

# TEACHING RADAR CROSS SECTION CONCEPTS TO UNDERGRADUATES WITH A SIMULATION SOFTWARE

Mauro A. Alves<sup>1</sup>, Mirabel. C. Rezende<sup>2</sup>

**Abstract** — The commercially available CADRCS software, sold as a simulation tool for military and industrial applications, was used to teach the main concepts of Radar Cross Section (RCS) to undergraduate students. Models of objects and targets are created in CAD; their surfaces are discretized with the Rhinoceros software and imported to CADRCS for the simulations. In this way, the RCS of objects with both simple and complex geometries can be simulated with relative ease and versatility with CADRCS. The visualization and analysis of these simulations serve as valuable teaching aids, helping students to obtain a better understanding of key issues related to the calculation and interpretation of the RCS signature of actual objects and targets.

**Index Terms** — Models, radar cross section, simulation software, undergraduate students

## INTRODUCTION

Any object illuminated by radar waves will scatter some of the incident energy. The radar cross section (RCS) is a parameter used to characterize the scattering properties of an object. It represents the size of this object as seen by the radar and has the dimension of square meters. The RCS area is not the same as physical area, but a measure of the ability of a target to reflect radar signals in the direction of the receiving antenna. RCS is defined as the area intercepting that amount of power which, when scattered isotropically, produces at the receiver an energy density equal to that scattered by the actual target. In general, the RCS of a target is a function of the polarization of the incident wave, the angle of incidence, the angle of observation, the geometry, the electrical properties of the target, and the frequency of operation. Thus, two targets with the same physical size and shape could have considerably different radar cross-section. The RCS of a target can be expressed as [1] [2]:

$$\sigma = -\lim_{r \rightarrow \infty} 4\pi r^2 \frac{|E^{scat}|^2}{|E^{inc}|^2}, \quad (1)$$

where  $E^{scat}$  is the scattered field, and  $E^{inct}$  is the incident field at the target. The RCS defined by (1) is often referred to as either monostatic or backscattered RCS. Equation (1) is

valid when the target is illuminated by a plane wave. This condition is satisfied by the far-field approximation, i.e., when the object is located at a distance at least  $r = 2D^2/\lambda$ , where  $D$  is the largest dimension of the object, and  $\lambda$  is the wavelength of the radar [2]. Usually, due to the large range of RCS values, a logarithmic power scale is used with the reference value of  $\sigma_{ref} = 1 \text{ m}^2$ :

$$\sigma_{dBsn} = 10 \log_{10} \left( \frac{\sigma_{m^2}}{\sigma_{ref}} \right) = 10 \log_{10} \left( \frac{\sigma_{m^2}}{1} \right). \quad (2)$$

It is important to note that (1) is deceptively simple. The calculation of scattered fields from a target is mathematically complex, requiring the solution of Maxwell's equations in either differential or integral forms and under the appropriate set of (usually complicated) boundary conditions. Analytical solutions for this problem exist only for objects with simple geometries. Solutions for (1) can also be obtained numerically, but they are complex, difficult to implement, and often their interpretation is rather difficult.

Another approach to estimate the RCS of actual targets is the measurement of real-sized objects or scale models. Although extremely desirable, not all schools or educational institutions have the facilities where such measurements can be performed. Alternatively, there are in the market [3] training systems that allow students to perform RCS measurements. These systems are obviously very useful, but have inherent limitations such as the required physical dimensions of the laboratory, the size and variety of targets, and the available range of frequencies that can be used in the measurements.

Depending on the circumstances, students that need to have a good understanding of the RCS of actual targets are faced with limitations. Usually, they will have only access to approximate methods to calculate the RCS and these methods do not convey all the complexity related to the actual RCS of a target. With the advent of new and powerful simulation tools and the widespread used of computers in the academic setting, the learning of RCS can be greatly facilitated. Simulation software can be used with an endless number of different objects and configurations, which allows the student to test and explore several ideas and concepts about RCS in depth and with relative ease.

<sup>1</sup> Mauro A. Alves, Guest Researcher, Grupo de Fadiga e Materiais Aeronáuticos, Faculdade de Engenharia de Guaratinguetá, UNESP. Av. Dr. Ariberto P. da Cunha, 333, 12516-410, Guaratinguetá, SP, Brazil, mauro@sepn.org

<sup>2</sup> Mirabel C. Rezende, Professor, Instituto de Aeronáutica e Espaço, Divisão de Materiais, Pça. Ma. Eduardo Gomes, 50, 12228-904, São José dos Campos, SP, Brazil, mirabel@iae.cta.br

We have been using the CADRCS [4] simulation software in our laboratory to calculate the RCS of aircraft and other targets of military interest. Our research goal is to find ways to minimize or maximize the RCS of these targets in order to increase their stealth characteristics or their visibility, respectively. But, it soon became apparent that the simulation software could also be used as a tool in the training of students to interpret RCS data. In what follows we present some of CADRCS capabilities and a few examples of the results one can obtain from it.

### THE SIMULATION TOOL

CADRCS uses ray tracing combined with physical optics to calculate the RCS of an object. Shadowing of rays is also taken into account, making the calculation very accurate for objects greater than the radar wavelength [5]. Its use is straightforward and requires minimal training. It allows the visualization of high radar-reflecting areas on an object, and is extremely versatile. With CADRCS is possible to simulate the RCS of an object under different conditions such as distance, material reflectivity, number of reflections, viewing aspect, radar wave polarizations, among others.

Computer-aided design (CAD) models of targets were generated with the Rhinoceros modeling software. After a representation of the target was constructed, its surface was subdivided into triangular elements by an automatic mesh generator. The only parameters used during the mesh generation process were the maximum and minimum linear dimensions of the triangular elements. These dimensions were chosen so that the simulations produce optimal results. The meshed object was then imported into CADRCS for the simulations. A Pentium 4 3.2 GHz PC computer with 3.0 GB RAM memory was used in this work. The complexity of the models dictates the time in which a simulation will be complete. Usually, detailed results from objects with simpler geometries are obtained within an hour.

### SIMULATIONS

Three types of targets with increasing level of complexity, a flat plate, dihedrals and a square cavity, are used to illustrate some of the results that can be obtained with the simulation software. These objects were chosen as they are representative of important radar reflectors. In Figure 1 is shown the CAD models of these targets. As an example of a more complex situation, the RCS of a vintage airplane was also simulated. Figure 2 shows the airplane model used in the simulations.

#### Flat Plate and Absorbing Materials

As the first object to be simulated, a flat plate seems to be the natural choice; it is easily represented as a CAD model, simple analytical formulas describe the plate's RCS as a function of the incident angle of a radar wave, and its frequency can be found in the literature [6, 7]. A perfectly

conducting flat square plate with a surface area of 1 m<sup>2</sup> and illuminated with 1 and 10 GHz radar waves was used in the simulations. The surface of the flat square plate was discretized into 3200 identical right triangular elements whose largest dimension is 3.5 cm. The results of CADRCS can be compared with the RCS of a square plate given by the formula [6]:

$$\sigma_{plate} = \frac{4\pi a^4}{\lambda^2} \left( \frac{\sin(ak \sin \theta)}{ak \sin \theta} \right)^4 \quad (3)$$

where  $\lambda$  is the wavelength of the radar,  $a$  is the length of a side of the square,  $\theta$  is the aspect angle, and  $k$  is the wave number. This formula is valid only for aspect angles of  $-20^\circ \leq \theta \leq 20^\circ$ .

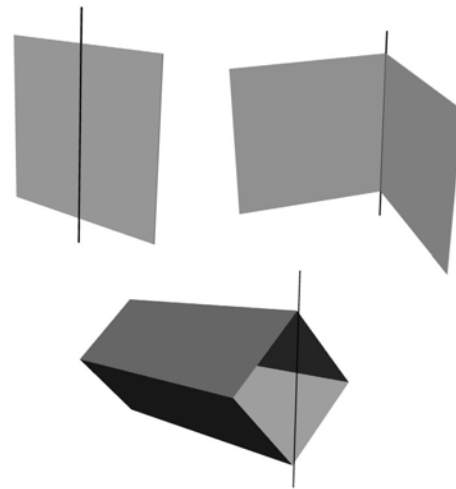


FIGURE 1

CAD MODELS OF TARGETS USED IN THE SIMULATIONS. DRAWINGS NOT TO SCALE. THE AREA OF THE FLAT PLATE IS 1M<sup>2</sup>, THE LENGTH OF THE SIDE OF THE SQUARE OF THE DIHEDRAL IS 0.5 M, AND THE LENGTH AND THE BASE AREA OF THE SQUARE CAVITY ARE 3 M AND 1M<sup>2</sup>, RESPECTIVELY. THE VERTICAL BLACK LINES ARE THE AXIS OF ROTATION OF THE TARGETS IN THE SIMULATIONS.

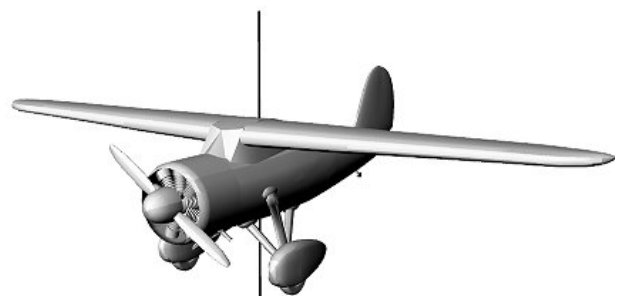


FIGURE 2

CAD MODEL OF AN AIRPLANE. WINGSPAN OF THE MODEL IS 12.5 M. THE VERTICAL BLACK LINE IS THE AXIS OF ROTATION OF THE TARGET IN THE SIMULATIONS.

Figure 3 shows the results of the RCS simulations with CADRCS.

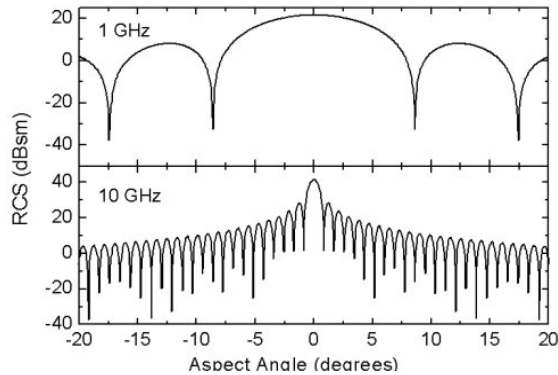


FIGURE 3

RCS SIMULATIONS OF A FLAT PLATE AT THE FREQUENCIES OF 1 AND 10 GHz. AT THE ASPECT ANGLE OF 0° THE SURFACE OF THE PLATE IS PERPENDICULAR TO THE LINE OF SIGHT OF THE HYPOTHETICAL RADAR.

An important result that is immediately observed is the presence of well-defined lobes at different values of the aspect angle, meaning that a plate will scatter energy back in the direction of incidence more efficiently at certain angles. Also, the width of the lobes is dependent on the frequency, with shorter radar wavelengths producing narrower lobes, as indicated by the modulating term  $\sin(ak \sin \theta)$  in (3).

With the development of aircraft stealth technologies and the need of microwave absorbing materials by the communication industry, new materials have been created that have the ability to absorb some or most of the energy of radar waves. With CADRCS, it is possible to simulate the effects of the reflectivity of a material on the RCS of a target. Figure 4 shows how the RCS of the same plate used above is changed when its reflectivity is equal to 0.1, 0.01 and 0.001. The simulations in this case were performed with a frequency of 1 GHz.

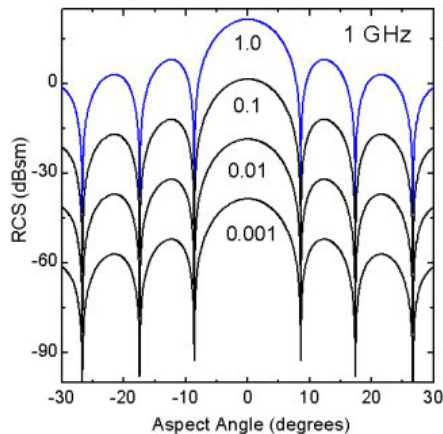


FIGURE 4

RCS SIMULATIONS OF A METALLIC FLAT PLATE WITH DIFFERENT REFLECTIVITIES. THE VALUE OF REFLECTIVITY OF 1.0 CORRESPONDS TO A METALLIC (PERFECTLY CONDUCTING) PLATE. RADAR FREQUENCY IS 1 GHz.

From the results shown in Figure 4, it can be derived that the RCS for a flat plate is proportional to the square of its reflectivity. Although this was expected, since for a simple object such as a flat plate the RCS is proportional to the square of the area, this result may serve as an indication of how RCS of an object will be altered by the application of a material that has the property to absorb some of the energy of the incident radar wave. For instance, if the flat plate is covered with a material that absorbs 90% of the energy of the incident wave (reflectivity = 0.1) its RCS will decrease by a factor of 100. It is important to note that this type of result is not usually found in the literature and its mathematical derivation is beyond the grasp of most undergraduate students.

### Dihedral and RCS Reduction by Shaping

The next example shows how the shape of an object can affect its RCS. The RCS patterns of a right-angled corner dihedral and of a 95° corner dihedral reflectors are compared. In the simulations, the faces of both dihedrals are squares with side length of 0.5 m, and their surfaces were discretized into 4624 identical right triangles whose largest dimension is 2.0 cm. The simulations were performed at a frequency of 10 GHz. A right-angled dihedral corner reflector is interesting due to the perpendicularity of its faces. A ray that enters the aperture of the dihedral in a direction perpendicular to its axis is sent back out of the aperture in the direction from whence it came as result of a pair of specular reflections [2]. This double bounce can be reduced if the faces of the dihedral are angled further apart. The RCS patterns of these two dihedral corner reflectors are shown in Figure 5.

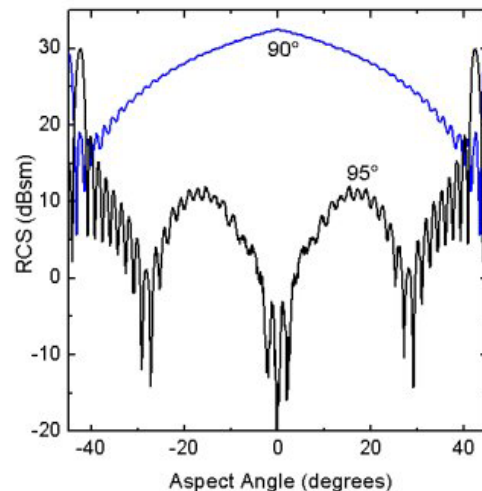


FIGURE 5

RCS OF A 90° AND A 95° CORNER DIHEDRALS. AT THE ASPECT ANGLE OF 0° BOTH FACES OF THE DIHEDRALS EXPOSE THE SAME AREA TO THE HYPOTHETICAL RADAR.

As it can be seen from Figure 5, a small change in the angle between the faces of the dihedral can have a dramatic effect on its RCS, and the results show a reduction of more than 40 dB at the center of the pattern. Simulation experiments with dihedrals with different dimensions would show that the larger the dihedral faces, the smaller is the angle needed to produce a significant reduction in the RCS. Another interesting result that can be obtained with CADRCS is depicted in Figure 6. In this figure is shown how the electromagnetic wave interacts with the surface of the metallic dihedral producing interference patterns caused by the interaction of the specular reflections.

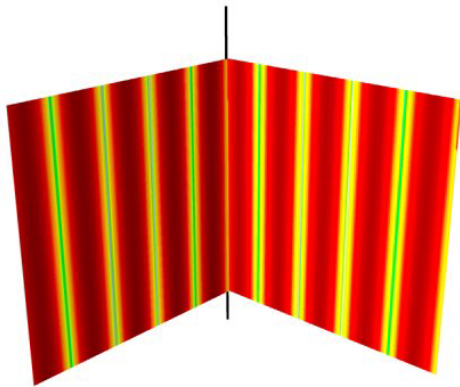


FIGURE. 6  
INTERFERENCE PATTERNS SHOWING REGIONS OF HIGH (DARK) AND LOW (LIGHT) REFLECTIVITY.

### Square Cavity

In Figure 1 is shown the model of the square cavity used in the simulations. The base of the cavity is a square with  $1 \text{ m}^2$  of area, and length of 3 m. The inner surface of the box was discretized into 43488 triangular elements.

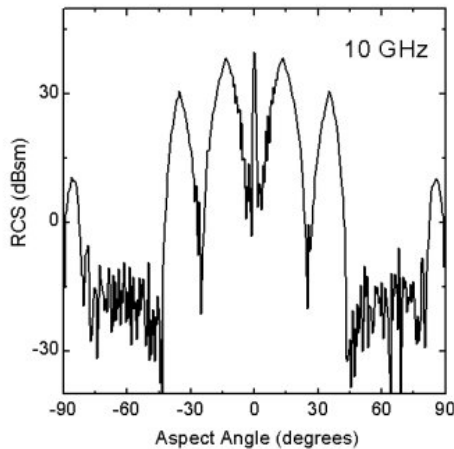


FIGURE. 7  
RCS PATTERN PRODUCED BY A SQUARE CAVITY (SEE FIGURE 1). AT THE ASPECT ANGLE OF  $0^\circ$ , THE CAVITY IS FACING THE HYPOTHETICAL RADAR. AT  $-90^\circ$  AND  $90^\circ$  THE SIDES OF THE CAVITY FACE THE RADAR.

In order to simulate only the response of the cavity itself to the incoming radar wave, the external surface of the model was coated with a radar absorbing material in the simulations. The simulation was performed with the box rotating with respect to a vertical axis at the entrance of the cavity. The radar frequency was 10 GHz. The RCS pattern produced by the cavity is shown in Figure 7. It is a rather complex pattern produced by the multiple reflections and their interactions within the cavity. Note also the presence of several lobes in the RCS pattern.

### Model Airplane

The surface of the model shown in Figure 2 was discretized into 19877 elements. As expected, the RCS pattern produced by the airplane model, shown in Figure 8, is more complex than the ones seen previously. A rather interesting result of this simulation is the fact that the RCS of the airplane can be smaller, depending on the aspect angle, than those of a flat plate (see Figure 3). This can be explained by the fact that curved surfaces have the property of scattering radar waves away from the observer and thus reducing the RCS of the target.

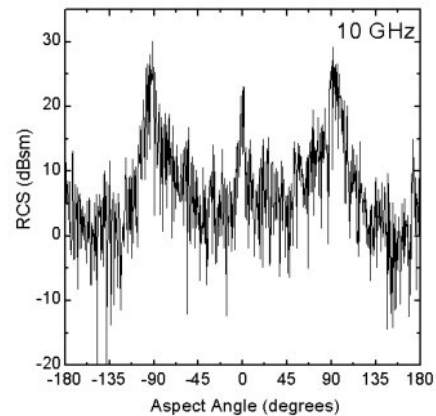


FIGURE. 8  
SIMULATED RCS OF THE MODEL OF AN AIRPLANE WITH A PERFECTLY CONDUCTING SURFACE AT 10 GHz. ROTATION IN YAW. THE ANGULAR POSITIONS OF  $0^\circ$ ,  $-90^\circ$  AND  $90^\circ$ , AND  $-180^\circ$  AND  $180^\circ$  CORRESPOND TO THE FRONT, SIDE AND REAR VIEWS OF THE MODEL, RESPECTIVELY.

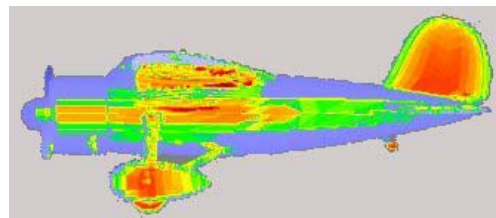


FIGURE. 9  
REFLECTIVITY OF THE SURFACE OF THE AIRPLANE MODEL. ASPECT ANGLE OF  $90^\circ$  AND FREQUENCY OF 10 GHz. THE BLUE COLOR REPRESENTS AREAS THAT DO NOT REFLECT RADAR WAVES IN THE DIRECTION OF THE OBSERVER. THE RED AND GREEN AREAS REPRESENT AREAS OF HIGH AND LOW REFLECTIVITY ON THE SURFACE OF THE MODEL, RESPECTIVELY.

In Figure 9 is shown the reflectivity of the side of the airplane. In this figure one can observe that flat areas of the model's fuselage and tail are very good radar reflectors.

## CONCLUSIONS

These examples show the potential of a simulation software to demonstrate some of the most important features related to the study of the RCS of targets. The software not only allows the calculation of the RCS of any object but also shows areas of high and low reflectivity on the surface of the targets being studied. By using this simulation tool we observed that our students could get a better grasp of the main concepts about the determination of RCS in a shorter time. Also, with the visualization of areas of high and low reflectivity on the surface of the targets, our students could suggest sensible strategies to alter the RCS of a target without having to resort to complex and time-consuming calculations.

## ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support received from the National Council for Scientific and Technological Development (CNPq, Brazil) and the Funding Agency for Studies and Projects (FINEP, Brazil)

## REFERENCES

- [1] "IEEE Standard Definitions for Terms for Antennas," *IEEE Trans. on Antennas and Propagation*, Vol. AP-37, June 1989, pp. 956-966.
- [2] Knott, E. F., Schaeffer, J. F. and Tuley, M., T. *Radar Cross Section*, Norwood, Artech House Inc., USA, 1993.
- [3] Labvolt (2007). Labvolt - Radar training system (8096). <http://www.labvolt.com>. Retrieved October, 2007.
- [4] CADRCS (2007). CADRCS - PC based radar cross section simulation software. <http://www.cadrcs.com>. Retrieved October, 2007.
- [5] Essen, H., Boehmsdorff, S., Briegel, G. and Wahlen, A. "On the Scattering Mechanism of Power Lines at Millimeter-Waves", *IEEE Trans. on Geoscience and Remote Sensing*, Vol. 40, No. 9, 2002, pp. 1895-1903.
- [6] Crispin, J. W. and Siegel, K. M. *Methods of Radar Cross-Section Analysis*, Academic Press, New Jersey, USA, 1968.
- [7] Mahafza, B.R. *Radar Systems Analysis and Design Using MATLAB*, Chapman & Hall, Oxford, UK, 2000.