A Novel Efficient Approach for Monostatic Radar Cross Section Calculation of Perfectly Conducting Complex Targets

Yacine Bennani[1], Youssef Kebbati[2], Sami Hebib[1]

Abstract – **In this paper, we have described a geometrical approach called linear projection-subdivision to compute the monostatic RCS of canonical and complex perfectly conducting objects based on the combination of geometrical and physical optics (GO-PO). This approach was modelled in Matlab and compared to ray-triangle intersection method in the case of a dihedral corner reflector. The results show a significant reduction in computing time. In addition, to validate the proposed linear projection-subdivision approach with a concrete case, we applied it to a more complex target, namely a generic boat. Thus, we have computed the monostatic RCS of the boat with taking into account simple and double reflection effects at 10 GHz. The obtained results validate the proposed method in terms of computational efficiency and prediction accuracy**

Keywords – **Radar Cross Section (RCS), Complex target, Physical Optics (PO), Geometrical Optics (GO), Shadowing effects, Multiple scattering, Computational time.**

I. INTRODUCTION

Prediction of scattering from a complex target is a subject of recent interest in the radar target recognition field [1]-[4]. The applications are varied, both in military and civilian fields [5,6], e.g., reconnaissance and surveillance of the objects in natural environment, such as a ship over rough sea surface, and search and rescue missions after an earthquake or an avalanche, etc. This led to technological advances in radar systems and their modelling tools in order to apprehend the interaction phenomena between the electromagnetic waves and the natural environment or a man-made target. An application of these modelling tools is calculating the radar cross section (RCS) [7] of complex targets which can be used for detection, characterization, and radar imagery [8,9]. The computation of the RCS for complex targets involves several kinds of scattering mechanisms, such as multiple scattering, specular reflection, diffraction by edges [10], creeping wave, surface wave, shadowing effect, etc. Several numerical [11,12] and asymptotic methods can be used to model these mechanisms [13,14].

Article history: Received March 07, 2022; Accepted December 09, 2022

[1]Yacine Bennani and Sami Hebib are with the Faculty of Technology, Electronic Department, University of Blida1, 09000 Blida, Algeria, E-mail: yacinebennani48@gmail.com, sami.hebib@gmail.com

[2]Youssef Kebbati is with the CNRS: LPC2E laboratory, University of Orleans, 3A Av. De la recherché scientifique, 45071 Orleans, France, E-mail: youssef.kebbati@cnrs-orleans.fr

Asymptotic techniques can be divided into two families [7,15-17].The first one, called ray asymptotic method, is based on the asymptotic expression for the scattered field, such as Geometrical Optics (GO) [7] and Uniform Theory of Diffraction (UTD) [7], [18]. The second family, called current asymptotic method, is based on the surface current distribution on the illuminated surface of the target. The scattered field is calculated as the scattering of these currents. An example of these current asymptotic methods is the Physical Optics (PO) which approximates the surface currents in order to obtain the fields [1], [4]. The choice of a method depends mainly on the characteristics of the object's surface, the frequency of the incident wave and the trade-off between results accuracy and computing time. Despite their accuracy, numerical methods are less efficient to compute the scattered field from 3D complex targets. In fact, a large amount of CPU time is required when taking into account the multiple scattering mechanisms among the different parts of these complex targets. For this reason, most recent simulators and studies are based on asymptotic methods which are faster and memory efficient in case of complex targets [1]-[3].

In this work, a novel efficient asymptotic approach, based on linear projection-subdivision technique, for monostatic RCS calculation is proposed. It takes into account simple and double reflection effects by combining Geometrical Optics (GO) and Physical Optics (PO) methods. Monostatic RCS at 10 GHz of two perfectly conducting (PEC) targets with triangular meshing are computed using the proposed approach. The first target is a dihedral corner reflector while the second one is a generic boat. As a first step, a geometrical pre-processing is performed, which consists in the determination of hidden triangular meshes and also those really contributing to the double reflection. The proposed approach was compared with the well-known ray-triangle intersection approach in the case of the first target (dihedral) and with Pofacets in the case of the second target (boat). The obtained numerical results validate the linear projection-subdivision approach and demonstrate its capability for monostatic RCS calculation of complex targets with reduced computational time. This approach is based on a linear projection of the three vertices of each triangular facet along the specular direction of the reflected ray, and then we linearly subdivide the new triangular facet until we reach the real boundary of the surface illuminated after the first reflection. Unlike the ray-triangle intersection method, the RCS calculationmay include non-illuminated surfaces, which can produce erroneous results, so this method needs to mesh the target with a very large number of triangular facets in order to be accurate, which means that the computation time increases accordingly. This model is useful for testing new detection and classification methods or designing the best operating configuration for maritime surveillance or ocean remote sensing. Other work in this field involves, for example, ISAR application, SAR polarization analysis for target classification [19], simulating SAR images through reflectance maps [20], or using commercial simulators to generate image databases of ground targets [21].

This paper is organized as follows. Section II introduces some theoretical background on geometrical modeling of complex targets and describes the two proposed approaches for monostatic RCS computation. In section III, the two approaches are numerically validated and compared at 10 GHz in the case of two PEC targets: dihedral corner reflector and a generic boat. Finally, the conclusion of this work is given in Section IV.

II. Geometrical Modelling of Complex Targets

For an object illuminated by an electromagnetic wave, the amount of backscattered energy is defined by its Radar Cross Section (RCS) value, which is given by the following relation

$$\boldsymbol{\sigma_{uv} = \lim_{R\to\infty}\left[4\pi R^2\left|\frac{\vec{E}_{s,u}}{\vec{E}_{i,v}}\right|\right]} \tag{1}$$

with $(u, v) = (\theta, \varphi)$, R is the distance between the receiver and the target, and $\vec{E}_{i,v}$ and $\vec{E}_{s,u}$ are respectively the incident and scattered electric field vectors. The first step in RCS computation is to model the target [7]. In this work, we have chosen to represent the target by a collection of triangular facets as shown in Fig. 1. In fact, the use of such model allows a good representation of complex targets and thereby achieving an accurate RCS calculation [22].

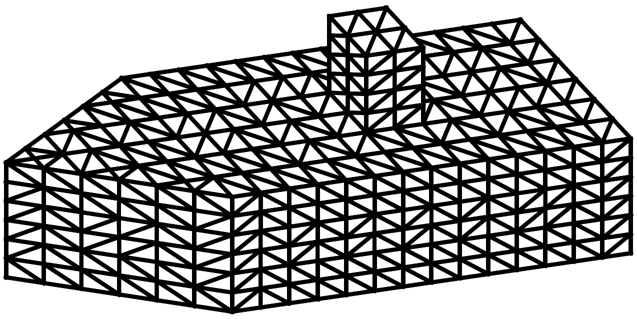
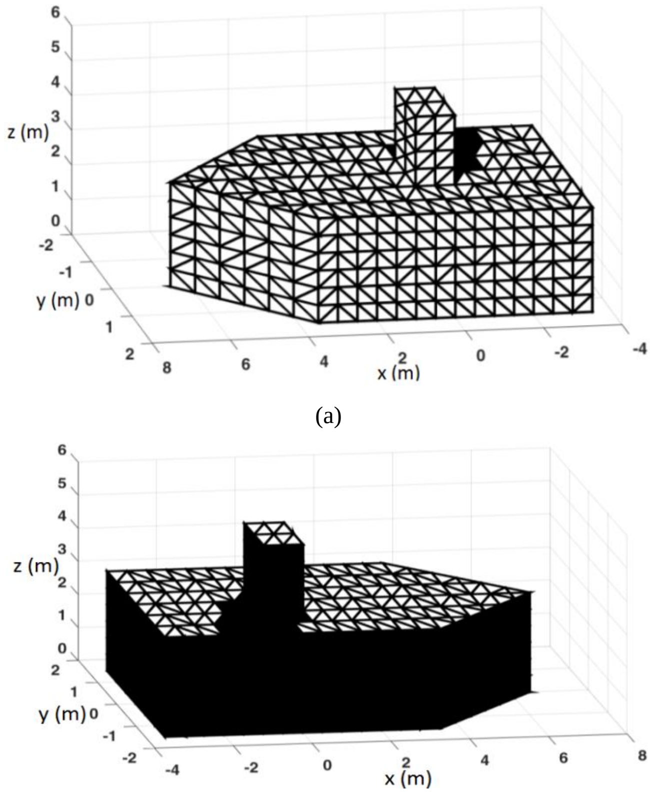


Fig. 1.Triangular mesh model of a generic boat.

A. Shadowing Effect

When a target intercepts an incident electromagnetic wave, a portion of its surface is illuminated and the rest remains dark. In fact, according to the propagation direction towards the target, some of its parts are hidden by other ones. A visibility test is then required since the RCS calculation takes into account only the illuminated parts of the target. In this work, the Möller–Trumbore ray-triangle intersection algorithm [23] is used for the visibility test. The main idea consists in checking whether the ray passing through a predetermined point of the first facet intersects with the second facet. Fig. 2 shows the results of the visibility test applied to a generic boat for a radar position given by ($\theta = \varphi = 45°$). The visible facets are represented in white color and the hidden ones are in black color. Once the real illuminated target by the incident wave is determined, the PO approximation is applied in order to calculate the contribution of Specular Reflection (SR).



(b)

Fig. 2.Shadowing effect for an observation direction given by θ = φ = 45°: (a) visible facets and (b) hidden facets.

B. Modeling of Specular Reflection

In order to compute the reflected field by a triangular facet in the specular direction, the Physical Optics (PO) method is chosen. As a matter of fact, this method is particularly suitable for electrically large objects and it is highly accurate in the specular direction [7]. According to the PO approximation [22], the reflected electrical field is given by the following equation.

$$\vec{E}_s = -\frac{jke^{-jkR}}{4\pi R}\oiint Z_0\vec{k}_s \times [\vec{k}_s \times \vec{J}] - [\vec{k}_s \times \vec{M}]e^{-jk\vec{k}_s\cdot\vec{r}}dS \tag{2}$$

where $\vec{J}$ and $\vec{M}$ represent the electric and magnetic currents on the surface, respectively, their expressions are given by:

$$\vec{J} = \vec{n} \times [\vec{H}_i + \vec{H}_r] \tag{3}$$

$$\vec{M} = -\vec{n} \times [\vec{E}_i + \vec{E}_r] \tag{4}$$

where $\vec{E}_i$; $\vec{E}_r$and $\vec{H}_i$; $\vec{H}_r$ represent the electric and magnetic incident and reflected fields, respectively. Eq. 2 is valid for $\vec{r}$ in S_i, where $S_i$is the illuminated surface. k is the wave number, R is the distance between the illuminated surface and the receiver, $\vec{k}_s$ is the unit vector in the direction of the receiver, and Z0 is the free space impedance; For a perfectly conducting surface, electric and magnetic currents become :

$$\vec{J} = 2\vec{n} \times \vec{H}_i \tag{5}$$

$$\vec{M} = \vec{0} \tag{6}$$

C. Modelling of Second Order Reflection

The study of multiple scattering is not a trivial subject and requires careful implementation. The combination of Geometrical and Physical Optics (GO-PO), developed in [1], [24], constitutes a solution for such multiple scattering problems. Multiple interactions are well approximated by GO while the contribution of the last reflection on the object surface is calculated using PO. Moreover, modelling complex targets in terms of facets reduces significantly the problem. In this work, the multiple scattering contributions are expressed in terms of facet-facet interaction using two approaches: (1) Ray-triangle intersection and (2) linear projection-subdivision.

1. Ray-Triangle Intersection Approach

The ray-triangle intersection consists in following the path of the incident ray in the specular direction. This approach provides quite good results when a large number of facets are used to model the target. However, by taking into account the facets that do not really contribute to the double reflection, this approach leads to an important computing time. Fig. 3 illustrates the principle of ray-triangle intersection in the case of a dihedral corner reflector.

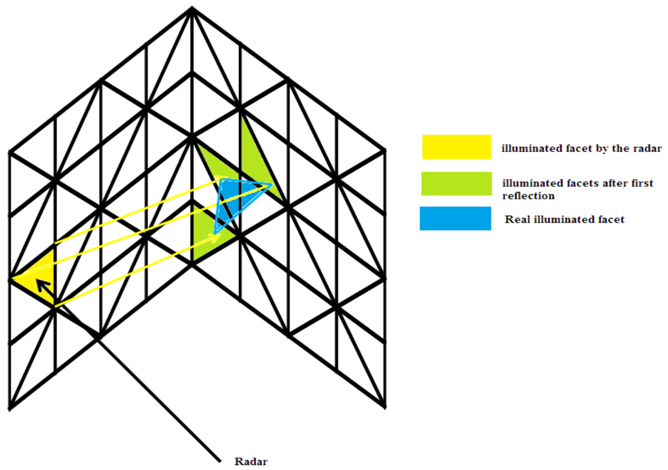
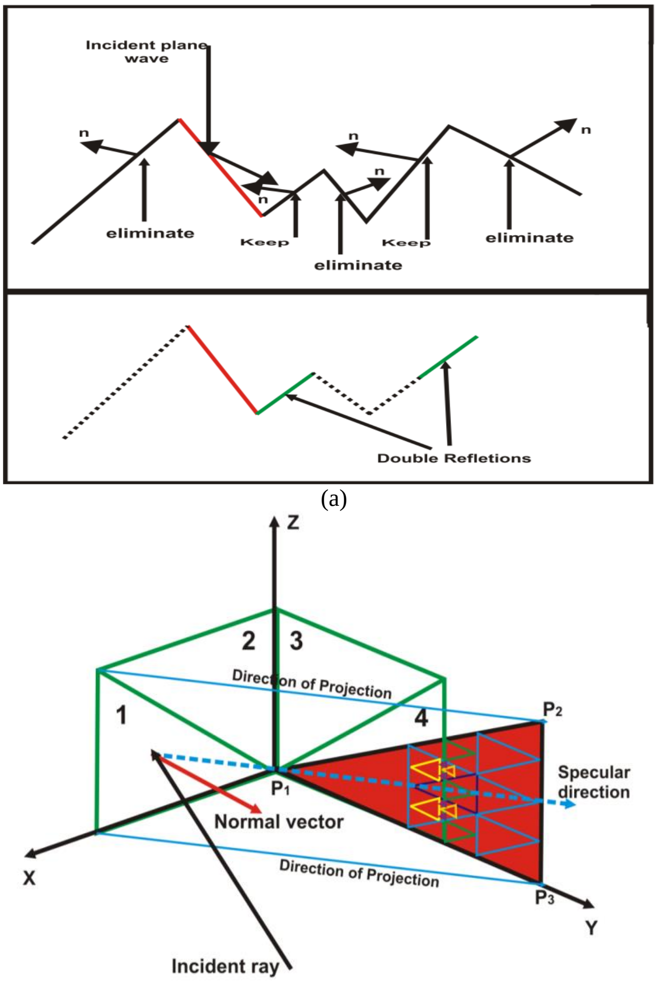


Fig. 3.Ray-triangle intersection principle.

2. Linear Projection-Subdivision Approach

The proposed linear projection-subdivision approach takes into account the double reflection contribution in the RCS calculation of complex targets. Its principle consists in finding all the facets which are subject to the double reflection mechanism. Firstly, as shown in Fig. 4(a), the first facet illuminated by an incident electromagnetic wave and all facets oriented towards it are identified. The double reflection is then expressed in terms of facet-facet interaction. Secondly, the illuminated facet along the specular directionis projected into the plane containing all facets candidate to the double reflectionand a linear subdivision is performed in order to obtain the real illuminated surface (Fig. 4(b)).



(b)

Fig.4. Linear projection-subdivision steps: (a) selection of candidate facets, (b) linear subdivision.

III. Numerical Results

In this section, the proposed linear projection-subdivision approach is used for monostatic RCS calculation of two perfect conducting (PEC) targets at 10 GHz. The first target is a simple dihedral corner reflector and the second one is a generic boat. For both cases, the multiple scattering contributions are taken into account. This approach is compared with the ray-triangle intersection approach in the case of the first target (dihedral) and with Pofacets in the case of the second target (boat). The ray-triangle intersection approach (called first approach) and linear projection-subdivision approach (called second approach) were implemented in Matlab and the calculation was performed using a desktop computer whose characteristics are:

- CPU: Processor Intel i7-4790 3.60 GHz
- Memory: 8GB
- Operating system: Windows 8.1 64-bits professional

A.Dihedral Corner Reflector

The first target to be considered is that of a simple dihedral corner reflector shown in Fig. 5. It is composed of two square PEC plates each with sides of 0.18 m with 90° interior angle. Fig. 6 shows this dihedral corner reflector modelled by 4, 64 and 216 triangular facets, respectively.

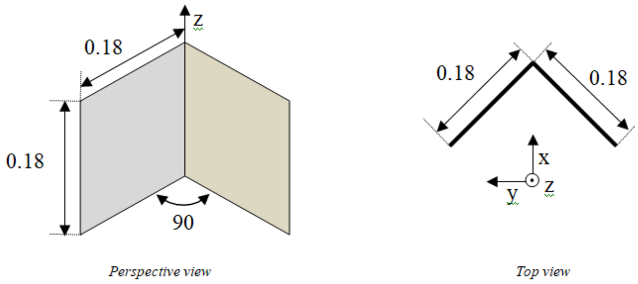


Fig.5.The PEC dihedral corner reflector geometry and dimensions.

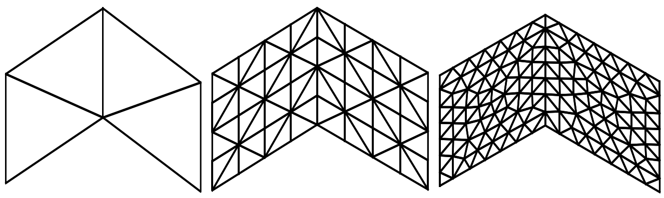


Fig. 6.Three models of PEC dihedral: (a) 4 facets, (b) 64 facets and (c) 216 facets.

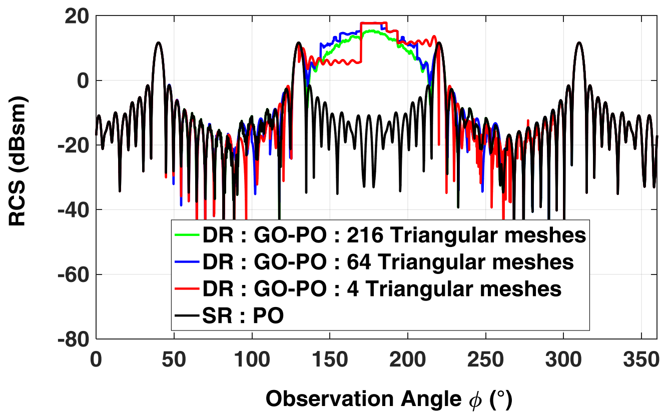


Fig. 7. Monostatic RCS of a PEC dihedral corner reflector at 10 GHz (first approach).

Fig. 7 presents the monostatic RCS at 10 GHz of the dihedral computed using the first approach, which is based on the ray-triangle intersection. The RCS is given for the three triangular facet models: 4 facets (red line), 64 facets (blue line) and 216 facets (green line). For comparison purposes, the computed RCS when considering only simple reflection (SR) contribution is also plotted in Fig. 7 (black line). The obtained results show the limit of this approach, particularly when a small number of facets are used. It is noted that increasing the number of facets would improve the precision, but at the expense of the computational time.

Fig. 8shows the monostatic RCS at 10 GHz of the dihedral computed using the second approach, which is based on the linear projection-subdivision technique. The computed RCS of the 4-facet dihedral model using the first and second approaches are compared in Fig. 8(a). It is noted that for a low number of triangular facets, the second approach (linear projection-subdivision) provides more accurate results than those obtained by the first approach (ray-triangle intersection). Fig. 8(b) shows the computed RCS by the second approach for the 4 facet model (blue line) compared to those computed by the first approach using 64 (red line) and 216 (black line) facet models. Unlike the first approach which requires a large number of triangular facets to obtain satisfactory results, the second proposed approach gives quite accurate results with only 4 triangular facets. Therefore, the use of the second approach allows a significant reduction in the computational time compared to the first approach. Table 1 summarizes the computational time of these two approaches for different number of triangular facets (4, 64 and 216). As can be seen from this table, the second approach is less time consuming than the first one for an identical number of triangular facets. In fact, using the second approach, instead of the first one, reduces the computational time by 87 %, 46 % and 50 % for 4, 64 and 216 triangular facets, respectively.

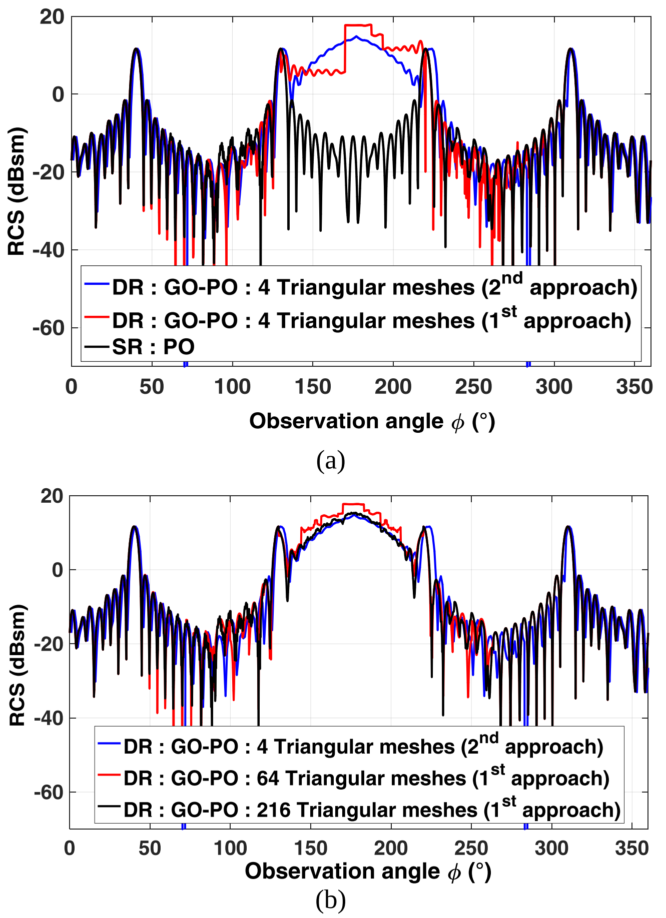


Fig. 8. Monostatic RCS of a PEC dihedral corner reflector at 10 GHz (first and second approaches).

TABLE 1
PERFORMANCE COMPARISON OF COMPUTATIONAL TIME
(PEC DIHEDRAL CORNER REFLECTOR)

Number of triangular facets	Computational time (in seconds)	
	First approach	Second approach
4	283	36
64	29487	15743
216	127393	63696

B. Generic Boat

A more complex target is considered in order to further validate the proposed second approach, which is based on the linear projection-subdivision technique. It consists of a PEC generic boat (10m length along the x-axis, 3m wide along the y-axis and 5m high along the z-axis) modeled with triangular facets as shown in Figs. 1 and 2. The obtained results in terms of monostatic RCS at 10 GHz are compared with those given by Pofacets, which is an implementation of the physical optics approximation for predicting the RCS of complex objects. Note that this comparison is achieved without taking into account the double reflection contribution, since multiple reflections, shadowing and edge diffraction are not supported in Pofacets. The RCS is calculated for two cases, without and with taking into account the multiple scattering effects.
By assuming the absence of multiple scattering, the second order reflection contribution due to the geometry of the target is neglected. Fig. 9 shows the computed monostatic RCS of the boat at 10 GHz for radar positions given by: φ=90°. The observation angle here is θranging from −90° to 90°. It is noted that the computed RCS using the proposed second approach (without double reflection contribution) is in a good agreement with that provided by Pofacets. The computational time, using the proposed second approach, was about 14107 seconds.

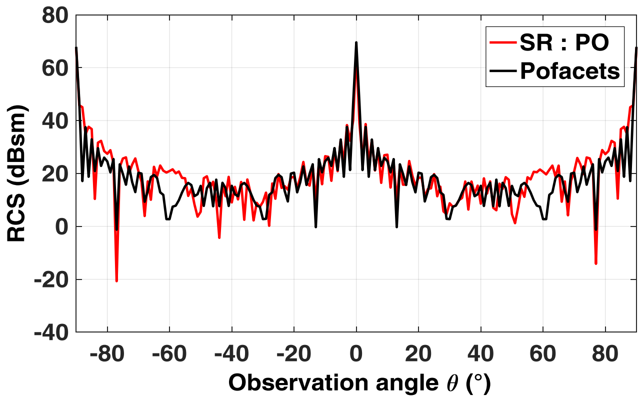


Fig. 9. Monostatic RCS of the PEC generic boat at 10 GHz (without multiple scattering): φ=90°.

By taking into account the multiple scattering effects, computed monostatic RCS of the generic boat at 10 GHz is given in Fig. 10. Two radar positions are considered: φ=0° (Fig. 10(a)) and φ=90° (Fig. 10(b)). In this case, the RCS computation lasts about 51051 seconds.

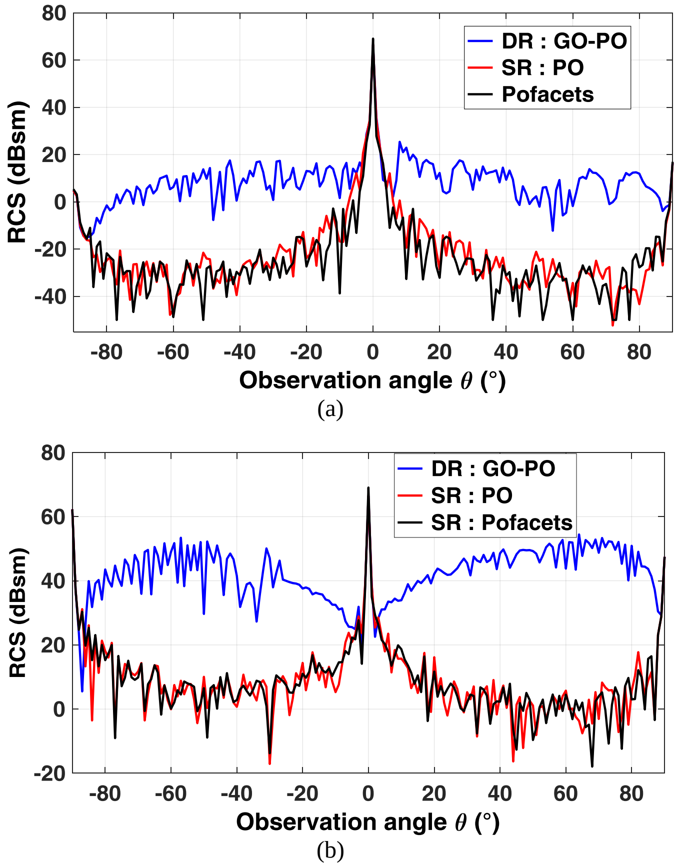


Fig. 10. Monostatic RCS of the PEC generic boat at 10 GHz (with multiple scattering): (a) φ=0° and (b) φ=90°.

As can be seen from Figs. 10(a) and 10(b), a good agreement of the computed RCS using the proposed second approach with Pofacets is found, when only the simple reflection is considered. The computed RCS taking into account the double reflection is quite different compared to that including only the simple reflection contribution. This difference emphasizes the importance of including the multiple reflection contribution in the RCS calculation of complex targets, but at the expense of longer computational time. In our case, considering the double reflection contribution increases the computational time by 72% and 47% for the radar positions given by φ = 0° (Fig. 10(a)) and φ = 90° (Fig. 10(b)), respectively.

IV. CONCLUSION

In this paper, a novel efficient asymptotic approach (GO-PO), based on linear projection-subdivision, for monostatic RCS calculation of canonical and complex targets is presented. It takes into account simple and double reflection effects on perfectly conducting targets. The proposed approach, implemented in Matlab, is compared with the well-known ray-triangle intersection approach in the case of a canonical target (dihedral corner reflector) and with Pofacets in the case of a complex target (generic boat). For an identical number of triangular facets of the dihedral reflector, the linear projection-subdivision approach allows a significant reduction in the computational time compared to the ray-triangle intersection approach (up to 87 % for 4 triangular facets). The computed RCS of a generic boat using linear projection-subdivision method (without double reflection contribution) is in a good agreement with that obtained by Pofacets. The RCS of the boat taking into account the double reflection effects is also calculated with the proposed approach, but with a significant increase in the computational time (up to 72% for the worst case). Finally, further work will deal with the improving of the proposed approach in order to take into account more scattering mechanisms such as the triple reflection and edge diffraction effects, which are neglected in this paper. Moreover, the bistatic case will be included in the linear projection-subdivision approach.This work can be improved by making collaboration with another laboratory with more efficient computing resources in order to test the algorithm for more complex targets and configurations.

REFERENCES

[1] O. Tulgar, K. Durgut and A. A. Ergin, "A Simple and Efficient SBR Implementation for RCS Calculation Using Target Scaling",*IEEE Transactions on Antennas and Propagation*, vol. 70, no. 5, pp. 3680-3687, May 2022, doi: 10.1109/TAP.2021.3137292.

[2] Y. Wang, Y. Li, and X. Zhang,"RCS Calculation based on Near Field L1-Regularized SAR Imaging", *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*,2021, pp.3277-3280,doi: 10.1109/IGARSS47720.2021.9554672.

[3] A. Murugesan, K.T.Selvan, A.K. Iyer, K.V. Srivatsav, and A. Alphones, "A Review of Metasurface-Assisted RCS Reduction Techniques", *Progress in Electromagnetic Research B*, vol. 94, pp. 75-103, 2021, doi:10.2528/PIERB21081401.

[4] N. Altin and E. Yazgan, "Radar Cross Section Analysis of a Square Plate Modeled with Triangular Patch", *Progress In Electromagnetics Research Symposium*, Kuala Lumpur, Malaysia, 27-30 March 2012, pp. 798-801.

[5] R. Firoozabadi, E.L. Miller, C.M. Rappaport, and A.W. Morgenthaler, "Subsurface Sensing of Buried Objects Under a Randomly Rough Surface Using Scattered Electromagnetic Field Data", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 1, pp. 104-117, Jan. 2007, doi: 10.1109/TGRS.2006.883462.

[6] S. Kidera, T. Sakamoto, and T. Sato, “High-Resolution 3-D Imaging Algorithm with an Envelope of Modified Spheres for UWB Through-the-Wall Radars”, *IEEE Transactions on Antennas and Propagation*, vol.57, no.11, pp. 3520-3529, November 2009, doi: 10.1109/TAP.2009.2032337.

[7] E.F. Knott, J.F. Shaeffer, and M.T. Tuley, *Radar Cross Section*, Artech House, Boston-London, 1993.

[8] F.T. Ulaby and C. Elachi, *Radar Polarimetry for Geoscience Applications*, Artech House, Norwood, MA, 1990.

[9] O. Airiau and A. Khenchaf,"A Methodology for Modeling and Simulating Target Echoes with a Moving Polarimetric Bistatic Radar", *Radio Science*, vol. 35, no. 3, pp. 773-782, May-June 2000, https://doi.org/10.1029/1999RS002158.

[10] N.N. Youssef, "Radar Cross Section of Complex Targets", *Proceeding of the IEEE*, vol. 77, no. 5, pp. 722-734, May 1989, doi: 10.1109/5.32062.

[11] L. Sevgi, *Complex Electromagnetic Problems and Numerical Simulation Approaches*, Wiley-IEEE Press, Hoboken, NJ, 2003.

[12] A. Ishimaru, *Electromagnetic Wave Propagation, Radiation and Scattering*, Prentice Hall, Englewood Cliffs, New Jersey, 1991.

[13] N. Engheta, W.D. Murphy, V. Rokhlin, and M.S. Vassiliou,"The Fast Multipole Method (FMM) for Electromagnetic Scattering Problems", *IEEE Transactions on Antennas and Propagation*, vol. 40, no.6, pp.634-641, June 1992, doi: 10.1109/8.144597.

[14] J. Song, C.-C. Lu, and W.C. Chew, "Multilevel Fast Multipole Algorithm for Electromagnetic Scattering by Large Complex Objects", *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 10, pp.1488-1493, October 1997, doi: 10.1109/8.633855.

[15] L. Gurel, H. Bagci, J.C. Castelli, A. Cheraly, and F. Tardivel, "Validation Through Comparison: Measurement and Calculation of the Bistatic Radar Cross Section of a Stealth Target", *Radio Science*, vol. 38, no. 3, pp. 12-1-12-8, June 2003, doi: 10.1029/2001RS002583.

[16] L. Sevgi and S. Paker,"FDTD Based RCS Calculations and Antenna Simulations", *AEU - International Journal of Electronics and Communications*, vol. 52, no. 2, pp. 65-75, 1998.

[17] L. Sevgi,"Target Reflectivity and RCS Interaction in Integrated Maritime Surveillance Systems Based on Surface Wave HF Radar Radars", *IEEE Antennas and Propagation Magazine*, vol. 43, no. 1, pp. 36-51, Feb. 2001, doi: 10.1109/ 74.920017.

[18] A.A. Kononov, A. Wyholt, G. Sandberg, and L. M.H. Ulander, "Statistical Analysis of VHF-Band Tree Backscattering Using Forest Ground Truth Data and PO Scattering Model", *IEEE Transactionson Geoscience and Remote Sensing*, vol. 49, no. 8, pp.3035-3046,August 2011, doi: 10.1109/TGRS.2011.2116158.

[19] G. Margarit, J.J.Mallaorqui, J.M.Rius, and J. Sans-Marcos, "On the Usage of GRECOSAR, an Orbital Polarimetric SAR Simulator of Complex Targets, to Vessel Classification Studies", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 44, no.12, pp.3517-3526, December 2006, doi: 10.1109/TGRS.2006.881120.

[20] S. Auer, S.Hinz, and R. Bamler,"Ray-Tracing Simulation Techniques for Understanding High-Resolution SAR Images", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 48, no. 3, pp. 1445-1456, March 2010, doi: 10.1109/TGRS. 2009.2029339.

[21] A.K.Mishra and B. Mulgrew, "Generation of SAR Image for Real-Life Objects Using General Purpose EM Simulators", *IETE Technical Review*, vol. 26, no. 1, pp. 18-27, Jan-Feb 2009.

[22] F. Weinmann,"Ray Tracing with PO/PTD for RCS Modeling of Large Complex Objects", *IEEE Transactions on Antennas and Propagation*, vol.54, no.6, pp.1797-1806, June 2006, doi: 10.1109/TAP.2006.875910.

[23] T. Moller and B. Trumbore, "Fast, Minimum Storage Ray/Triangle Intersection", *Journal of Graphics Tools*, vol. 2, no. 1, pp. 21-28, 1997.

[24] T. Griesser and C. Balanis,"Backscatter Analysis of Dihedral Corner Reflectors Using Physical Optics and the Physical Theory of Diffraction", *IEEE Transactions on Antennas and Propagation*, vol. 35, no.10, pp. 1137-1147, October 1987, doi: 10.1109/TAP.1987.1143987.