

HELIOS: Light scattering in homogeneous, periodic, and stratified systems with a surface integral approach

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The rigorous modeling of light-matter interactions in stratified environments is essential for modern nanophotonics, not only to understand fundamental phenomena, but also to study experimentally-relevant applications such as optical antennas, biosensing platforms, and multilayer semiconductor devices, to name a few. Surface integral equation (SIE) methods provide an efficient framework for these problems because they restrict the unknowns to material interfaces and inherently satisfy radiation conditions [1]. However, extending SIE formulations to layered media requires the use of dyadic Green's tensors that rigorously account for reflection and transmission at planar interfaces. The mathematical complexity and numerical cost associated with these Green's functions have historically limited the efficiency and robustness of layered SIE solvers.

In this work we present HELIOS, a C++ implementation of a SIE framework designed to overcome these limitations. HELIOS models arbitrary penetrable scatterers embedded in stratified backgrounds without increasing the number of unknowns compared to homogeneous formulations. The solver relies on a matrix-friendly representation [2] of the layered Green's tensor, ensuring compatibility with standard Rao-Wilton-Glisson discretization and Galerkin testing within the Poggio-Miller-Chang-Harrington-Wu-Tsai formulation. By transferring differential operators from the Green's kernels to the basis and testing

functions, the resulting system matrix remains stable and well structured, enabling an efficient numerical implementation [3].

A major challenge in layered SIE approaches is the evaluation of Sommerfeld integrals describing the secondary (indirect) contribution of the Green's tensor. These integrals encode all reflection and transmission processes at planar interfaces and must be handled carefully to ensure convergence and numerical stability. HELIOS employs stable contour integration strategies in the complex plane, with integration paths selected according to the vertical separation between source and observation points [4].

To address the singular behavior inherent to layered Green's functions, HELIOS incorporates a singularity extraction procedure that analytically isolates quasi-static contributions [6]. This guarantees stable matrix assembly even when scatterers are directly on, or intersect, layer interfaces. In addition, a tabulation-interpolation scheme is used to accelerate matrix filling: the smooth part of the Green's function is precomputed and interpolated, while the quasi-static contribution is treated analytically [7]. This significantly reduces computational overhead without compromising precision.

The performance of the framework is demonstrated for a gold nanoscatterer embedded in a stratified medium, as shown in Fig. 1. The geometry consists of a single penetrable metallic particle discretized with a triangular surface mesh, illustrated in Fig. 1(a). The surrounding environment is a three-layer system (air-dielectric-air), where the dielectric slab has relative permittivity $\varepsilon_r = 2.25$ and is bounded by planar interfaces located at $z_1 = 0$ nm and $z_2 = 50$ nm. The structure is illuminated by a plane wave propagating in the $-z$ direction and polarized along the x -axis.

Panels (b) and (c) of Fig. 1 present the total electric near-field intensity distributions in the $y = 0$ plane at an excitation wavelength of $\lambda = 500$ nm. The horizontal lines indicate the positions of the two interfaces delimiting the dielectric slab. The field maps clearly show the influence of the layered background on the spatial distribution of the electromagnetic field. The

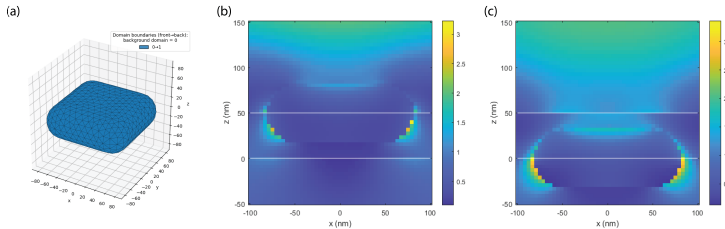


Figure 1: Au nanoscatterer embedded in a stratified medium. (a) Discretized surface mesh of the scatterer’s geometry, and (b)-(c) total electric near-field distributions in the $y = 0$ plane at an excitation wavelength of $\lambda = 500$ nm. The system is illuminated by a plane wave propagating in the $-z$ direction and polarized along the x -axis. The layered background consists of a dielectric slab ($\epsilon_r = 2.25$) bounded by air, with interfaces located at $z_1 = 0$ nm and $z_2 = 50$ nm.

presence of the dielectric slab significantly modifies the vertical field profile. The field intensity is redistributed across the interfaces, with visible discontinuities in slope at the slab boundaries, reflecting the change in material properties. Part of the electromagnetic energy is confined within the dielectric layer, while another portion extends into the surrounding air regions.

The comparison of the near-field distributions highlights the sensitivity of the electromagnetic response to the layered background. The solver accurately captures both the local field enhancement near the particle surface and the global redistribution of energy induced by the slab. The smooth transitions across regions, together with the correct enforcement of boundary conditions at the planar interfaces, confirm the robustness of the layered Green’s tensor implementation and the stability of the numerical scheme.

Overall, these results demonstrate that HELIOS models reliably light scattering by nanostructures embedded in stratified media, resolving fine near-field features while rigorously accounting for multiple reflections and transmissions within the

layered background.

References

- [1] P. S. Mavrikakis and O. J. F. Martin, *Surface integral equations in computational electromagnetics: A comprehensive overview of theory, formulations, discretization schemes and implementations*, Appl. Comput. Electromagn. Soc. J., **40**, (2025), no. 4, 279–301.
- [2] W. C. Chew, J. L. Xiong, and M. A. Saville, *A matrix-friendly formulation of layered medium Green's function*, IEEE Antennas Wireless Propag. Lett., **5** (2006), 490–494.
- [3] Y. P. Chen, W. C. Chew, and L. Jiang, *A new Green's function formulation for modeling homogeneous objects in layered medium*, IEEE Trans. Antennas Propag., **60** (2012), no. 10, 4766–4776.
- [4] M. Paulus, P. Gay-Balmaz, and O. J. F. Martin, *Accurate and efficient computation of the Green's tensor for stratified media*, Phys. Rev. E, **62** (2000), 5797–5807.
- [5] W. C. Chew, M. S. Tong, and B. Hu, *Integral Equation Methods for Electromagnetic and Elastic Waves*, Morgan & Claypool, San Rafael, 2008.
- [6] U. Hohenester, *Nanophotonic resonators in stratified media with the nanobem toolbox*, Comput. Phys. Commun., **294** (2024), 108949.
- [7] S. Pratama and D. van Oosten, *Efficient and versatile surface integral approach to light scattering in stratified media*, Opt. Express, **23** (2015), no. 17, 21741–21760.