associated with an incremental length of the edge and to describe this scattering in terms of an Incremental Length Edge Diffraction Coefficient (ILEDC). In this report the theory of the ILEDC is developed, taking into account the actual distribution of surface current near the edge. The theory is illustrated by applying it to the problem of scattering from a perfectly conducting polygonal plate. The Incremental Length Diffraction Coefficient (ILDC), which is the generalization of the ILEDC for linear scattering features other than edges [such as rounded corners], is also treated....
>
> "... The 2-D DC [2-Dimensional Diffraction Coefficient] provides a simple and compact way of expressing the well-known edge diffraction results of Ufimtsev and Keller.
>
> "The ILDC [Incremental Length Diffraction Coefficient], which is defined for all directions of incidence and scattering, is shown to be a generalization of the 2-D DC, which is defined only for certain combinations of incident direction and scattering direction. Wherever the 2-D DC is defined, it is equal to the corresponding ILDC...." (ref. 15)

Mitzner's work was part of an extensive program of RCS prediction research at Northrop, begun in the mid-1960s and sponsored by the Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio. Although Mitzner still neglected corner effects and the interactions of multiple edges with each other, his results compared well with experimental data for the polygonal plate of his example. The use of a polygonal plate as a test case for Mitzner's method hints at the approach of faceting to design low RCS aircraft. Northrop used a faceted design approach for their entry in the 1975 DARPA XST (Experimental Survivable Testbed) Program, and although Lockheed won, the competition was extremely close (ref. 19).

LIMITATIONS

Because each theory has its limitations, it is usually necessary to use a composite of various theories, using the most appropriate method for each major source of backscatter. Furthermore, RCS predictions should be verified using model tests at appropriate points during the design process.

None of the theories predict higher-order mechanisms involving, for example, the interaction of multiple edges (although, if such mechanisms are understood, they can in some cases be treated by the repeated application of the methods described). They all therefore fail to predict the scattering at a corner, where several edges come together.

The common theories also fail to predict a sometimes important mechanism known as the surface traveling wave. This is an electromagnetic wave which is initiated when the incident radiation strikes a surface very close to the "grazing angle." The primary surface wave does not directly affect the monostatic RCS because it is traveling away from the source. However, if there is a sharp discontinuity at the far end of a long, thin object, then a reflected surface wave will be generated, which can radiate a significant amount of energy back toward the source. This occurs in many practical situations, for example in the nose-on RCS of a missile or a long slender aircraft, or at the trailing edge of an airfoil. This is why trailing edges, as well as leading edges, must be swept if nose-on signature is to be minimized. A creeping wave is similar to the traveling surface wave, for objects which are rounded at the far extremity. In this case, instead of being reflected back from a sharp discontinuity, the creeping wave propogates around the far end of the object and emerges on the other side.

There are ways to predict the effects of surface waves and similar phenomena with reasonable accuracy, but these usually require separate calculations in addition to the predictions of scattered radiation by one or more of the methods just described. There is also a way to minimize the effects of these waves: magnetic surface coatings will cause traveling surface waves to be attenuated, hopefully to an insignificant level by the time they travel the length of a body and back. However, one must remember that "frequency and polarization may be varied at will by the enemy" (ref. 2), and it is unlikely that any one material will effectively attenuate all possible waves, particularly within the weight and thickness constraints associated with aircraft applications. The principals of shaping must therefore still be applied.

APPLICATIONS TO AIRCRAFT DESIGN

EARLY EFFORTS

Very early efforts at vehicle RCS reduction consisted primarily of the application of radar absorbent materials to as much of the vehicle as could be managed. Several things were eventually learned.

First, radar cross section is not necessarily related to physical size, and small details can produce a large radar return. Inlets and cockpits were identified as major sources of backscatter, and special treatments for these areas were devised. For inlets, the most effective treatment was found to be a screen or grid over the inlet, with a fine spacing relative to the wavelength of the incident radiation. Such a grid appears opaque to the radar, and thus prevents the large returns which otherwise are generated by internal reflections in the duct, and/or reflections from the engine compressor face. Some engine performance penalties are incurred. Other airframe features require similarly special treatment, including the engine nozzles if aft-aspect signature reduction is desired. Strict attention to detail is necessary throughout the design, construction and maintenance of low signature aircraft.

Second, shaping was found to be important. No material is 100% absorptive, so there is always some scattered radiation. Shaping is necessary to direct the scattered radiation away from its source. Early efforts at aircraft shaping were guided primarily by intuition, and most were fairly successful at eliminating specular reflections for those aspects considered to be important. This was accomplished through the avoidance of flat surfaces oriented normal to the most likely detection aspects. A few of these early low RCS designs are illustrated and briefly discussed below.

LOCKHEED GUSTO 2 (1956-7 DESIGN STUDY)

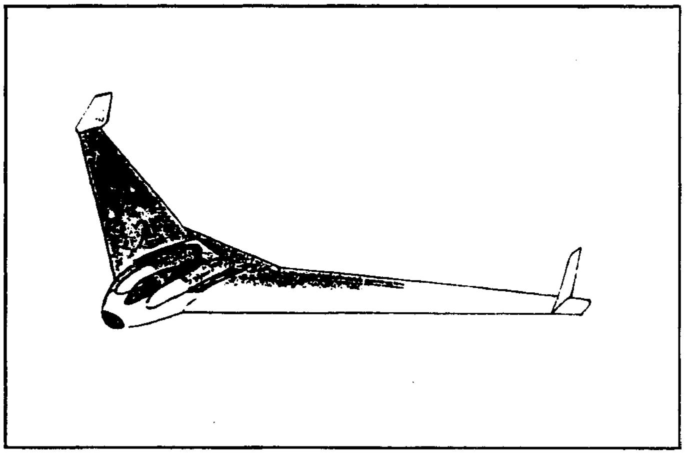


Figure 11: Lockheed Gusto 2 (ref. 14)

This was a high-altitude, subsonic aircraft design intended as a possible replacement for the U-2, after it was discovered that Soviet radars were easily tracking the U-2 on its overflights. Because of its rounded wing leading edge and only moderate sweep - both features necessary for efficient subsonic flight - there would certainly have been a considerable signature spike not very very far from the nose-on aspect, associated with the specular return from the wing leading edge. This might have created an appreciable chance of detection, considering that Gusto's intended mission involved long-duration, deep penetrations of Soviet airspace, where hostile radars might not just be ahead of the aircraft, but all around it.

Studies were conducted by the Lockheed Skunk Works in conjunction with the CIA, on the effects of speed, altitude and RCS on survivability. It was concluded, given the levels of signature reduction which were considered achievable, that high supersonic speed in combination with high altitude and some amount of RCS reduction, provided the best chances of survival. Attention therefore shifted away from the long-endurance, subsonic design towards what would become the A-12 (ref. 14).

LOCKHEED A-12 (FIRST FLIGHT 1962)

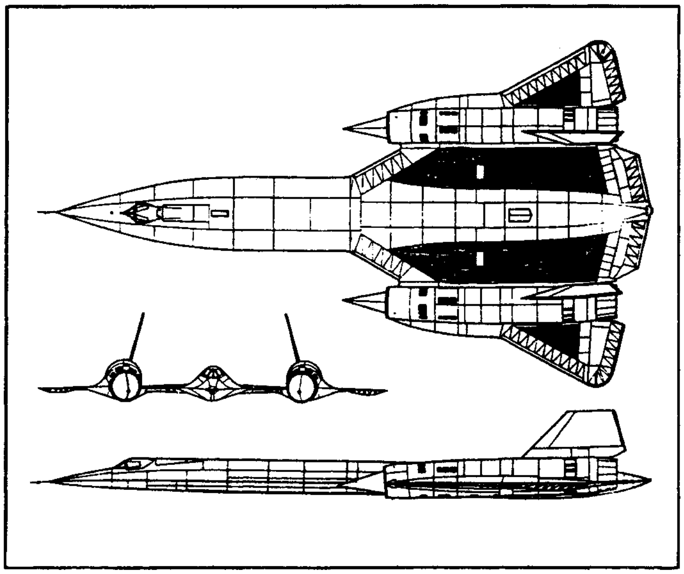


Figure 12: Lockheed A-12 (ref. 14)

This Mach 3, high-altitude reconnaisance aircraft was effectively shaped so as to eliminate specular reflections from both the nose and side aspects. Fuselage shaping was recognized as an important contributor to the side aspect signature, and the design shows considerable emphasis on the avoidance of vertical or near-vertical surfaces. The high design Mach number allowed planform edges to be sharp and highly swept, both of which characteristics facilitated the reduction of signatures from the nose-on aspect. Furthermore, the construction included special edge structures which were intended to attenuate electromagnetic waves; and absorbent paints were also tried (ref. 14). The A-12 had a low nose-on signature, and extremely low side signature, relative to conventional aircraft.

However, there is one obvious source of significant scattering in the frontal sector: the inlets. Even aside from the issues of internal multiple reflections and compressor face return, the inlet lips of the A-12 provide excellent examples of *caustics*, where not just one point on the curve but the whole curve may diffract toward the receiver (see Figure 8). Because the inlets are canted slightly down and inward, these caustics would appear slightly to either side of the nose-on aspect, and slightly below the horizontal plane. Even at aspects slightly off the caustics, there would still be two flare spots on each inlet lip (at the farthest and nearest points, respectively). Kelly Johnson, during the development of the

A-12, wrote that: "Inlets are the problem in the forward aspect and the exhaust in the rear, as expected." (ref. 14) With the demands to withstand high temperatures and to operate efficiently over an extreme speed range, little could be done to reduce the radar returns of the inlets. Grids or screens were out of the question, and titanium was the only material from which the inlet lip itself could be made. However, the penalty in forward sector RCS was apparently acceptable for an aircraft which travelled at Mach 3 and at an altitude of around 17 miles.

LOCKHEED D-21 (FIRST FLIGHT 1966)

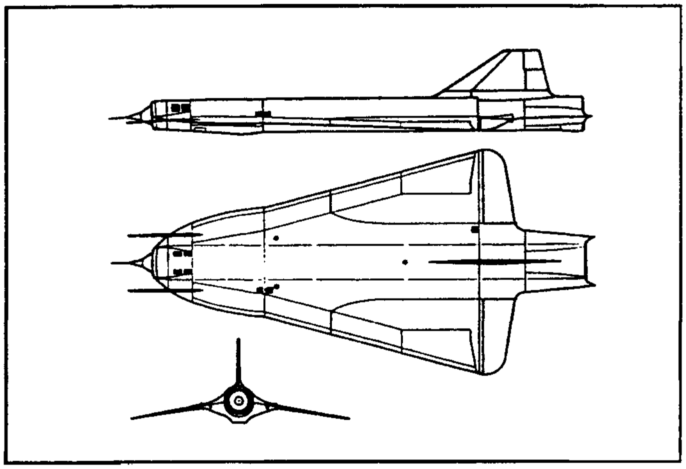


Figure 13: Lockheed D-21 Drone (ref. 14)

The D-21 was a high-altitude, Mach 3.8 reconnaisance drone intended to be launched from the back of a specially-modified A-12 "mother ship." The approach to RCS reduction for the D-21 was similar to that used on the A-12, and it may be assumed that similar results were achieved. The nose-on signature of the D-21, like that of its larger cousin, was probably dominated by the inlet. Although it met its speed and RCS design goals, the D-21's career was plagued by various difficulties, and it was cancelled in July 1971 after only four operational missions (ref. 14).

RYAN COMPASS ARROW (FIRST FLIGHT 1969)

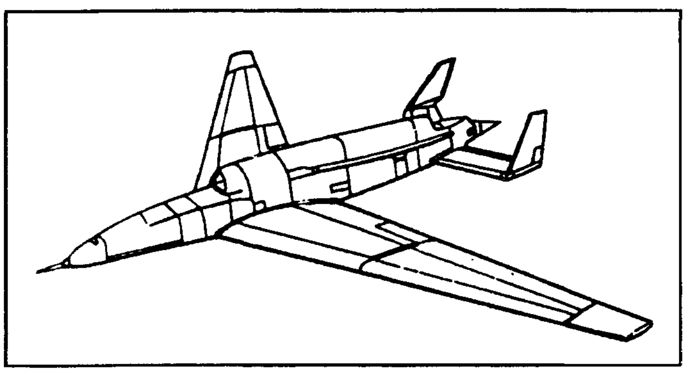


Figure 14: Ryan AQM-91A Compass Arrow (ref. 23)

Development of this high-altitude reconnaisance drone was initiated in 1966. Although fairly conventional in its design, the AQM-91A incorporated several RCS-reducing features. Because its mission involved high altitude flight, special attention was paid to reducing the RCS of the aircraft as seen from below. The bottom of the aircraft is therefore smooth and nearly featureless. The vertical tails and fuselage sides were canted inward to eliminate specular reflections from the side aspect at or below the horizontal plane. Although the engine inlet did not appear to have extensive treatment, it was located on top of the fuselage so that it would be entirely or partially concealed to viewing angles below the horizontal plane. RAM was applied to the wing leading edges and to portions of the fuselage. This drone achieved fairly low signatures and saw successful operational use which included overflights of mainland China. It was considered successful enough that it provided significant impetus for further efforts in RCS reduction (ref. 2).

MCDONNELL QUIET ATTACK AIRCRAFT (1972-3 DESIGN STUDY)

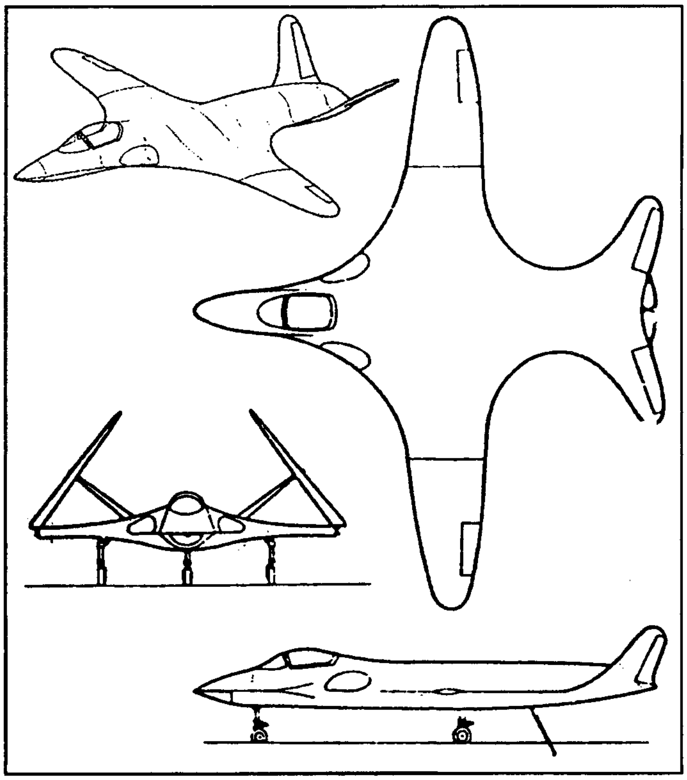


Figure 15: McDonnell Quiet Attack Aircraft (ref. 24)

This aircraft was designed by McDonnell Douglas under contract to the Office of Naval Research, for minimum radar, infra red, visual, and acoustic signatures. In keeping with the concept of a slow, quiet, covert attack aircraft, it embodied a much more extensive effort to control engine signatures than was typical for earlier low RCS aircraft. This effort included hidden inlets, a high bypass tip-driven turbofan engine, and a special plug nozzle (ref. 24). The aircraft's shape was carefully blended so as to slant all surfaces quite far from the vertical, indicating the typical appreciation for the importance of specular reflection. The shaping philosophy is summarized as follows:

> "The most important technique for RCS reduction is a blended shape. This means no straight leading or trailing edges, no flat sides on the fuselage, no single vertical tail..." (ref. 24)

However, this approach leads to problems with edge diffraction. It is apparent from the top view in Figure 15 that the continuously curved planform edge would have created a "flare spot" at some point along the edge, for nearly every viewing aspect.

RYAN LOW RCS VEHICLE (1973-4 DESIGN STUDY)

The Remotely Piloted Vehicle (RPV) Special Projects Office at Wright-Patterson Air Force Base, Ohio, conducted studies in conjunction with Teledyne Ryan and other companies, of low RCS drones. The Ryan Low RCS Vehicle was to consist of a small metal centerbody surrounded by a large amount of lossy dialectric material. The configuration was all-wing, with a simple delta planform and inward-canted twin vertical tails. The engine and equipment were buried in the fairly thick wing root. Tail surfaces and other features were to be made of "radar-transparent" materials (ref. 23). Although impressive RCS results were achieved in model tests, the approach was impractical and the vehicle still did not meet RCS goals at all frequencies of interest (ref. 19). The goals had been derived from extensive threat analyses, and covered a broad range of frequencies corresponding to the various elements of the latest Soviet air defense systems. (Air defense systems are discussed in more detail in reference 11).

SUMMARY OF EARLY EFFORTS

RCS reduction efforts prior to 1974 had succeeded in eliminating the greatest sources of scattering, thereby reducing signatures by an amount that was useful in some applications. However, these efforts still did not produce the levels of RCS reduction necessary to provide acceptable survivability to manned aircraft in a true high-threat environment, such as that encountered by Israeli aircraft during the 1973 war in the Middle East, which had a devastating effect.

THE FIRST VERY LOW OBSERVABLE (VLO) DESIGNS

As specular reflections are eliminated, signatures become dominated by other far less intuitive mechanisms which can still generate a detectable return. Edge diffraction is in many cases the next largest contribution to scattering, after specular reflection. RCS reductions necessary to allow manned aircraft to penetrate heavily defended airspace with an acceptable degree of survivability were not achieved until this mechanism was understood and controlled. Ufimtsev and Keller developed theories of diffraction in the 1950s. At least two companies in the United States - Lockheed and Northrop - were able to incorporate edge diffraction considerations into their practical techniques for the design of low RCS aircraft in the early- to mid-1970s. This development, combined with the extensive earlier progress in radar absorbent materials and the proper treatment of airframe details, put the art of RCS reduction on the threshold of a new era.

XST / HAVE BLUE (FIRST FLIGHT 1977)

In 1974, DARPA sponsored some studies which led to a joint Air Force - DARPA program to design a low RCS vehicle called the XST - Experimental Survivable Testbed. Lockheed, Northrop, and several other companies were involved. Proposals for a four-month design development phase, which would culminate in a competitive evaluation of full scale RCS models at the RATSCAT measurement range, were informally requested in August 1975, and submitted in October. According to Colonel John K. Twigg, USAF (Ret), who became the Air Force Program Manager for the project in April 1976, "Only two companies were close to being in the running - Lockheed and Northrop." This is not to make any presumption regarding the relative capabilities of the different companies to design low RCS aircraft today; only to say that twenty years ago, there were apparently only two companies which had progressed beyond "intuitive" shaping techniques, and taken the next step by applying analytical techniques which captured some less intuitive phenomena.

Lockheed and Northrop were selected to proceed with the preliminary design and competitive model test phase, and in April 1976 both entries demonstrated much lower RCS values than any previous design had been able to achieve. The major distinction between the XST models and all previous efforts at RCS reduction, was the understanding of diffraction and the consequent rigorous application of edge management. The two XST designs are illustrated below.

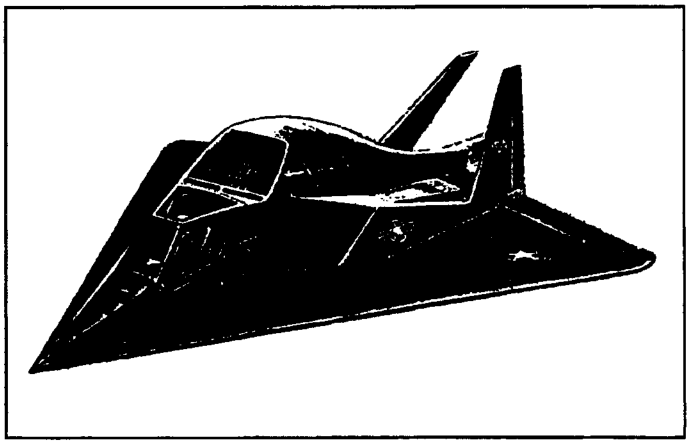


Figure 16: Northrop XST (ref. 6)

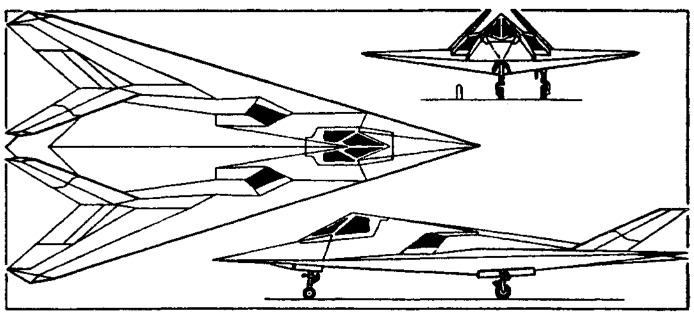


Figure 17: Lockheed XST (Have Blue) (ref. 6)

As a result of the dramatic results of the model test phase, increased security was applied to the already classified XST program and it became the Air Force Have Blue program. Although the competition was very close, Lockheed Advanced Development Company (also known as the Skunk Works) was selected for the full-scale manned flight demonstration phase. Two aircraft were built, the first one solely to validate the flying qualities and air vehicle performance of the unusual design, and the second one to validate the signature performance. The first Have Blue aircraft flew from December 1977 until May 1978, and the second one from July 1978 through July 1979. Although both aircraft were eventually lost, all demonstration goals were achieved and the program was considered outstandingly successful.

LOCKHEED F-117A (FIRST FLIGHT 1981)

In June 1977, even before the first Have Blue flight, a special project office had been established in the Pentagon to study military applications of the low observables breakthrough. This office conducted design studies of operational weapon systems, in parallel with the ongoing Have Blue demonstration accomplishments. In 1978 it was decided to initiate Full Scale Development of the aircraft which would become known as the F-117A, with the Lockheed Skunk Works as the prime contractor.

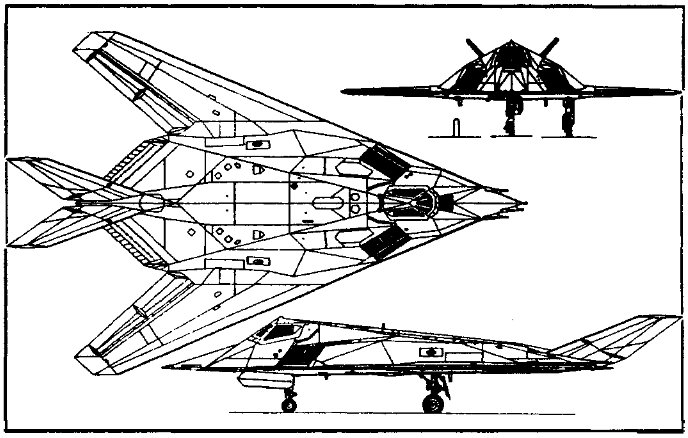


Figure 18: Lockheed F-117A (ref. 6)

The Lockheed Have Blue aircraft and its successor, the F-117A, both featured extremely sharp, highly swept wing leading edges - a serious compromise on a subsonic aircraft, but necessary to avoid the frontal-sector signature spike associated with specular reflection from the leading edges. On the F-117A, there is no rounded leading edge to produce such a spike. The large sweep insures that even the diffracted return from the sharp edge is oriented far off the nose aspect. Trailing edges and access panel edges are also rigorously managed.

In addition to the shaping considerations, appropriate types of materials are applied to the surfaces and edges. Engine inlets are covered with grids and screens. In keeping with the unprecedented level of RCS reduction achieved on the basic air vehicle, the detail treatments had to progress to a similar level of refinement. Even the smaller details such as the air data probes are specially designed for low RCS. The targeting system is completely passive except for the laser designator, and is concealed behind screens. Rear-aspect RCS, as well as infra-red signatures, are minimized through the use of a special exhaust nozzle. The F-117A first flew in June 1981 and achieved an initial operational capability in October 1983. By that time other low observable projects were underway as well.

NEWER DESIGNS

NORTHROP TACIT BLUE (FIRST FLIGHT 1982)

Concurrently with the Air Force studies which led to the development of the F-117, a variety of other projects were initiated. One of the first of these was Tacit Blue, a program to demonstrate a reconnaisance aircraft which could loiter undetected while observing the movements of ground forces well behind enemy lines. Designed by Northrop, where Dr. Mitzner had developed his method of Incremental Length Diffraction Coefficients (ILDCs), the Tacit Blue aircraft is considered the first VLO design to utilize curved surfaces.

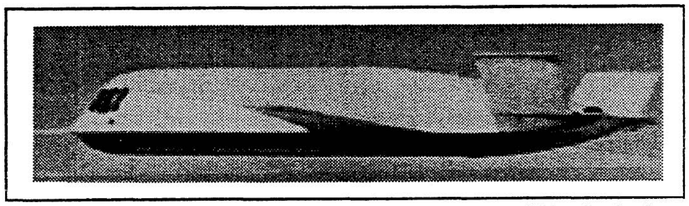


Figure 19: Northrop Tacit Blue, from the Side (ref. 4)

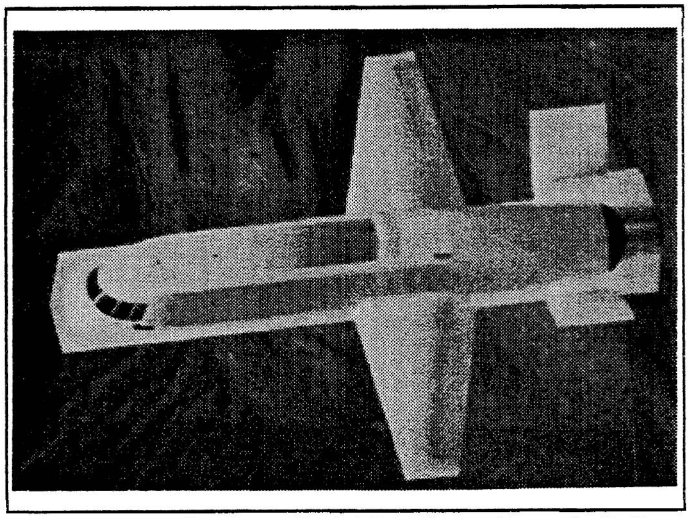


Figure 20: Northrop Tacit Blue, from Above (ref. 4)

However, the design is only a very moderate departure from the earlier faceted configurations. Tacit Blue's surface still consists largely of flat faces with straight sides, but now they are bounded by rounded edges, rather than sharp edges. Both Mitzner and Ufimtsev had made the observation that PTD was applicable, not only to sharp edges, but to "diffracting elements" of arbitrary cross section (ref. 15, 21). Diffraction coefficients could be determined from a 2-dimensional solution for the cross section of interest, and then applied to the 3-dimensional problem.

NORTHROP TRI-SERVICE STANDOFF ATTACK MISSILE (TSSAM) (MID-TO-LATE 1980s PROGRAM)

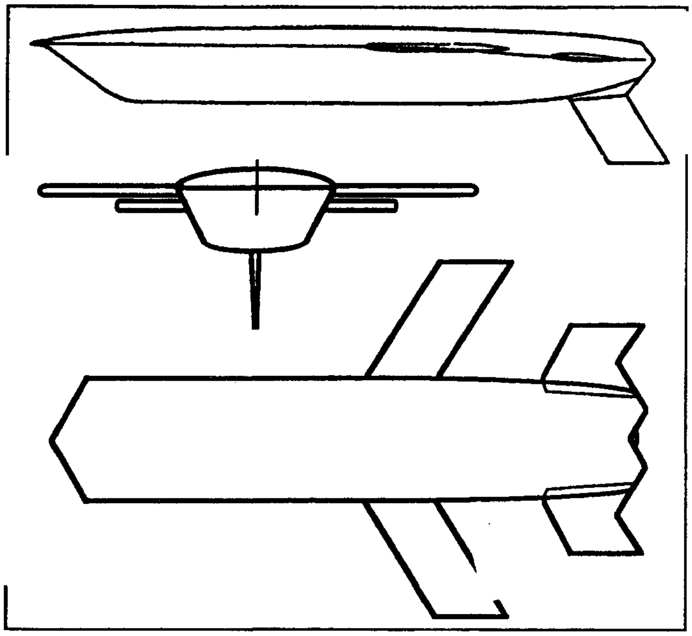


Figure 21: Northrop TSSAM (ref. 22)

The shape of this VLO air-launched standoff missile is almost identical to that of Tacit Blue, turned upside-down. Like Tacit Blue, the TSSAM was built by Northrop. There are small differences related to the specific mission needs of the two aircraft. For example, on Tacit Blue, the wing trailing edges are parallel to the leading edges on the opposite side, producing a tapered wing with zero sweep at the 50% chord line. On TSSAM, the trailing edges are parallel to the leading edges on the same side, producing a wing that is swept but not tapered, consistent with the smaller size and higher speed of the TSSAM. However, the two aircraft indicate a common approach to shaping for low RCS.

NORTHROP B-2 (FIRST FLIGHT 1989)

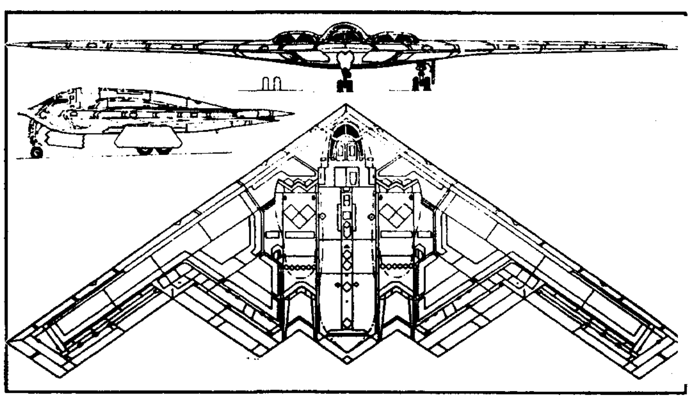


Figure 22: Northrop B-2 (ref. 6)

The fuselage of the B-2 follows the lineage of Tacit Blue and TSSAM, although it is slightly more curvaceous. However, on the B-2 the fuselage is a relatively small "lump" on a large wing, whereas the fuselage was the dominant feature of both of the earlier Northrop VLO designs. What really makes the B-2 a more complex shape are the nacelles, which protrude above the upper surface of the wing very close to the fuselage on either side. Interactions certainly had to be considered in predicting the RCS of this configuration. The B-2 was apparently the first VLO aircraft to have such complexity, and may therefore be indicative of a significant advance in predictive capability.

As seen from the front or side, all surfaces on the B-2 appear to be slanted at least 45 degrees from vertical. In planform, all edges are oriented in only two directions - parallel to either the port or starboard wing leading edge. Streamwise edges were completely elimated, presumably providing a reduction in side-aspect signature, which is valuable for a subsonic aircraft which must make extended penetrations of enemy airspace, and therefore may be subject to detection from any aspect.

ADVANCED TACTICAL FIGHTER: LOCKHEED YF-22 AND NORTHROP YF-23 (FIRST FLIGHTS 1990)

The most recent low RCS aircraft designs have taken advantage of further advances in prediction techniques, primarily in the area of computational power, which have made it possible to design more complex configurations with curved surfaces, and confidently refine their scattering characteristics through computational modeling. The designers of the YF-22 and YF-23 have used these advances to exercise greater freedom in designing configurations with high aerodynamic performance and high maneuverability as well as low signatures. Nevertheless, basic shaping principals must still be applied, and are evident on all of the newer designs.

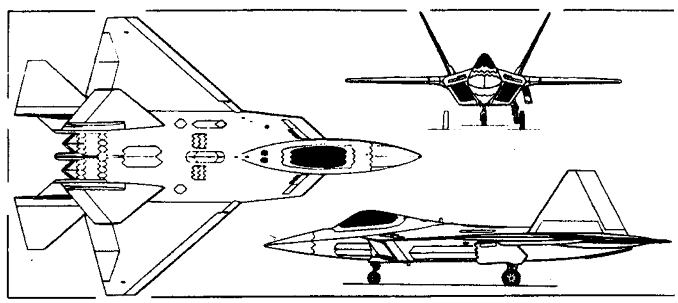


Figure 23: Lockheed YF-22 (ref. 6)

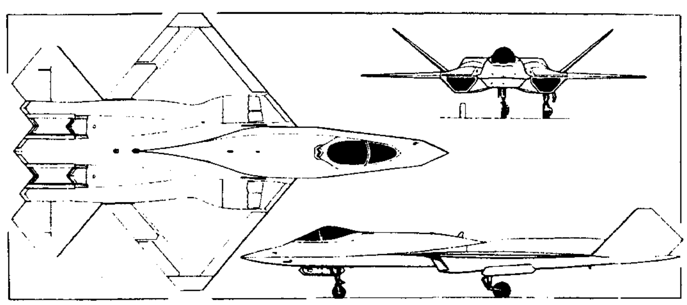


Figure 24: Northrop YF-23 (ref. 6)

SUMMARY

There are striking similarities between the recent generation of VLO aircraft, and some of the early designs such as the McDonnell Quiet Attack Aircraft, particularly when viewed from the side or front. The distinction is obvious however, when viewed in planform. Truly low signature aircraft all show a rigorous application of edge management, in addition to the surface shaping considerations which are necessary to eliminate specular reflection, the careful treatment of details, and the extensive application of radar absorbent materials. Improvements in prediction techniques, including especially the understanding of edge diffraction which was achieved theoretically from the 1950s through the early 1970s and was first applied to aircraft design during the mid-1970s, were necessary to bridge the gap between moderately LO aircraft, and true VLO aircraft.

NOMENCLATURE

$\vec{B}$	Magnetic induction
c	Speed of light
$\vec{E}$	Electric field intensity
G	Antenna gain
GO	Geometric Optics
GTD	Geometric Theory of Diffraction
$\vec{H}$	Magnetic field intensity
ILDC	Incremental Length Diffraction Coefficient
ILEDC	Incremental Length Edge Diffraction Coefficient
i	(as a subscript): Pertaining to the incident field
J	Electrical current density
j	Surface electrical current density
MEC	Method of Equivalent Currents
P_{min}	Minimum detectable received signal power
P_t	Transmitted power
PO	Physical Optics
PTD	Physical Theory of Diffraction
S	Energy flux of an electromagnetic wave
s	(as a subscribt): Pertaining to the scattered field
α	Angle of incidence relative to a surface normal; or wedge half-angle, depending on context
β	Angle of incidence relative to an edge
ε_o	Permittivity of vacuum; ε_o=8.854x10^{-12} farad/meter
λ	Wavelength
μ_o	Permeability of vacuum; μ_o=4πx10^{-7} henry/meter
ρ	Charge density
σ	Radar cross section in square meters
σ_{dBsm}	Radar cross section in decibels relative to a one square meter reference value

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