1 Introduction

1.1 Stealth Design

1.1.1 What is Stealth Design?

The purpose of designing an object in stealth technology is to reduce the likelihood of betraying its presence and to minimize the probability of its detection when active search and tracking techniques are employed [1]. For an object to be “stealth”, it needs to have a low optical visibility in addition to being low-observable in the infrared spectrum and at all radar frequency bands. Also, the emission of acoustic noise should be low.
The theory and techniques presented in this text relate only to the behaviour of objects illuminated by electromagnetic waves at radar frequencies. Although the popular image of stealth is the realisation of “invisible” targets, the practical aim is to achieve “low observability” for certain aspect angles [2].

Stealth technology is generally associated with aircraft (Fig. 1.1), however this technology also receives increasingly more attention in ship designs. This is clearly demonstrated by the well-known French marine frigate “La Fayette” and United States “Arsenal” and “Sea Shadow”. The Sea Shadow (Fig. 1.2) has the ability to navigate on the information received from a tactical data link solely, thus eliminating the need for a large number of windows and onboard sensors [3]. The scarcity of external features further reduces the radar cross section of the vessel. UK’s plans to build stealth ships are also taking shape in the form of the “Sea Wraith” and “Project Cougar” [4].

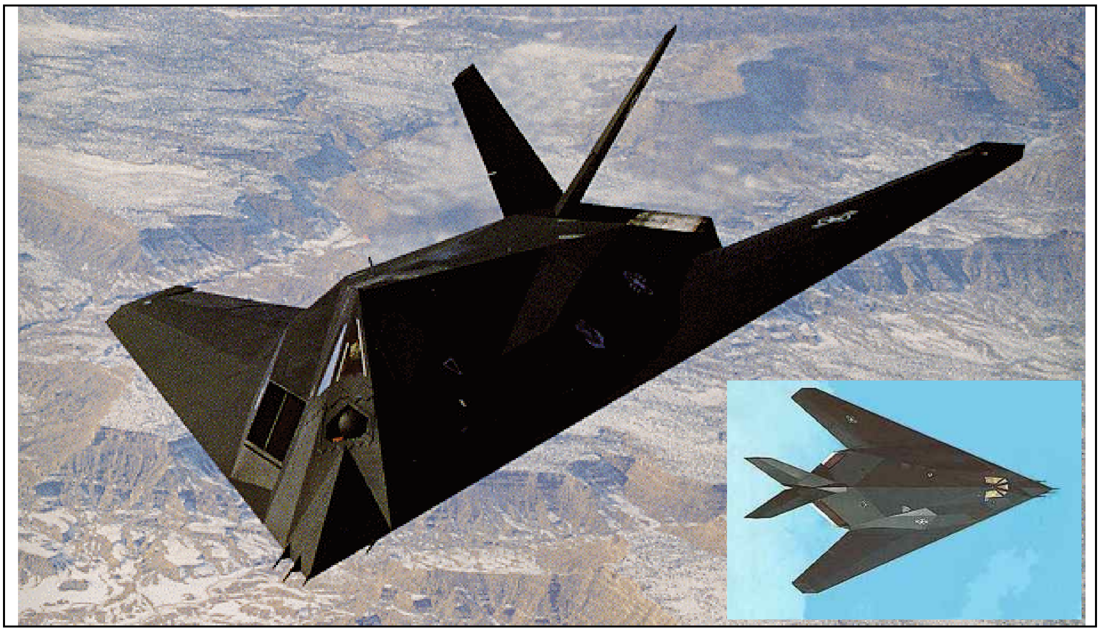


Figure 1.1: The F-117A stealth fighter plane; its “faceted” shape, internal weapon bays and location of jet inlets are characteristic for many stealth aircraft designs. Note also that the jet intakes are located on top of the wings. Inset: The wings are indented at the rear end and the usual 90° dihedral corner reflectors at the tail have been eliminated.

(a)

(b)

Figure 1.2a: The United States “Sea Shadow”
Figure 1.2b: The number of discontinuities in the hull have been reduced to an absolute minimum; only two hatches for the crew and one air inlet on the roof of the vehicle.

Some of the stealth techniques employed in military designs also have civilian applications. The “invisible” struts and masts described in [5] and [6] are an excellent example of this. In these references is explained how a ship-born radar will suffer less from blockage and unwanted echoes when the masts in its immediate vicinity are treated with an electromagnetic hard surface. (See also Chapter 5 in this text.)

1.1.2 What is the Radar Cross Section (RCS) of an Object?

The *radar cross section (RCS)* of an object is defined as the projected area of an equivalent perfect reflector with uniform properties in all directions (i.e. a sphere) and which will return the same amount of power per unit solid angle (steradian) as the object [1]. The datum reference for RCS is often taken as a sphere of $1m^2$ echoing area, that is a sphere with diameter $D = \sqrt{\frac{4}{\pi}} \approx 1.1284 m^2$.

A more mathematical definition of RCS is [2]

$$\sigma = \lim_{R \to +\infty} 4\pi R^2 \frac{\overline{E}_s \cdot \overline{E}_s^*}{\overline{E}_i \cdot \overline{E}_i^*}$$

where σ is the RCS and $\overline{E}_i$ and $\overline{E}_s$ are the phasor representations of the incident and scattered electric field intensities, respectively. The superscript * denotes the complex conjugate. σ has the units of area and is usually expressed in square meters.

The RCS of some common perfectly conducting scatterers can easily be calculated from geometrical optics ($\sigma = \pi \rho_1 \rho_2$ where ρ_1 and ρ_2 are the radii of curvature) and have been tabulated (see for example [2]).

For most objects, radar cross section is a three-dimensional map of scattering contributions located on the object and which vary as a function of frequency, aspect angles (azimuth ϕ and elevation θ) and polarization [7]. The *scattering matrix* describes the scattering behaviour of the target as a function of polarization, as it contains four RCS values (VV, VH, HV and HH; the first letter denotes the transmission polarization, the second letter is the polarization at receive) from which the RCS can be derived at any polarization:

$$\sigma(f,\theta,\phi) = \begin{bmatrix} \sigma_{VV}(f,\theta,\phi) & \sigma_{VH}(f,\theta,\phi) \\ \sigma_{HV}(f,\theta,\phi) & \sigma_{HH}(f,\theta,\phi) \end{bmatrix}.$$

Radar cross section is the only factor in the radar equation that is within control of the stealth design engineer, hence its importance:

$$P_r = \frac{P_t G_t}{4\pi R^2} \cdot \frac{\sigma}{4\pi R^2} \cdot A_r \qquad (1)$$

where
P_r is the received power,
P_t is the transmitted power,
G_t is the antenna gain on transmit,
R is the distance between the target and the radar (i.e. the range),
σ is the radar cross section and
A_r is the effective antenna aperture on receive.

Of course, active electronic countermeasures (ECM) can further reduce the probability of radar detection. However, ECM is not regarded as a stealth technique.

1.1.3 Why Reduce RCS?

There are several reasons for reducing the RCS of any target [7]:
- Prevent, or at least delay or deteriorate enemy radar detection,
- Force the enemy radar to increase its transmitting power, thus increasing its detection range and vulnerability,
- Prevent correct target classification through the analysis of “hot spots”,
- Induce the enemy to underestimate target dimensions,
- Reduce the jamming power necessary to protect the target,
- Increase the effectiveness of chaff,
- Simplify the construction and deployment of decoys.

In conclusion, all the above considerations have the common purpose of increasing target survivability. However, as has been mentioned previously, RCS reducing techniques can also be employed to prevent one’s own radar from receiving unwanted echoes from nearby “friendly” objects.

Quite often the direction of radiation will result in head-on illumination of the target [1]. As can be deduced from the table below ([1], [2] and [8]), the aim is to make a fighter plane’s head-on RCS approach that of a bird. However it is obvious that consideration must also be given to other aspects, including those from below or to one side when ground- or space- based radar is the threat. In this context it should also be noted that a different approach is likely to be necessary when the threat is a bi-static, as opposed to a mono-static radar [1].

Table 1.1: Typical head-on RCS values at microwave frequencies

Object	$\sigma(m^2)$
Pickup truck	200
Automobile	100
Jumbo jet airliner	100
B-52	100
Tank	50
Large bomber or commercial jet	40
Cabin cruiser boat	10
Large fighter aircraft	6
Small fighter aircraft or four-passenger jet	2
Adult male	1
Cruise missile	0.80
B-1B	0.75
Conventional winged missile	0.50
B-2	0.10
F-117A	0.025
Bird	0.010

1.1.4 Scattering Mechanisms

The electromagnetic waves that impinge upon the target are scattered by a variety of mechanisms [1]:

– *Specular*: Specular wave scattering is essentially a reflection of the incoming wave. The main contribution arises when the Poynting vector of the incoming wave vector is perpendicular to the local surface.
– *Diffraction*: Diffraction occurs when there is a discontinuity in the target geometry or a discontinuity in the electromagnetic material properties of the object.
– *Diffracted surface waves*: A surface wave (which belongs to the group of traveling waves; see also Section 3.4.8) may result when the incoming wave is more or less aligned along the length of a long thin coated body. The scattering arises when the surface wave encounters surface discontinuities, the end of the body or changes in the electromagnetic properties of the surface of the body. (See also Fig. 1.6.)
– *Radiation from creeping waves*: When the surface which supports a surface wave makes a gentle bend in the longitudinal plane of the surface wave, the surface wave will convert into an attenuated creeping wave that continues to follow the surface and space waves that radiate away from the surface, also called surface diffracted waves (Fig. 1.3) [9].

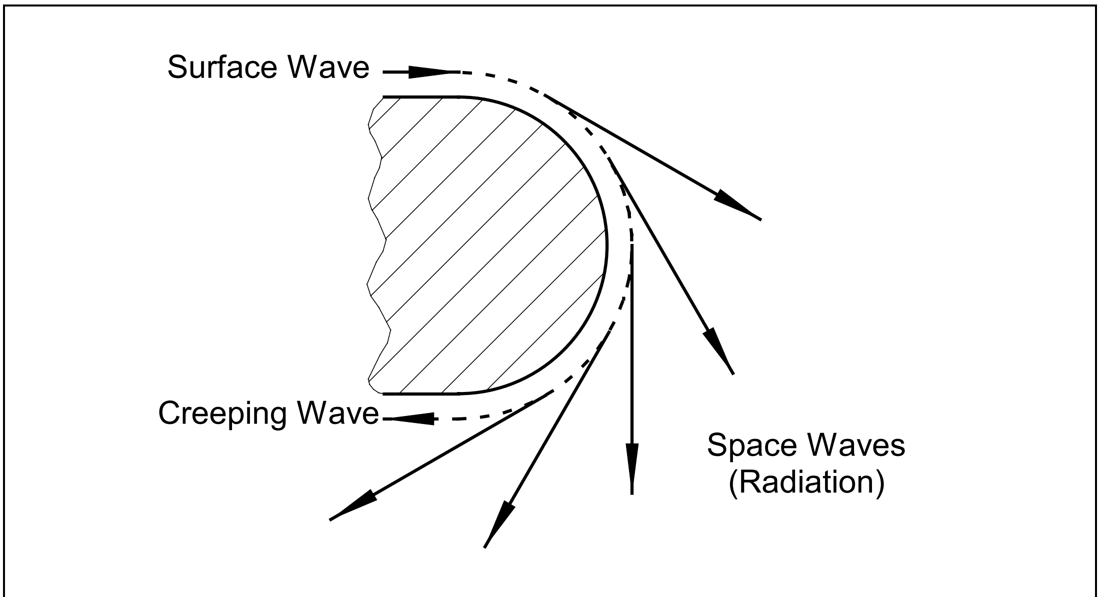


Figure 1.3: Radiation from creeping waves

All scattering mechanisms have one thing in common: the scattered waves are needed in addition to the incoming wave to satisfy the boundary conditions at the object.
The dependence of RCS upon wavelength can be categorized into three regimes (a is a major dimension of the target) [1]:

– The Rayleigh regime where $\lambda \geq 2\pi a$: In this regime σ varies smoothly with variation of λ. Moreover, $\sigma \sim V^2 \lambda^{-4}$ where V is the volume of the body,
– The resonant regime where rapid changes of σ are likely to occur,
– The optical regime where $\lambda \leq 2\pi a$: Here σ varies smoothly with λ and may tend to a definitive value for $\lambda << 2\pi a$.

1.1.5 Where to Reduce RCS

At radar frequencies of practical interest, the wavelength is often much smaller than the target's typical dimensions, and the electromagnetic scattering is practically a local phenomenon (i.e. optical regime). Besides particular resonance or multiple reflection effects, the scattering of each single reflecting element of a complex structure is not affected by the presence of the rest of the structure (except for masking effects) [7]. Hence, a radar echo can be seen as the superimposition of several echoes, each with a different amplitude and phase

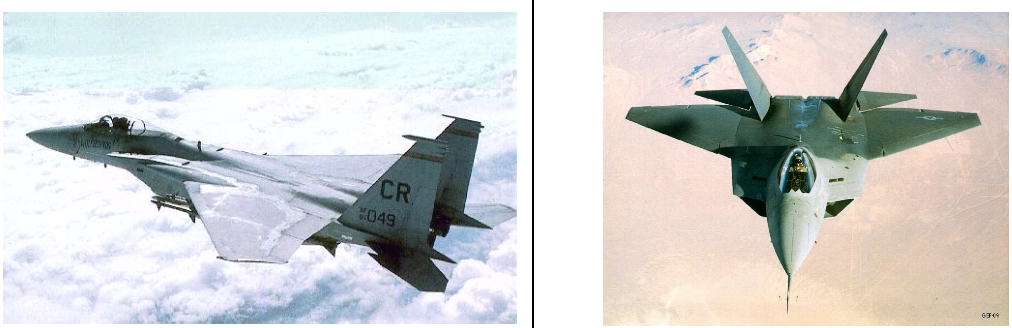
$$\sigma = \sqrt{\sum_{n=1}^{N} \left(\sigma_n e^{j\varphi_n}\right)^2} .$$

An average RCS value can be computed by assuming that phases are random uniform variables (this assumption is true for short wavelengths)

$$\sigma = \sum_{n=1}^{N} \sigma_n . \qquad (2)$$

As can be seen from the radar equation (1), a reduction in σ by an order of magnitude only reduces the detection range by 44%. A very large reduction in σ is therefore essential to have a significant effect [1]. In view of (2), it is very important to work first on the main scattering contributions ("hot spots") of a target, because their reduction has the maximum effect on the overall RCS [7]. An overview of what contributes to the RCS of a typical fighter aircraft is given in Figure 1.5.

Only RCS contributions that can be accompanied by surface wave propagation (12 to 15 in Fig. 1.5) are dealt with in this text. These contributions are in general small compared with other contributions. However, in order to achieve RCS values that are as small as that of a bird, these smaller contributions need to be reduced as well. The methods and techniques presented in this text are intended to help achieve this. They are also helpful with the new, taxpayer-friendly trend of retrofitting or redesigning existing vehicles which were originally not designed in stealth technology.



(a) (b)

Figure 1.4a: The F-15, a conventional fighter plane
Figure 1.4b: The F-22, a stealth redesign of the F-15 with new low-observable jet intakes, shielded nozzles, cant rudders and internal weapon bays

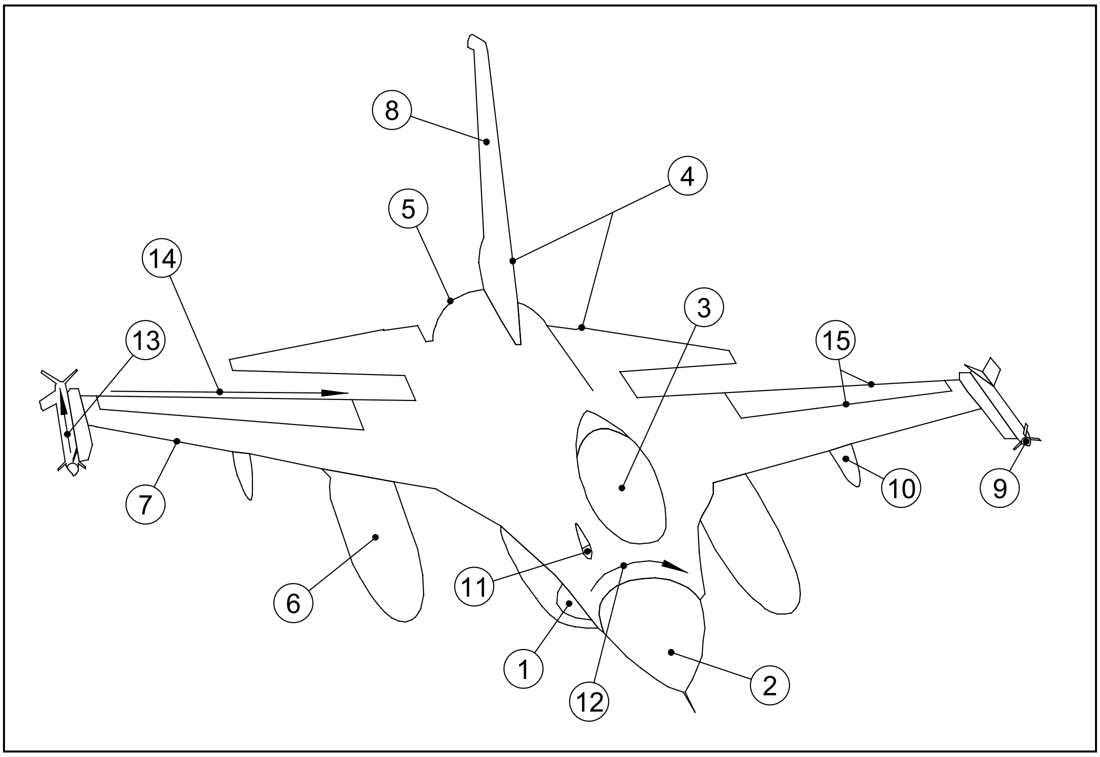


Figure 1.5: Contributions to the radar cross section of a fighter jet [1], [9]

Large scattering contributions (mainly due to reflection) are:
1) Air intake cavity (only for head-on illumination),
2) Antenna behind radome, if transparent to illuminating radar,
3) Canopy and cockpit cavity,
4) Dihedral 90° corner reflector at tail junction (only for side illumination),
5) Exhaust cavity (when viewed from rear (e.g. like in a missile attack)),
6) Drop tank,
Not shown: Glint from flat, slab sided fuselage (from normal to its side).

Scattering contributions that could be large, but not necessarily are:
7) Leading wing edge, especially if unswept,
8) Glint from vertical and horizontal tails in isolation,
9) Seeker,
Not shown: Glint from propeller and rotor blades.

Smaller, but nevertheless significant scattering contributions are:
10) Weapon hard point,
11) Gun muzzle and other local surface protuberances,
12) Creeping wave along the fuselage,
13) Axial surface wave along coated missile,
14) Surface wave along trailing wing edge (only with side illumination) [10],
15) Scattering at trailing wing edge and control surface gaps,
Not shown: Scattering at edges of undercarriage fairing,
Not shown: Local air intakes for cooling or air conditioning.

Contributions 12 to 15 can be accompanied by surface wave propagation effects if the surfaces are coated.

1.1.6 Techniques for Reducing RCS

There are essentially four techniques for reducing RCS:
- By shaping and masking,
- By treating the surface of the target with radar absorbing materials (RAM),
- By using local lumped impedances on the surface of the target,
- By employing electromagnetic soft or hard surfaces.

All four methods involve a change in the boundary conditions at the object: either a change in the location of the boundary or a change in the type of the boundary or both. The fourth technique is a relatively new technique [5] and [6]. Especially the potential benefits of electromagnetic soft boundaries for reducing RCS contributions from edge diffracted waves (13, 14 and 15 in Figure 1.5) are shown for the first time in this text (see Chapter 5).

Shaping and Masking

By using proper shapes, it is possible to reduce RCS for particular aspects, at the expense of other aspects, so that the target has minimum RCS in the most probable direction of radar illumination [7].

There are two distinctly different approaches to establishing the overall shape of a stealth object [1]:
- By adopting a compact, smooth blended external geometry. This technique is exemplified by the Northrop B-2 (Fig. 1.8 and 1.9),
- By employing a faceted configuration, using flat surfaces arranged to minimize normal reflections back toward the illuminating radar and, it is hoped, eliminate glint. The Lockheed-Martin F-117A (Fig. 1.1) is based on this design concept.

In this context it should also be noted that a flat plate focuses its back-scattering on a very narrow angular sector, with a high RCS value. A sphere, by contrast, has a low RCS value which is uniform at all angles. Thus, on a limited angular sector around the specular direction, spheres and cylinders give the lowest RCS values. If otherwise, RCS must be kept low on a wide angular sector, then it is better to use very narrow-beam shapes such as the flat plate, correctly aimed in order to avoid the specular flash [7].

The design of a stealth aircraft usually results in a flying-wing shape (Fig. 1.1 and 1.8). With such a shape, most contributions of Figure 1.5 are absent or significantly reduced. For more tips on designing stealth aircraft, refer to [1] and [7].

Radar Absorbing Materials

RAM may function in one of two distinctly different ways [1]:

- By admitting the signal and then attenuating its intensity. This type is particularly suited for use against a wide range of radar frequencies, and is sometimes referred to as broadband RAM. However, this type RAM has the disadvantage of being difficult to manufacture and is heavy and expensive [7]. Surface wave absorbing materials work in very much the same way but are polarization dependent,
- By generating internal reflections which interfere with the waves reflected from the outer surface. This type of RAM is called resonant RAM because it is only effective at a number of discrete frequencies.

Lumped Impedances

It is not inconceivable that for example the wings of an aircraft could be resonant at the low frequency of an over-the-horizon early warning radar. In such a case, the wings could be detuned and hence the RCS significantly reduced by inserting an inductance or capacitance at some point in the wings.

Electromagnetic Soft and Hard Surfaces

(See [5], [6] and Chapter 5 in this text for more information.)

1.2 Reducing the RCS Contribution of Edge Diffracted Waves

An illuminating radar beam parallel to an object's surface encountering a surface discontinuity generates edge diffracted waves in order to satisfy the boundary conditions at the discontinuity (Fig. 1.6).

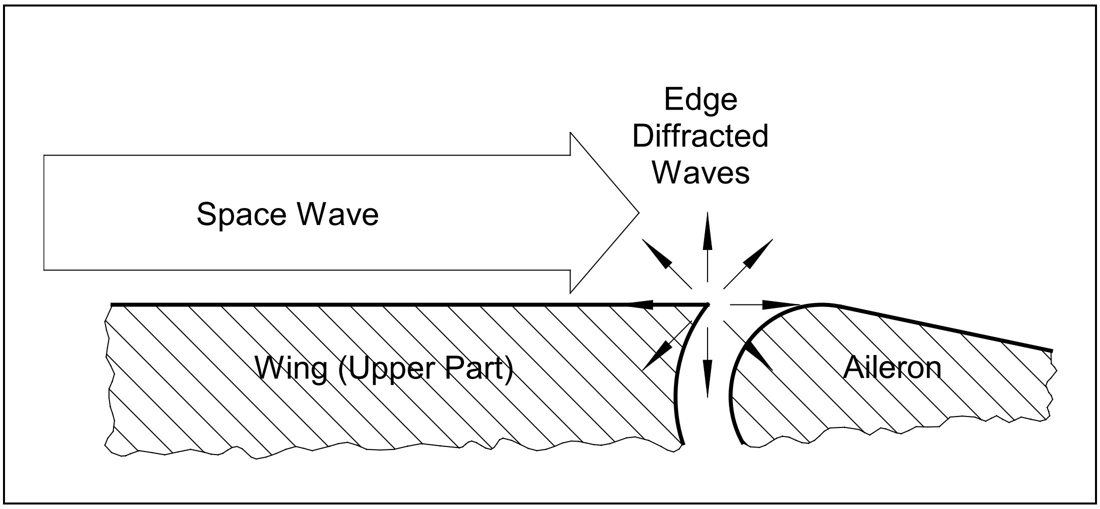


Figure 1.6: Edge diffracted waves at a surface discontinuity

The back-scattered edge diffracted waves are in phase if the discontinuity lies on a straight line perpendicular to the illumination direction (Fig. 1.7a). This leads to a strong RCS contribution [9].

For an ordinary aircraft the problem arises at the trailing edges of wings, at the gaps between wings and control surfaces (ailerons, flaps and rudders), at the edges of cargo doors, service hatches and undercarriage fairing and at the end of wing-mounted missiles (see Fig. 1.5).

There are three ways to overcome this problem:

- By indenting the edge discontinuity or
- By converting the illuminating space wave to surface waves whose intensity is significantly reduced before reaching the surface discontinuity. This can be achieved by employing isotropic surface wave absorbing materials backed by a metal surface,
- By replacing the surface by an electromagnetic soft surface.

The first method is depicted in Figure 1.7b where the approximate contour of a stealth air plane is shown (see also Fig. 1.8). Due to the indented shape of the rear edge, the edge diffracted waves going back to the radar are not in phase. Moreover, when this plane turns around its vertical axis (or the mono-static radar movers around this target), only two directions vulnerable for detection exist in a 180° sector [9]. This technique is however not particularly effective in the case of bi-static radars.

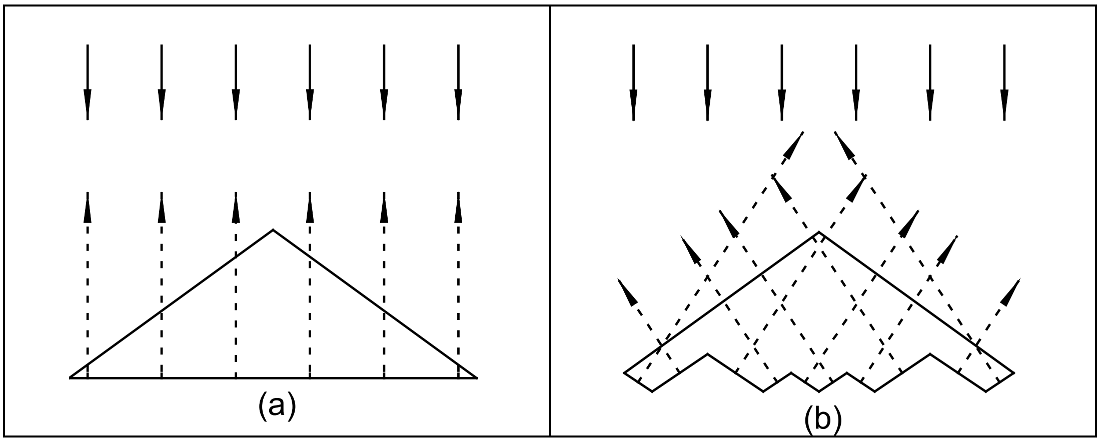


Figure 1.7a: Edge diffraction from the trailing edge of a straight wing
Figure 1.7b: Edge diffraction from the trailing edge of an indented wing

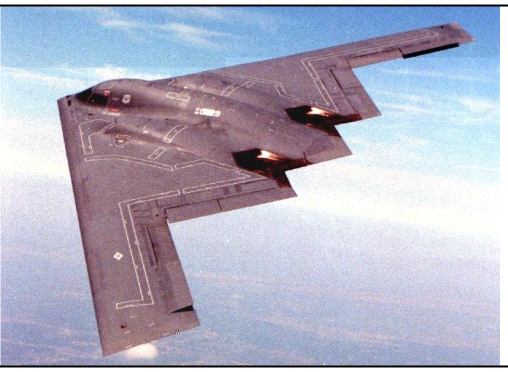


Figure 1.8: The B-2 stealth bomber plane. A flying-wing design and an indented rear edge result in an extremely low RCS value.

Edge indentation can be found at many locations along the fuselage of a stealth aircraft, as is exemplified by Figures 1.8 to 1.12. However, it is not always possible to employ this technique due to aerodynamic requirements. This is especially true for the gaps between wings and control surfaces and for ordinary aircraft being retrofitted. In such cases, one has to resort to one of the other two methods which are discussed in Chapter 5.

Figure 1.9: The indented payload doors of a B-2

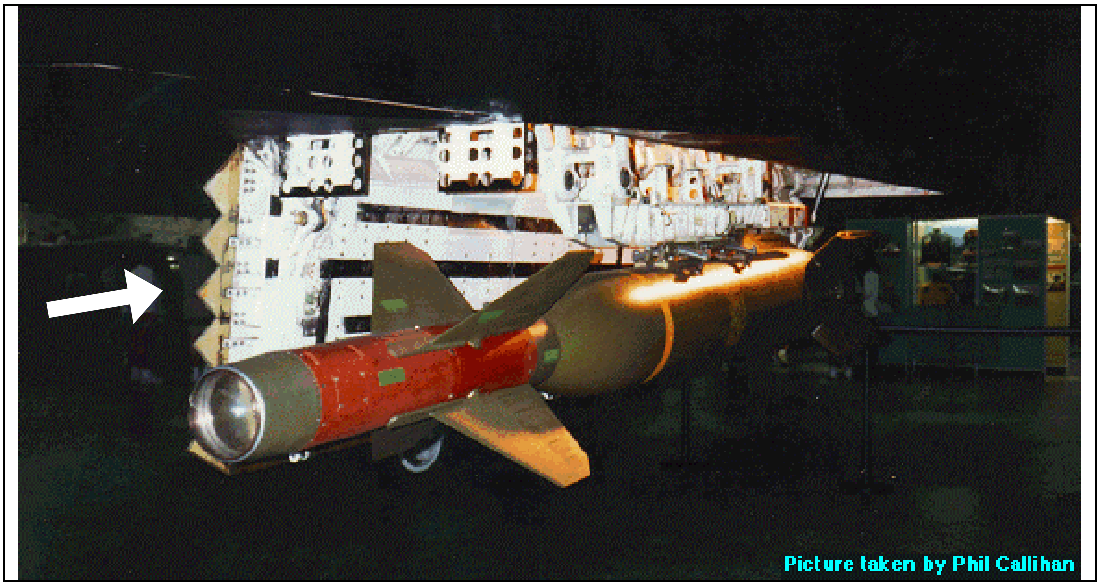


Figure 1.10: A close-up at the indented hatch of one of the F-117A's weapon bays

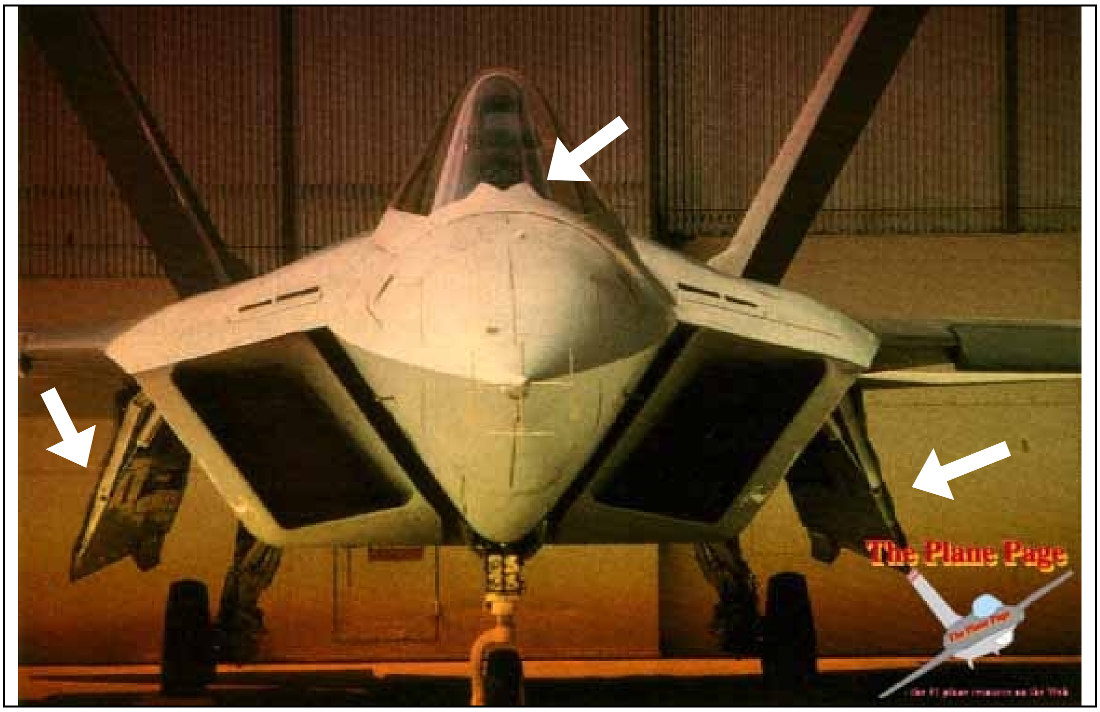


Figure 1.11: Indented surface discontinuities on the F-22's fuselage

Figure 1.12: The F-22 seen from aside.

1.3 Outline of this Text

Chapter 2 gives a review of Hertz potential theory. The convenience of expressing source free electromagnetic fields in terms of Hertz potentials is clearly demonstrated.

An unambiguous definition of plane surface waves is given in Chapter 3, followed by a rigorous investigation into the propagation mechanisms of plane surface waves along various planar and isotropic multi-layered surface wave absorber configurations. Dispersion equations are derived by treating these structures as boundary-value problems and solving them using Hertz potentials. Surface waves are compared with other kinds of traveling waves and the requirements for surface wave propagation are discussed. For a given isotropic layer structure, the propagation of plane surface waves is found to be strongly polarization dependent.

Axial surface waves are the type surface waves that can propagate along a coated metal cylinder (e.g. a missile (see Fig. 1.5)). They also very much resemble the waves that might propagate along the trailing edge of a wing (see also Fig. 1.5 and [10]). The dispersion equation of these axial surface waves is derived in Chapter 4.

Chapter 5 starts off by explaining the many restrictions of employing isotropic surface wave absorbing materials for reducing the back-scattering of edge diffracted waves. Once more is stressed that the effectiveness of isotropic surface wave absorbers strongly depends upon the polarization of the illuminating radar beam. An alternative technique which does not suffer from this problem is suggested for eliminating edge diffracted waves in the radar direction. This new technique consists in replacing the scattering surface by an electromagnetic soft surface. Ways to produce such a soft surface are also discussed.

Although soft boundaries form an electromagnetic superior solution for reducing the RCS resulting from edge diffracted waves, surface wave absorbers may still find many useful applications, even within RCS management. From this perspective it is obvious that there is a lot interest in determining the quality and efficacy of commercially available surface wave absorbers. Chapter 6 gives a brief historical overview of surface wave measurement techniques and their limitations. It appears that none of the existing techniques can be applied to measure the propagation characteristics of plane surface waves in a convenient way. However, this work resulted in the development of a new measuring apparatus, based on a partially filled rectangular waveguide, for determining the attenuation constant and phase constant of plane surface waves propagating along metal-backed surface wave absorbing materials. Measurements are presented which validate this new measuring method.

Finally, the conclusions of this work are drawn in Chapter 7 and suggestions are made for further work.

1.4 Conclusions

Edge diffracted waves resulting from surface discontinuities contribute significantly to the radar cross section of an object. Although this problem could be alleviated by indenting the edge discontinuity, this is not always possible due to other mission requirements.

However, the back-scatter from edge diffracted waves may also be reduced by converting the incoming radar waves into surface waves whose intensity is significantly reduced before reaching the surface discontinuity. This can be achieved by employing surface wave absorbing materials.

1.5 References

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