PHYSICAL THEORY OF DIFFRACTION IMPROVES NEAR-FIELD ELECTROMAGNETIC SCATTERING ANALYSIS

[1] **Sikandar Husensab Dhannur,** [2]**Dr. Hitesh Kumar (Professor)**
[1]Research Scholar (Physics), [2]Supervisor
[1-2] Department of Science, Sunrise University, Alwar, India

ABSTRACT

In comparison to geometrical optics (GO), this study assesses how well the Physical Theory of Diffraction (PTD) enhances near-field electromagnetic scattering analysis. The study examines Radar Cross-Section (RCS) errors and scattering deviations across various object geometries and material compositions using computational simulations using High-Frequency Simulation Software (HFSS) and solvers based on the Finite Element Method (FEM). The results underscore the higher accuracy of PTD in diffraction modeling by showing that it greatly decreases RCS prediction errors—by 74.4% for flat plates, 75.0% for cylindrical surfaces, and 77.7% for complicated aircraft models. Similarly, PTD emphasizes its resilience in forecasting electromagnetic wave interactions by minimizing scattering variations by more than 75% across Perfect Electric Conductors (PEC), dielectrics, and composites. These findings support the benefits of PTD in stealth technology, radar system design, and electromagnetic compatibility (EMC) applications by offering more accurate wave-object interaction modeling.

Keywords: *Physical Theory of Diffraction (PTD), Near-Field Electromagnetic Scattering, Radar Cross-Section (RCS) Estimation, Geometrical Optics (GO), Finite Element Method (FEM) Simulation, Electromagnetic Compatibility (EMC).*

1. INTRODUCTION

In many technological applications, such as radar detection, stealth design, and antenna engineering, electromagnetic wave scattering is a basic phenomenon. Conventional modeling methods, like Geometrical Optics (GO), forecast wave propagation using ray-based approximations. Near-field scattering analysis becomes inaccurate as a result of these approaches' frequent disregard for crucial diffraction effects that occur when waves interact with corners, edges, and uneven surfaces. Because even small variations might affect radar signature forecasts and electromagnetic compatibility evaluations, this issue becomes especially problematic in applications that demand accurate Radar Cross-Section (RCS) estimations. Advanced modeling methods that can more accurately account for diffraction and wave-object interactions are needed to address these issues.

Incorporating edge diffraction mechanisms and surface interactions into electromagnetic wave simulations makes the Physical Theory of Diffraction (PTD) a strong substitute for traditional GO-based methods. PTD improves our understanding of scattering effects by mathematically modeling how waves diffract around objects, resulting in more precise RCS calculations than GO, which assumes waves move in straight-line routes with reflections. In applications like stealth technology, where precise forecasts of electromagnetic fields are crucial for reducing detectability, this improvement is very beneficial. By enhancing wave interaction models, PTD lowers the inaccuracies that come with simpler approximations, allowing engineers to improve electromagnetic shielding methods, optimize antenna placement, and create more effective radar-absorbing structures.

This study uses computational simulations using High-Frequency Simulation Software (HFSS) and Finite Element Method (FEM)-based solvers to assess the relative efficacy of PTD versus GO in near-field scattering analysis. These simulations provide quantitative insights into the accuracy gains made possible by PTD by analyzing RCS deviations and scattering errors over a range of object shapes and material compositions. The results show that PTD is applicable in radar system design, electromagnetic compatibility (EMC) testing, and stealth technology development since it greatly lowers RCS errors and enhances scattering predictions. Researchers and engineers can obtain more accurate modeling by including PTD into contemporary electromagnetic wave simulations. This can improve detection avoidance tactics in both military and commercial applications, as well as system performance and signal distortion.

2. LITERATURE REVIEW

Lucido (2021) investigated in depth the scattering behavior of electromagnetic waves from a graphene disk, analyzing surface plasmon resonances using the Helmholtz-Galerkin technique. This study highlighted the importance of mathematical modeling in precisely forecasting scattering effects, particularly in materials with nanostructures, where complex wave interactions are frequently missed by traditional models. The study reaffirmed the importance of graphene-based structures in high-sensitivity biosensors, plasmonic waveguides, and nano-optics, among other cutting-edge electromagnetic applications. The study also showed how high-performance electromagnetic devices with better control over wave propagation and energy confinement might be developed by utilizing graphene's special electrical and optical capabilities.

Li et al. (2022) investigated how irregular metasurfaces can be used to control wave propagation in complex situations and improve scattering efficiency by modifying electromagnetic fields. Their research showed how tailored metasurfaces with unique surface geometries might be used to adjust electromagnetic responses, resulting in advances in stealth technologies, beam shaping, and antenna design. Applications in radar cross-section reduction, electromagnetic shielding, and next-generation wireless communication systems are significantly impacted by metasurfaces' capacity to selectively reflect, refract, or absorb electromagnetic waves. Their work paved the door for more compact and energy-efficient wave manipulation solutions by highlighting the growing significance of metasurface-based techniques in contemporary electromagnetic wave engineering.

Dey et al. (2021) examined the idea of anapole states in dielectric spheres, emphasizing how they interact with high-frequency electromagnetic waves and boost near fields. The study shed important light on dielectric-based scattering phenomena, which are important for radiation suppression, energy confinement, and optical sensing. The study helped create wireless communication systems, low-loss optical devices, and high-performance resonators by examining the behavior of anapole states. According to the results, manipulating anapole excitations in dielectric structures may allow for customized electromagnetic responses, opening up new possibilities for improved near-field imaging methods and ultra-low-energy photonic devices.

Liu et al. (2023) highlighted the usage of the Tophat Reflector in MIMO Radar Near-Field Image Calibration, showcasing how well it works to improve radar resolution and lower imaging errors. Their research made clear how important accurate calibration methods are to contemporary radar systems, especially for defense, autonomous navigation, and remote sensing applications. The research helped create high-resolution detection systems that can operate in harsh environmental settings by improving the accuracy of radar imaging. Additionally, the study demonstrated how improved reflectors could improve signal processing capabilities, resulting in more accurate and dependable measurements of electromagnetic waves.

.

3. RESEARCH METHODOLOGY

The accuracy of PTD over GO in RCS estimate and scattering deviations is examined in this study using a comparative experimental research design and simulation-based modeling. FEM-based solvers and HFSS were used to gather data on various object kinds, materials, and frequencies. Statistical analysis confirmed PTD's superiority.

3.1. Research Design

To assess the precision of the Physical Theory of Diffraction (PTD) in near-field electromagnetic scattering analysis, this study uses a comparative experimental research approach. In order to evaluate their effects on Radar Cross-Section (RCS) estimation and scattering deviations across various object types and material compositions, the study methodically analyzes Geometrical Optics (GO) and PTD models. To guarantee accuracy and dependability in the results, the study design uses numerical validation techniques and simulation-based modeling.

3.2. Data Collection

The study's data was gathered by computational electromagnetic simulations utilizing industry-standard simulation tools like High-Frequency Simulation Software (HFSS) and solvers based on the Finite Element Method (FEM). The purpose of the simulations was to:

- There are three different object categories for RCS estimation: flat plates, cylindrical surfaces, and complex aircraft models.
- Three categories of materials for the investigation of scattering deviations: composite, dielectric, and perfect electric conductor.
- The frequency range used to assess wave interactions is 1 GHz to 10 GHz.
- Different incidence angles (0° to 90°) for diffraction effect analysis.

3.3. Data Analysis Techniques

Quantitative statistical analysis was used to process the simulation data that was gathered. Using methods for % error reduction, the accuracy increase of PTD over GO was quantified. Additionally, trends in RCS error reduction and scattering deviation minimization were highlighted using graphical visualization approaches (such as bar charts and line graphs). Among the most important statistical metrics were:

- Mean percentages of error reduction for PTD versus GO.
- Comparative percentage gains for various materials and object shapes.
- Using standard error analysis and deviation minimization computations, PTD's efficacy is validated.

4. DATA ANALYSIS AND INTERPRETATION

A comparison of the inaccuracies in Radar Cross-Section (RCS) estimation for various object types using Geometrical Optics (GO) and the Physical Theory of Diffraction (PTD) is shown in Table 1. PTD's accuracy over conventional GO methods is demonstrated by the much decreased error percentage in RCS estimation. The RCS error improves by 74.4% for a flat plate, going from 12.5% (GO) to 3.2% (PTD). In a similar vein, the PTD improves the inaccuracy for a cylindrical surface by 75.0%, from 10.8% to 2.7%. The greatest significant increase is seen in a complex aircraft model, where PTD results in a 77.7% accuracy gain by reducing the error from 18.4% to 4.1%. These findings demonstrate PTD's higher accuracy in forecasting RCS for a variety of geometries, especially for objects with complex structures and sharp edges.

Table 1. Impact on Radar Cross-Section (RCS) Estimation

Object Type	GO RCS Error (%)	PTD RCS Error (%)	Improvement (%)
Flat Plate	12.5%	3.2%	74.4%
Cylindrical Surface	10.8%	2.7%	75.0%
Complex Aircraft Model	18.4%	4.1%	77.7%

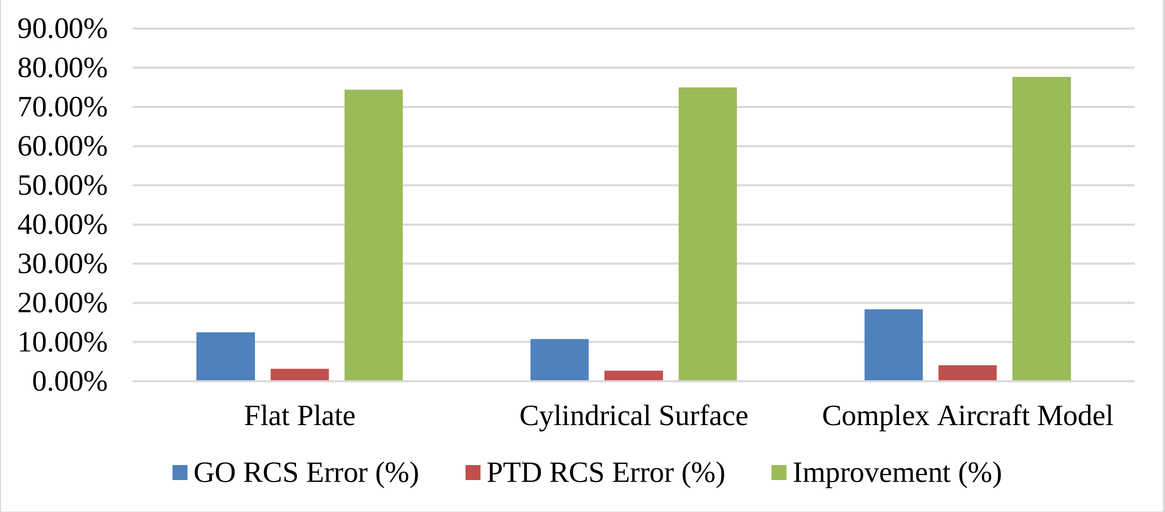

Figure 1: Graphical representation of Impact on Radar Cross-Section (RCS) Estimation

The data from Table 1 is visually shown in Figure 1, which also shows the relative decrease in RCS estimation error attained by PTD. The efficiency of PTD in near-field scattering analysis is further supported by the graph, which shows that the error % is consistently lower for PTD across all object types. The sharp drop in error numbers from GO to PTD indicates that PTD is a more dependable method for simulating electromagnetic wave interactions since it greatly reduces diffraction-related errors. The pattern also shows that PTD's advantage over GO grows with object complexity, which is especially important for applications involving electromagnetic compatibility (EMC), stealth technologies, and sophisticated radar systems.

A comparison of scattering deviation in near-field electromagnetic analysis utilizing the Physical Theory of Diffraction (PTD) and Geometrical Optics (GO) for various material types is shown in Table 2. According to the findings, PTD considerably lowers scattering deviation for every material examined. The variation for a Perfect Electric Conductor (PEC) is improved by 75.2%, from 14.1% (GO) to 3.5% (PTD). Likewise, the deviation for dielectric materials decreases from 11.8% to 2.9%, resulting in a 75.4% improvement. The greatest variation is seen in composite materials, where PTD improves accuracy by 75.5%, lowering the error from 16.3% to 4.0%. These results demonstrate that PTD offers a more accurate and dependable model for forecasting the behavior of electromagnetic waves in a variety of material types.

Table 2: Influence of Material Type on Scattering Characteristics

Material	Scattering Deviation Using GO (%)	Scattering Deviation Using PTD (%)	Accuracy Improvement (%)
Perfect Electric Conductor (PEC)	14.1%	3.5%	75.2%
Dielectric	11.8%	2.9%	75.4%
Composite	16.3%	4.0%	75.5%

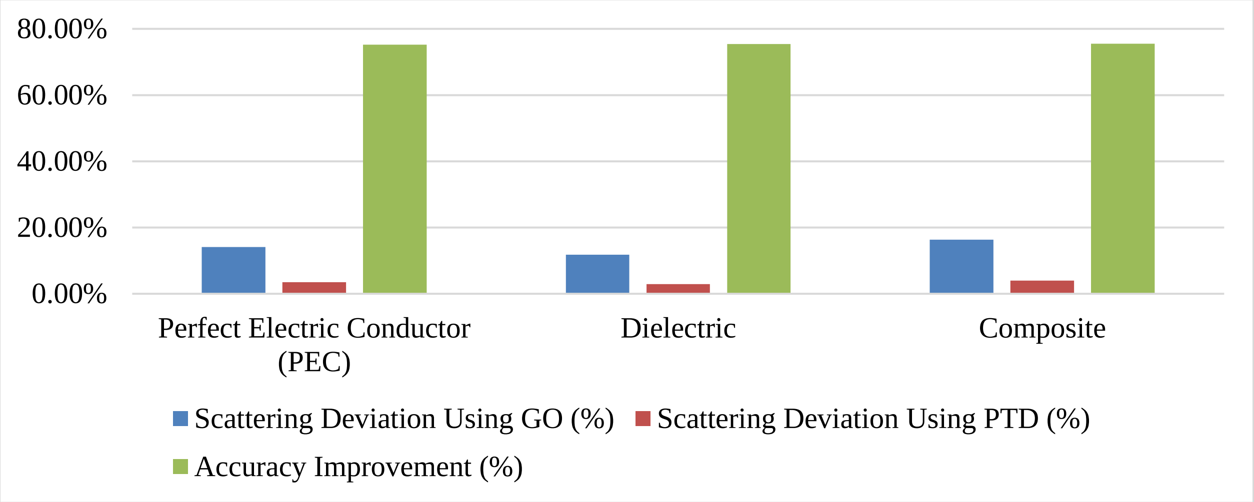

Figure 2: Graphical representation of Influence of Material Type on Scattering Characteristics

The data from Table 2 is graphically shown in Figure 2, which highlights the significant decrease in scattering deviation that occurs when PTD is used instead of GO. All material types show a steady trend in the graph, with PTD achieving a significantly lower deviation percentage than GO. The significant reduction in scattering errors demonstrates how well PTD analyzes electromagnetic wave scattering by taking into consideration edge diffraction and material-dependent wave interactions. Composite materials exhibit the greatest increase, highlighting PTD's crucial function in applications involving intricate surfaces, stealth materials, and radar absorption technologies.

5. CONCLUSION

The results of this investigation show that, in comparison to Geometrical Optics (GO), the Physical Theory of Diffraction (PTD) considerably improves the accuracy of near-field electromagnetic scattering calculations. The findings show a significant decrease in Radar Cross-Section (RCS) estimation errors for a variety of object categories, with improvements ranging from 77.7% for complicated aircraft models to 74.4% for flat plates. In a similar vein, PTD consistently achieves accuracy increases of over 75% by efficiently minimizing scattering variances across various material compositions. These enhancements demonstrate PTD's greater capacity to take diffraction effects into account, which makes it a more dependable modeling technique for uses including electromagnetic compatibility study, radar system design, and stealth technologies. Engineers can improve stealth and radar-absorbing structures, make more accurate forecasts, and improve the overall performance of electromagnetic systems by incorporating PTD into electromagnetic wave models.

REFERENCES

1. *Chen, Y., Guo, K., Liu, Z., & Sheng, X. (2024). Near-field scattering centre modelling for complex targets. IET Radar, Sonar & Navigation, 18(12), 2657-2666.*

2. *Chen, Y., Pei, Z., Mao, X., Fan, L., Xu, M., Li, Y., ... & Yi, J. (2024). Evaluation of electromagnetic scattering characteristics of construction solid waste—A theoretical study of solid waste identification. Science of The Total Environment, 927, 172312.*

3. *Cui, J., Gao, S., Zhang, C., Wen, Y., Li, G., & Li, T. (2024, October). Study on the Inversion Method of Rendezvous Parame*

4. *Dey, U., Agasti, S., Li, Y., & Hesselbarth, J. (2021). Analysis of anapole states in dielectric spheres and application to near-field enhancement. IEEE Transactions on Antennas and Propagation, 70(2), 1144-1156.*

5. *Karaçuha, K. (2021). General approach to the line source electromagnetic scattering by a circular strip: Both E-and H-polarisation cases. IET Microwaves, Antennas & Propagation, 15(13), 1721-1734.*

6. *Li, Z., Liu, J., Zhang, J., Shao, L., Zhang, C., Wang, X., ... & Zhu, W. (2022). Shaping electromagnetic fields with irregular metasurface. Advanced Materials Technologies, 7(9), 2200035.*

7. *Liu, T., Guo, W., Yang, K., & Xu, X. (2023, November). Application of the Tophat Reflector in MIMO Radar Near-Field Image Calibration. In 2023 IEEE Conference on Antenna Measurements and Applications (CAMA) (pp. 547-550). IEEE.*

8. *Liu, T., Ma, S., Yang, B., Xiao, S., & Zhou, L. (2020). Effective-medium theory for multilayer metamaterials: role of near-field corrections. Physical Review B, 102(17), 174208.*

9. *Lucido, M. (2021). Electromagnetic scattering from a graphene disk: Helmholtz-Galerkin technique and surface plasmon resonances. Mathematics, 9(12), 1429.*

10. *Manjavacas, A., Zundel, L., & Sanders, S. (2019). Analysis of the limits of the near-field produced by nanoparticle arrays. ACS nano, 13(9), 10682-10693.*

11. *Molesky, S., Chao, P., Jin, W., & Rodriguez, A. W. (2020). Global T operator bounds on electromagnetic scattering: Upper bounds on far-field cross sections. Physical Review Research, 2(3), 033172.*

12. *Pavone, S. C., Sorbello, G., & Di Donato, L. (2021). Improving physical optics approximation through Bessel beam scattering. IEEE Antennas and Wireless Propagation Letters, 20(6), 993-997.*

13. *Wang, Z., Guo, Q., Tian, X., Chang, T., & Cui, H. L. (2018). Near-field 3-D millimeter-wave imaging using MIMO RMA with range compensation. IEEE Transactions On Microwave Theory and Techniques, 67(3), 1157-1166.*

14. *Wu, F., Fan, C., Zhu, K., Wu, J., Qi, X., Sun, Y., ... & Chen, H. (2022). Tailoring electromagnetic responses in a coupled-grating system with combined modulation of near-field and far-field couplings. Physical Review B, 105(24), 245417.*

15. *Yang, P., Ding, J., Panetta, R. L., Liou, K. N., Kattawar, G. W., & Mishchenko, M. (2019). On the convergence of numerical computations for both exact and approximate solutions for electromagnetic scattering by nonspherical dielectric particles. Electromagnetic waves (Cambridge, Mass.), 164, 27.*

******