Chapter 1

INTRODUCTION

The history of radar dates back to the experiments of Heinrich Hertz in late 1880s, but the serious development of the radar equipment began in the middle 1930s simultaneously in several countries. The term RADAR stands for Radio Detection and Ranging and is coined during the World War II, when tremendous strides were made both in theory and practice of radar technology. Nowadays, radars are built in a wide range of sophistications, both in military and civilian applications.

Radar detects objects and locates them in range and angle, by transmitting electromagnetic waves of known waveform. These waves are reflected from the objects in space, and a portion of the wave energy comes back towards the radar. The radar reads this returned signal and analyzes it. This signal can be processed to determine many properties of the original object that the wave reflected off. Thus the location of the object (distance and angular position) as well as its velocity can be obtained by analyzing the returning signal.

A functional radar system consists of four basic elements. These are transmitter, antenna, receiver and an indicator. The transmitter produces radio frequency signals which are beamed towards the object using the antenna. The energy intercepted by the object is scattered in all directions. The scattered energy in a particular direction depends on the size, shape and composition of the obstacle as well as the frequency and
polarization of the incident wave. The energy scattered in the direction of the receiver is termed as ‘echo’ which is collected by the antenna and processed by the receiver. The target information is then displayed on the indicator.

In principle, a radar can operate in any frequency, but due to reasons like propagation effects, availability of components, target scattering characteristics, antenna size and angular resolution requirements, the frequency of operation is limited. Eventhough the electromagnetic spectrum in the frequency range of 3 MHz to 300 GHz is suitable for radar operation, the largest number of operational radars fall within the microwave frequency range.

1.1 RADAR CROSS SECTION

Radar cross section (RCS) is a measure of the target’s ability to reflect the radar signals in the direction of the radar receiver. RCS is a characteristic of the particular target and is a measure of its size as seen by the radar. RCS is also a function of frequency, polarization, target configuration and orientation with respect to the incident field. The basis for the design and operation of dynamic RCS test ranges is the radar range equation. The radar range equation shows how the received power is influenced by the RCS of the target and other parameters. The radar equation for free space propagation is given by

\[ P_r = \frac{P_i G_i G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \]
Where

\[ P_r = \text{received power} \]
\[ P_t = \text{transmitted power} \]
\[ G_t, G_r = \text{transmitting and receiving antenna gains} \]
\[ \lambda = \text{operating wavelength} \]
\[ R = \text{range from radar to target} \]

and \( \sigma = \text{RCS of the target} \)

The power reflected or scattered by a target is the product of its effective area and the incident power density. In general the ‘area’ is called scattering cross section of the target. For directions back towards the radar, it is called ‘backscattering cross section’ or the ‘Radar Cross Section’. The scattering cross section is not a constant. It is an angular dependent property of the target. The far field RCS does not vary with changes in range. Although RCS is defined in terms of area, it has no general relationship with the physical area of the object. RCS can be expressed as

\[
\sigma = 4\pi \lim_{R \to \infty} R^2 \frac{|E_s|^2}{|E_i|^2} = 4\pi \lim_{R \to \infty} R^2 \frac{|H_s|^2}{|H_i|^2}
\]

Where \( E_s \) and \( H_s \) are the scattered electric and magnetic fields and \( E_i \) and \( H_i \) are the incident electric and magnetic fields respectively. The unit of cross section is usually given in square meters. Due to the large variation in RCS pattern from one aspect angle to another, it is convenient to display the RCS in logarithmic form. The unit commonly used is decibel over a square meter or dBsm i.e.
RCS (dBsm) = 10 \log_{10} \sigma

RCS of a target will have a wide variation, if the illuminating electromagnetic wave has got a wide range of frequencies. The variation of RCS with frequency is classified into three regions, depending on the size of the object. In the first region, the target dimensions are small compared to wavelength. This is called the Rayleigh region and RCS is proportional to the fourth power of frequency. In the second region, the target dimensions are approximately equal to the wavelength. This region is known as the resonance region. In the third region, the object dimensions are much larger than the wavelength. This region is called the optical region.

The knowledge of RCS characteristics of some simple targets is very important in RCS measurement and analysis of complex targets. Complex targets such as missiles, ships, aircrafts etc. can be described as collections of relatively simple shapes like spheres, flat plates, cylinders, cones and corner reflectors. In measuring the RCS of complicated objects, the measurements are often calibrated by comparing the echo levels of the test objects with those of the calibration target. As the echo strength of the calibration target must be known with high degree of accuracy, the calibration target is always a simple one.

A practical justification for RCS measurements is that it is an incentive to develop products that satisfy RCS requirements in addition to the more usual requirements of mission, range and payload. RCS measurements are necessary to verify anticipated performance as well as to
evaluate design approaches. In addition, these measurements are important for the evaluation of microwave absorbers.

The instrumentation for the measurement of RCS takes different forms. There are simple systems with continuous wave operation configured from conventional microwave components and standard receivers and transmitters. Modern network analyzers and frequency synthesizers have greatly expanded the RCS measurement facility. The transformation techniques like frequency domain to time domain available in most modern network analyzer systems further increased speed, accuracy and convenience. The study of Radar Cross Section and its reduction is of great importance in modern communication, and defense applications.

1.2 RCS REDUCTION

Reduction of Radar Cross Section is a method for increasing the survivability by reducing the detectability of objects of strategic importance like aeroplanes, rockets, missiles etc. There are four basic methods for reducing the RCS of a target. They are:

- shaping of targets
- use of radar absorbing materials
- passive cancellation
- active cancellation
Each of these techniques adopts different philosophic approaches and exploits different aspects of the encounter between radar and the object.

In the shaping technique, the target surfaces and edges are reoriented or reshaped to deflect the incident wave away from the radar. But this cannot be done for all viewing angles, since a reduction at one viewing angle is usually accompanied by an enhancement at another. For structures such as ships and ground vehicles, internal trihedral and dihedral corners can be avoided by bringing intersecting surfaces together at obtuse or acute angles. The disadvantage of shaping is that it can be made only at the engineering design phase of the target.

Radar absorbing material (RAM) reduces the energy reflected back to the radar by absorbing electromagnetic energy through a kind of Ohmic loss mechanism in which electromagnetic energy is converted to heat energy. At microwave frequencies, the loss is due to the finite conductivity of the material and the friction experienced by the molecules in attempting to follow the alternating fields of an impressed wave. Early absorbers used carbon as the basic material. But they are too bulky and fragile in operational environments. Magnetic absorbers are widely used for operational systems and the loss mechanism is due to a magnetic dipole moment. Magnetic absorbers offer the advantage of compactness even though they are heavy.

The basic concept of passive cancellation (also known as impedance loading) is to introduce an echo source whose amplitude and phase can be
adjusted so as to cancel the activity of another source. However the reduction caused for one frequency rapidly disappears as the frequency is changed. Consequently passive cancellation has been discarded as a useful RCS reduction technique.

In active cancellation method, electromagnetic waves of proper amplitude and phase are emitted from the target so as to cancel the reflected wave. For this, the target must sense the angle of arrival, intensity, frequency and waveform of the incident energy. This method is not widely used because of the complexity of the system design.

RCS reduction involves a lot of compromises, in which advantages are balanced against disadvantages. The requirement for reduced RCS conflicts with the conventional target structures. The final system design is a compromise which increases cost of the overall system. Reduced payload, added weight, and increased maintenance are other penalties of RCS reduction.

Reduction of radar cross section using fractal based structures is discussed in this thesis.

1.3 FRACTAL

Mandelbrot introduced the term 'fractal' (from the Latin *fractus*, meaning 'broken') in 1975, to characterize spatial or temporal phenomena that are continuous but not differentiable. Unlike more familiar Euclidean constructs, every attempt to split a fractal into smaller pieces results in the resolution of more structure.
A fractal is a rough or fragmented geometric shape that can be subdivided in parts, each of which is (at least approximately) a reduced-size copy of the whole. Fractal structures are of infinite complexity with a self-similar nature. What this means is that as the structure is zoomed in upon, the structure repeats. There never is a point where the fundamental building blocks are found. This is because the building blocks themselves have the same form as the original object with infinite complexity in each one. Euclidean structures have whole number dimensions, while fractal structures have fractional dimensions. Fractal geometries have been used previously to characterize unique occurrences in nature that were difficult to define with Euclidean geometries, including the length of coastlines, the density of clouds, and the branching of trees. Therefore, there aroused a need for a geometry that handles these complex situations better than Euclidean geometry.

An example of fractal geometry found in nature can be seen in a fern, shown in the figure 1.

Figure 1 Fern, a fractal geometry found in nature
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The entire frond has the same structure as each branch. If the individual branches are zoomed in upon, it is quite conceivable to imagine this as a completely separate frond with branches of its own.

Some of the deterministic fractal structures are Sierpinski gasket, Sierpinski carpet, cantor bar etc. For example, a Sierpinski gasket fractal is constructed by taking a filled equilateral triangle as the 'initiator' and an operation which excises an inverted equilateral triangle as the 'generator' which is the initiator inverted and scaled by one half. Each stage of fractal growth is found by applying the generator, or its scaled replica, to the initiator. The initiator governs the gross shape of the fractal structure while the generator provides the detailed structure and ensures self similarity and long range correlation. Repeated scaling and application of the generator yields a structure as shown in figure 2.

![Figure 2 Various iterated stages of Sierpinski gasket fractal geometry](image)
Different iterated stages of Sierpinski carpet are shown in figure 3 which is constructed using generator as a small filled square of size $1/3$ of the initiator.

![Initiator and Generator](image)

Figure 3 Different Iterated stages of Sierpinski carpet geometry (a) Stage 1 (b) Stage 2 (c) Stage 3 (d) Stage 4

Similarly, the Cantor bar is formed by a line segment whose $1/3$ position from the middle is repeatedly removed. In this case the initiator is defined as a line segment of unit length and the generator is defined as excising line segment of length one-third. The bar is formed by repeated application of the generator and its scaled replica to the middle third of the
 initiator or the previous stage of growth. When the thickness of the Cantor bar becomes vanishingly small, the resultant fractal becomes Cantor dust. The growth of Cantor bar fractal geometry is shown in figure 4.

![Figure 4 Growth of Cantor bar fractal](image)

In fractal analysis, the Euclidean concept of 'length' is viewed as a process. This process is characterized by a constant parameter D known as the fractal (or fractional) dimension. The fractal dimension can be viewed as a relative measure of complexity, or as an index of the scale-dependency of a pattern. The fractal dimension is a summary statistic measuring overall 'complexity'.

Dimension of a geometry can be defined in several ways, most of these often lead to the same number, even though not necessarily. Some examples are topological dimension, Euclidean dimension, self-similarity dimension and Hausdorff dimension. Some of these are special forms of Mandelbrot's definition of the fractal dimension. However, the most easily understood definition is for self-similarity dimension. A self-similar set is one that consists of scaled down copies of itself. To obtain this value, the geometry is divided into scaled down, but identical copies of itself. If there
are $n$ such copies of the original geometry scaled down by a fraction $f$, the similarity dimension $D$ is defined as:

$$D = \frac{\log n}{\log \left( \frac{1}{f} \right)}$$

$D = \log \text{(number of self similar pieces)}/\log \text{(magnification factor)}$

For example, a square can be divided into 4 copies of $\frac{1}{2}$ scale, 9 copies of $\frac{1}{3}$ scale, 16 copies of $\frac{1}{4}$ scale, or $n^2$ copies of $\frac{1}{n}$ scale. Substituting in the above formula, the dimension of the geometry is ascertained to be 2. Similarly we can decompose a cube into $n^3$ self similar pieces of $\frac{1}{n}$ scale, with a dimension of 3. The same approach can be followed for determining the dimension of fractal geometries.

Another property associated with fractal geometries include lacunarity. Lacunarity is a term coined to express the nature of the area of the fractal having hollow spaces ("gappiness") [151]. The concept of 'lacunarity' was introduced by Mandelbrot [150] as one of the geometric parameters to characterise fractal. A fractal is 'lacunar' if its gaps tend to be large, in the sense that they include large intervals, while fractals with small gaps have small lacunarity. Highly lacunar fractals are those which are very inhomogeneous and far from being translationally invariant, while fractals of low lacunarity are more homogenous and approach translational invariance. There can be several fractals with the same dimensionality but different lacunarities, reflecting that the eliminated areas are scattered differently. Lacunarity gives an idea of the way in which it is filled or the texture of the set while fractal dimension gives a measure of how much space is filled by the set [170].
The structures shown in the figure 5 have the same fractal dimension but the distribution of the patches is different, keeping the area occupied constant.

**Figure 5** Sierpinski carpets with varying lacunarity with $D = 1.915$
1.4 MOTIVATION

A complex target can be represented as collection of basic target elements like flat plates, corner reflectors, cones and spheroids etc. It is convenient to isolate the dominant sources in target echo and fix our attention on a limited number of individual elements instead of composite target. Flat plates and corner reflectors are the major scattering centres in the complex target structures. RCS reduction of these scattering centres is the major concern to the design of targets invisible to radar's eye. The dominant scattering centers of the targets can be covered with fractal based metallo–dielectric structures with proper parameters, thereby reducing the RCS. These structures do not offer any air resistance because the metallisations is in the same plane as the dielectric sheet. Multipath interference from building surfaces is a problem familiar to urban TV reception. It is a serious problem for air traffic control systems at airports due to interference from hanger walls near airport runways. An approach to design hanger walls with these surfaces can eliminates unwanted reflections.

In this thesis, the effect of embedding fractal structures on flat plates, cylinders, dihedral corners and circular cones is investigated. It is observed that this technique offers a good amount of reduction in the RCS of these targets.
1.5 OUTLINE OF THE PRESENT WORK

The scattering property of a periodic structure depends on the frequency of the electromagnetic wave as well as the angle of incidence. By properly selecting the periodicity, one can achieve minimum reflection/transmission at certain frequencies and angles of incidence. Thus the structure becomes ‘frequency selective’. By properly combining different layers of the periodic surfaces, it is possible to obtain the frequency selective property for a wide range of angles of incidence. These structures find applications in electromagnetics as frequency selective surfaces (FSS). They can be used as radomes, frequency scanned gratings, sub reflectors for multifrequency antenna systems.

An FSS backed by a ground plane can be used for reducing the RCS of a target. These structures which can give selective reflection can be used to reduce unwanted reflection which may interrupt other communication systems. Development of frequency selective surfaces has wide range of applications in communication and radar systems. For example, communication between the aircraft and the terminal buildings is affected by unwanted reflections from nearby structures such as walls of a building.

Specular reflections from conducting surfaces can be eliminated by corrugations of proper period and depth. These corrugations can be of any shape like saw tooth, rectangular or fin. Corrugations on a conducting surface with proper parameters can be applied to targets to divert the power of an incident electromagnetic wave away from the radar and
thereby reduce the RCS. However, corrugated surfaces on a metallic plate are heavy and bulky and its fabrication is a tedious and time consuming task. A strip grating, made by etching thin periodic metallic strips on a dielectric sheet (metallo-dielectric structure) placed over a conducting plane, shows similar effects of corrugated surface and is called as Simulated Corrugated Surface (SCS) [132]. Corrugations and SCS have the property of eliminating specular reflections obeying the principle of Bragg scattering. An important advantage of SCS over corrugations is in the ease of fabrication technique using the photolithographic technique.

The main disadvantage of strip gratings developed earlier is that eliminations of specular reflection is effective only for limited frequency range and limited angular range, which impose a constraint on its use in the design of reflection free surfaces. The use of SCS proved that the frequency bandwidth and angular range of suppression of specular reflection can be increased appreciably, when the period of the grating etched on a dielectric of appropriate thickness satisfies the Bragg condition, but the reduction in backscattered power obtained is only for a limited range of frequencies. Reduction of backscattered power is also not obtainable simultaneously for TE and TM polarizations of the incident wave using strip grating. Figure 6 shows the schematic diagram of a corrugated surface and a reflector backed strip grating.
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Figure 6 Schematic diagram of
(a) Corrugated surface
(b) Reflector backed strip grating

The present work aims at the reduction of RCS of targets using metallo-dielectric structures based on fractal geometry. The effect of loading these structures over a flat plate, cylinder, dihedral corner reflector and circular cone are investigated. Fractal structures have certain properties like self similarity and space filling property. So fractal based metallization on a dielectric substrate backed with a conducting surface can be useful in reducing the backscattered power simultaneously at different frequency bands and also with improved bandwidth. Also RCS reduction can be obtained for both TE and TM polarization of the incident field over a large bandwidth for structures that are symmetric.
1.6 ORGANISATION OF THE THESIS

The scheme of the work presented in this thesis is given below:

An exhaustive review of the work done in the field of Radar Cross Section studies and fractal electrodynamics is presented in chapter 2.

The methodology adopted for the work presented in this thesis is highlighted in chapter 3. The methods used for the measurements of monostatic and bistatic RCS are presented.

Chapter 4 highlights the experimental results of the investigations carried out on the scattering behaviour of flat plate, cylinder, dihedral corner reflector and circular cone loaded with fractal based metallo-dielectric structures. The effect of various parameters such as dielectric thickness, dielectric constant, Shape of metallizations and fractal geometry are investigated.

In chapter 5, the results of the experimental studies are validated by analyzing the structures using electromagnetic simulation softwares. The simulation and experimental results are compared for different cases. Comparisons of the backscattering properties of different structures are also presented for different frequency bands.

Conclusions drawn from the investigations are presented in chapter 6. The scope of future work in this field is also discussed.
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Work done by the author in the related fields is presented in appendices I and II. The design of a band pass filter employing metallo-dielectric structure based on cantor bar fractal geometry is presented as appendix I. The development of an Arch method for RCS measurements and its automation is presented in appendix II.