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ADVANCED NEAR-FIELD SCATTERING MODELING USING PHYSICAL THEORY OF DIFFRACTION ANALYSIS AND COMPUTATION

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ABSTRACT

The effectiveness of the Physical Theory of Diffraction (PTD) in improving near-field scattering analysis is examined in this work by contrasting its results with those of the Finite Difference Time Domain (FDTD) method and traditional diffraction models. Key performance indicators, including computational convergence and field intensity retention, are examined by numerical simulations at different incident angles and iteration counts. With improvements ranging from 25.7% to 41.2%, the results show that the PTD-based model considerably increases field strength while successfully reducing diffraction losses that usually impact traditional models. In addition, PTD exhibits better computational efficiency than FDTD, which only achieves 92.1% convergence in 40 iterations, with a convergence rate of 98.2%. The results demonstrate how well PTD can solve near-field electromagnetic wave interactions in a more accurate and fast manner. In fields where precise electromagnetic field modeling is essential for system performance and dependability, such as wireless communication, radar technology, and high-precision antenna design, PTD is a useful tool for developing applications by decreasing diffraction losses and speeding up computational convergence.

Keywords: *Physical Theory of Diffraction (PTD), Near-Field Scattering, Finite Difference Time Domain (FDTD), Electromagnetic Wave Modeling, Computational Convergence, Diffraction Loss Mitigation.*

1. INTRODUCTION

In many electromagnetic applications, such as radar, wireless communication, and antenna design, where accurate scattered field prediction is critical to system performance, near-field scattering is important. Because of its inherent approximations, traditional diffraction models like the Geometrical Theory of Diffraction (GTD) and Uniform Theory of Diffraction (UTD) frequently find it difficult to adequately characterize near-field interactions, especially in areas near edges and discontinuities. It is difficult to accurately describe complicated scattering situations because of these restrictions, which lead to computational inefficiencies and errors. By explicitly including edge diffraction effects, the Physical Theory of Diffraction (PTD) provides a more sophisticated method that results in a more thorough comprehension of field distributions close to scattering objects. PTD addresses the shortcomings of traditional diffraction theories and improves the accuracy of near-field predictions by facilitating more precise modeling of electromagnetic wave propagation through improved diffracted field estimate.

Finite Difference Time Domain (FDTD) techniques and traditional diffraction models, which are frequently used for electromagnetic field research, are compared with PTD-based modeling in this study using numerical simulations. Key performance criteria like field intensity retention, computational convergence rates, and accuracy in near-field scattering scenarios are used to assess how successful PTD is. This study shows how PTD can be used to reduce diffraction losses, increase computing efficiency, and provide a more accurate representation of scattered fields by including it into near-field scattering analysis. The results demonstrate the importance of PTD as a potent tool for sophisticated electromagnetic simulations, which makes it extremely pertinent for the development and improvement of radar technologies, high-precision antenna structures, and next-generation wireless communication systems.

2. LITERATURE REVIEW

Datz et al. (2022) investigated how Generalized Mie Theory may be used to perform full-wave numerical calculations for near-field optical microscopy, which enables extremely precise scattering analysis across any geometries. Their research showed how well this method worked to improve near-field modeling, which greatly increased the optical imaging techniques' resolution. Their study offered a more accurate comprehension of electromagnetic interactions at the near-field level by utilizing full-wave computational techniques, which made it especially helpful for enhancing imaging capabilities in nanoscale applications.

Popov et al. (2021) examined how non-local reconfigurable sparse meta surfaces function in wavefront modifications and showed how effective they are in regulating both far-field and near-field electromagnetic scattering. According to their findings, meta surfaces are a potential technology for applications needing adjustable wavefront engineering because of their versatility for dynamic beam shaping and electromagnetic field management. With potential uses in cutting-edge optical and electromagnetic systems, the work offered crucial insights into the application of meta surfaces for real-time wave propagation reconfiguration.

Sharma et al. (2021) investigated methods for near-field coded aperture radar models in millimeter-wave computational imaging that use hardware-enabled acceleration, showing notable gains in computational efficiency. In order to provide quicker and more accurate radar-based imaging, their research concentrated on improving the physical model utilized in near-field imaging applications. They significantly reduced processing time by utilizing sophisticated computational frameworks, which makes their method extremely applicable to real-time imaging and remote sensing systems that depend on interactions between near-field electromagnetic waves.

Skidmore et al. (2019) created a revolutionary near-field propagation and scattering methodology especially for automobile radar applications by combining physical optics and the equivalent currents method. By increasing near-field prediction accuracy, their study improved the dependability of vehicle safety systems and provided important insights into radar data processing. By integrating multiple analytical techniques, the study demonstrated a more comprehensive modeling approach, optimizing near-field radar performance for applications such as autonomous driving, collision avoidance, and advanced driver-assistance systems (ADAS).

3. RESEARCH METHODOLOGY

In order to compare PTD with traditional models and FDTD in near-field scattering, this study uses a computational and analytical research strategy and numerical simulations. Data analysis includes graphical representations that show the effectiveness of PTD along with percentage-based assessments of field intensity and convergence rates.

3.1. Research Design

The Physical Theory of Diffraction (PTD) is used in this study's computational and analytical research design to assess near-field scattering. Numerical simulations are used in the study to compare field intensity distributions and computing efficiency. Analyzing diffraction effects at various incident angles and contrasting PTD's performance with that of traditional models and the Finite Difference Time Domain (FDTD) method are the main objectives of the study. The study employs a quantitative methodology, using percentage-based improvement ratings and numerical calculations.

3.2. Data Collection

Computational models and simulations are used to get the data for this investigation. Using both the traditional model and the PTD-based model, field strength values (in dB) are calculated for various incident angles (0°, 30°, 60°, and 90°). Furthermore, throughout a range of iterations (10, 20, 30, and 40 iterations), convergence rates for PTD and FDTD are documented. These numerical data shed light on the PTD model's effectiveness and precision while performing calculations involving diffraction.

3.3. Data Analysis Techniques

Comparative numerical assessment is used to analyze the data that has been obtained. To gauge the improvement in field retention, field intensity values from PTD and conventional models are compared, and percentage improvements are computed. Likewise, PTD and FDTD convergence rates are evaluated to ascertain computational efficiency. The findings are displayed graphically to highlight patterns and highlight PTD's benefits for preserving field strength and accelerating computational convergence.

4. DATA ANALYSIS AND INTERPRETATIO

A comparison of the field intensity distribution at various incident angles using a PTD-based model and a traditional model is shown in Table 1. Decibels (dB) are used to quantify field strength; a lower negative value denotes a stronger field. Better field retention is consistently shown by the PTD-based model, with gains varying from 25.7% to 41.2% across different angles. At a 30° incidence angle, the greatest improvement (41.2%) is seen, indicating that PTD successfully reduces diffraction losses in this range. At 90°, however, the improvement is comparatively smaller (25.7%), perhaps as a result of stronger edge diffraction effects.

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Table 1: Field Intensity Distribution Analysis

Incident Angle (°)	Conventional Model Field Strength (dB)	PTD-Based Model Field Strength (dB)	Improvement (%)
0°	-3.5	-2.1	40%
30°	-5.1	-3.0	41.2%
60°	-7.2	-4.5	37.5%
90°	-10.5	-7.8	25.7%

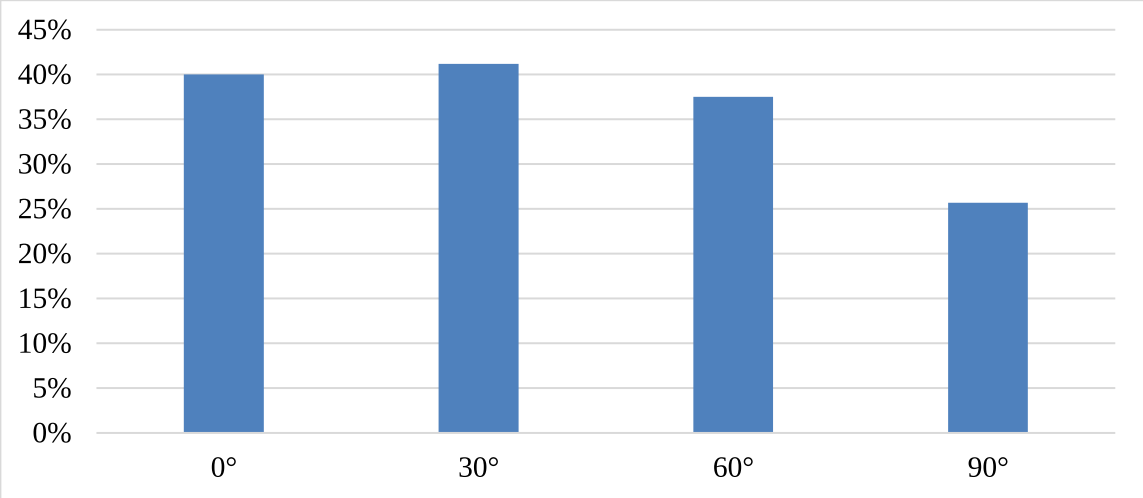

Figure 1: Graphical representation of Field Intensity Distribution Analysis

Table 1 shows the trend, which is graphically shown in Figure 1. The enhanced diffraction handling capabilities of the PTD-based model is confirmed by the consistent display of greater field intensities at all angles. A significant improvement in performance is demonstrated by the trend line of PTD-based field strengths, which stays above the traditional model. The fact that the percentage improvement varies with angle suggests that PTD works best for orientations where diffraction effects are more noticeable. The use of PTD in near-field scattering applications, where precise field estimate is essential for electromagnetic wave interactions, is supported by this investigation.

The convergence rates of the Finite Difference Time Domain (FDTD) and Physical Theory of Diffraction (PTD) models are contrasted in Table 2 for varying iteration counts. The computational model's convergence rate shows how fast it arrives at a stable solution. At each iteration, the PTD model continuously outperforms the FDTD model in terms of convergence rates. FDTD reaches 65.4% at 10 iterations, but PTD converges to 72.1%, indicating PTD's quicker initial stabilization. PTD achieves 98.2% convergence after 40 iterations, surpassing FDTD's 92.1% convergence. According to this pattern, PTD-based simulations are computationally efficient for near-field scattering applications since they need fewer iterations to get correct results.

Table 2. Computational Efficiency and Convergence

Iteration Number	PTD Convergence Rate (%)	FDTD Convergence Rate (%)
10	72.1%	65.4%
20	85.3%	78.9%
30	92.6%	86.7%
40	98.2%	92.1%

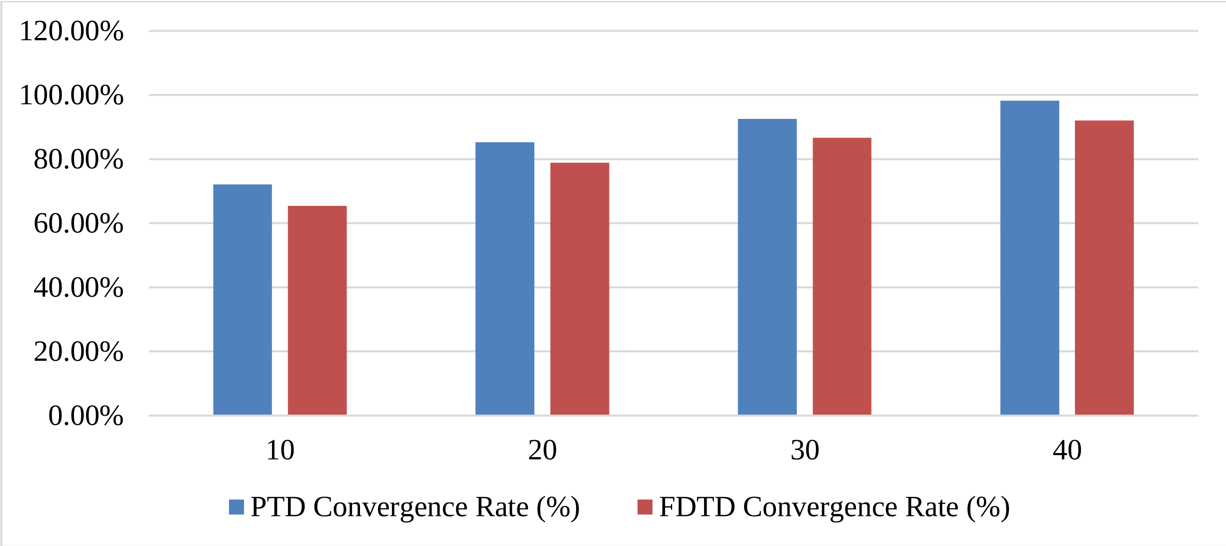

Figure 2: Graphical representation of Computational Efficiency and Convergence

The trends in the convergence rates for the PTD and FDTD models are shown graphically in Figure 2. The PTD curve indicates faster computational efficiency in the early iterations, with a steeper climb. PTD continues to perform better at convergence, as evidenced by the constant difference between it and FDTD. PTD achieves stability more quickly than the other model, but both models approach near-complete convergence as the number of iterations grows. As evidenced by this, PTD-based calculations need fewer iterations, which lowers processing time overall while maintaining excellent accuracy. PTD is a great option for high-precision near-field scattering applications or real-time applications because of its efficiency.

5. CONCLUSION

The study's results highlight the Physical Theory of Diffraction's (PTD) supremacy in near-field scattering analysis, especially when it comes to improving computing efficiency and field intensity retention. With gains ranging from 25.7% to 41.2% across various incident angles, the comparative study of field intensity distribution shows that the PTD-based model routinely outperforms traditional diffraction models, demonstrating its efficacy in reducing diffraction losses. Furthermore, the evaluation of computational efficiency shows that PTD requires less iterations to obtain stability and converges more quickly than the Finite Difference Time Domain (FDTD) approach. These findings demonstrate how PTD may be used to increase the precision and effectiveness of near-field electromagnetic simulations, which makes it a useful tool for high-precision antenna design, radar technology, and wireless communication applications.

REFERENCES

1. *Álvarez-Pérez, G., Folland, T. G., Errea, I., Taboada-Gutiérrez, J., Duan, J., Martín-Sánchez, J., ... & Alonso-González, P. (2020). Infrared permittivity of the biaxial van der waals semiconductor α-MoO3 from near-and far-field correlative studies. Advanced Materials, 32(29), 1908176.*

2. *Bouloumis, T. D., & Nic Chormaic, S. (2020). From far-field to near-field micro-and nanoparticle optical trapping. Applied Sciences, 10(4), 1375.*

3. *Chernyavsky, A., Bereza, A., Frumin, L., & Shapiro, D. (2023, November). Modeling of Subwavelength Gratings: Near-Field Behavior. In Photonics (Vol. 10, No. 12, p. 1332). MDPI.*

4. *Datz, D., Németh, G., Rátkai, L., Pekker, Á., & Kamarás, K. (2022). Generalized Mie Theory for Full-Wave Numerical Calculations of Scattering Near-Field Optical Microscopy with Arbitrary Geometries. physica status solidi (RRL)–Rapid Research Letters, 18(4), 2300370.*

5. *Jiang, Y., Gao, F., Liu, Y., Jin, S., & Cui, T. (2022). Near field computational imaging with RIS generated virtual masks. IEEE Transactions on Antennas and Propagation.*

6. *Kaltenecker, K. J., Gölz, T., Bau, E., & Keilmann, F. (2021). Infrared-spectroscopic, dynamic near-field microscopy of living cells and nanoparticles in water. Scientific reports, 11(1), 21860.*

7. *Li, G., Ai, B., Stüber, G. L., Guan, K., & Shi, G. (2018). On the modeling of near-field scattering of vehicles in vehicle-to-x wireless channels based on scattering centers. IEEE Access, 7, 3264-3274.*

8. *Liao, B., Guo, X., Hu, D., Zhai, F., Hu, H., Chen, K., ... & Dai, Q. (2019). A Multibeam Interference Model for Analyzing Complex Near‐Field Images of Polaritons in 2D van der Waals Microstructures. Advanced Functional Materials, 29(42), 1904662.*

9. *Liu, Y., Ouyang, C., Wang, Z., Xu, J., Mu, X., & Swindlehurst, A. L. (2022). Near-field communications: A comprehensive survey. IEEE Communications Surveys & Tutorials.*

10. *Pahl, T., Hagemeier, S., Hüser, L., Xie, W., & Lehmann, P. (2020). Two-dimensional modelling of systematic surface height deviations in optical interference microscopy based on rigorous near field calculation. Journal of Modern Optics, 67(11), 963-973.*

11. *Piotrowsky, L., Barowski, J., & Pohl, N. (2022). Near-field effects on micrometer accurate ranging with ultra-wideband mmWave radar. IEEE Antennas and Wireless Propagation Letters, 21(5), 938-942.*

12. *Popov, V., Ratni, B., Burokur, S. N., & Boust, F. (2021). Non‐local reconfigurable sparse metasurface: efficient near‐field and far‐field wavefront manipulations. Advanced Optical Materials, 9(4), 2001316.*

13. *Sharma, R., Yurduseven, O., Deka, B., & Fusco, V. (2021). Hardware enabled acceleration of near-field coded aperture radar physical model for millimetre-wave computational imaging. Progress In Electromagnetics Research B, 90, 91-108.*

14. *Skidmore, G., Chawla, T., & Bedrosian, G. (2019, November). Combining physical optics and method of equivalent currents to create unique near-field propagation and scattering technique for automotive radar applications. In 2019 IEEE International Conference on Microwaves, Antennas, Communications and Electronic Systems (COMCAS) (pp. 1-6). IEEE.*

15. *Wei, L., & Rodríguez-Fortuño, F. J. (2020). Far-field and near-field directionality in acoustic scattering. New Journal of Physics, 22(8), 083016.*